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THE GEOLOGY OF THE LAKE SUPERIOR REGION

BY

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AND

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THE GEOLOGY OF THE LAKE SUPERIOR REGION.

By C. R. Van Hise and C. K. Leith.

CHAPTER I. INTRODUCTION.

OUTLINE OF MONOGRAPH.

The Lake Superior region is a part of the southern margin of the great pre-Cambrian shield of northern North America. It is bordered and overlapped on the south by Paleozoic rocks of the Mississippi Valley and on the southwest by Cretaceous deposits. The pre-Cambrian rocks of the area, which may be divided into a considerable number of lithologic and time units, contain the great iron and copper deposits by which the region is most widely known. The great development of the mineral industry in this region has afforded the geologist unusual opportunity for study, as it has not only made the region more accessible but has justified larger expenditures for geologic study than would otherwise have been made. This fortunate combination of a field containing an exceptionally full record of a little-known part of the geologic column with the means of studying it has warranted the study of the pre-Cambrian with a degree of detail that has been practicable in but few other significant pre-Cambrian regions.

Geologic surveys of various parts of the Lake Superior region have been conducted under national, state, and private supervision almost without interruption since the early part of the nineteenth century, especially since the opening of the mining industry in the middle of the century. The later reports have naturally been more adequate than the earlier ones, because they have included the results of the earlier work and have gained the advantage derived from the greater accessibility of the district. The reports thus far issued have dealt with small parts of the region or with certain phases of its general geology. State and private surveys have necessarily worked within prescribed areas, so that notwithstanding the multiplicity of reports certain parts of the region have not yet been adequately covered. It has been the proper function of the United States Geological Survey to make detailed surveys designed to accomplish the uniform treatment and correlation of the several ore-bearing districts, and finally to publish a monographic report on the region as a whole. Work under a general plan for these surveys was begun in the early eighties under the direction of Prof. R. D. Irving, whose monograph on the copper-bearing rocks of Lake Superior [a] appeared in 1883, though it was partly prepared at an earlier date, while he was connected with the Wisconsin Geological Survey. The development of this plan has since been continuous. Until 1888 the work was in charge of Professor Irving; since that time it has been under the direction of Dr. Charles R. Van Hise, the senior author of this monograph. Detailed monographs on the five leading iron ranges have been published and also papers covering different phases of the general geology of the region.

This monograph represents the first attempt to give a connected account of the geology of the Lake Superior region as a whole, with special reference to the iron and copper bearing formations. Attention is directed primarily to general features of correlation of the formations,

[a] Mon. U. S. Geol. Survey, vol. 5, 1883.

to the geologic history of the region, and to the origin of the iron and copper ores. In addition, brief chapters are presented on several parts of the district which had not yet been reported on by the United States Geological Survey. No attempt is made to give details. For these the reader is referred to the publications of the United States Geological Survey and of state geological surveys and to other sources specified in appropriate places in this volume.

Though this monograph may be regarded as completing a stage in the progress of the geologic survey of the region, and hence may be considered final in one sense, it may also properly be regarded as only the first of a series of general studies of the district. The area is so large and the record is so complex that this monograph will accomplish its purpose if it discloses the elements of some of the major problems of the region and affords a basis for a better-directed attack on them than has heretofore been possible. Future monographs will undoubtedly be written on each of the many phases of subjects that are barely touched upon in this monograph, such, for instance, as the petrography and consanguinity of the igneous rocks of different periods, the conditions of sedimentation of various series, the relations of volcanism to ore deposition, and the correlation of major and minor structural features of the Lake Superior region with one another and with the various structural features of North America. Besides, certain areas not yet fully reported on will require detailed monographic description. It is hoped that the work of the United States Geological Survey in the Lake Superior region may be continued along the lines indicated.

Parts of the region have been studied at different times by men occupying different viewpoints. Some areas which have recently become commercially prominent have not yet been adequately studied in detail. Finally, mining, drilling, and various public and private surveys are so rapidly extending the knowledge of the geology of the region that it is practically impossible at the present time to write a monograph that will not require modification in some particulars almost before it comes from the press. Because of these facts this work shows inequalities and inadequacies of treatment for different parts of the region and for different phases of the subject. It is hoped, however, that the monograph will be measured by the advance it represents over previous available knowledge and especially by its attempt to bring out significant general features of the geology not heretofore discussed, and not by its deficiencies, of which the writers have a lively appreciation.

The parts of the report written partly or wholly by others than the authors bear the names of the writers. It will be understood that any chapter or section for which no names are given has been written by C. R. Van Hise and C. K. Leith.

ACKNOWLEDGMENTS.

The completion of this monograph and the detailed studies leading up to it have been facilitated by the cordial cooperation of the mining men of the region. To attempt to mention the names of all who have gone out of their way to render aid in these studies would involve the publication of a list including the greater number of local mining men, and even from such a list some names would probably be inadvertently omitted. Especially valuable has been the information furnished by the Oliver Iron Mining Company (United States Steel Corporation), which has a most highly developed and efficient engineering and geologic staff. Valuable aid has been given by state and provincial surveys and by the Minnesota tax commission. To all these men and organizations we express our indebtedness and thanks.

We are indebted to Messrs. W. J. Mead, Lawrence Martin, Alexander N. Winchell, A. C. Lane, R. C. Allen, and Edward Steidtmann for sections of this report bearing their names, and to numerous other men mentioned in the report who have contributed in different ways. Not the least of our indebtedness is to Mr. A. C. Deming for efficient clerical service.

GEOGRAPHY.

The Lake Superior region comprises parts of Michigan, Wisconsin, Minnesota, and Ontario adjacent to Lake Superior. (See figs. 1 and 2.) The accompanying general geologic map

(Pl. I, in pocket) covers the area between parallels 44° and 49° north and meridians 84° and 95 west, comprising approximately 181,000 square miles—an area almost equal to that of the six New England States and New York, New Jersey, Pennsylvania, and Maryland, or that of Sweden and Belgium.

FIGURE 1.—Key map showing location of Lake Superior region.

The region includes several ore-bearing districts of comparatively small area—the Keweenaw copper-bearing district of Keweenaw Point, Michigan, about 1,350 square miles; the Marquette iron-bearing district of Michigan, extending westward from the city of Marquette on the lake shore, about 330 square miles; the Menominee iron-bearing district, extending from Iron Mountain in Michigan eastward along Menominee River, aggregating 112 square miles; the Crystal Falls iron-bearing district in Michigan, in the vicinity of the town of Crystal Falls, 540 square miles; the Iron River district, west of the Crystal Falls district, in the vicinity of the town of Iron River, 210 square miles; the Florence iron-bearing district, in Wisconsin, west of the Menominee district, 75 square miles; the Calumet and Felch Mountain iron-bearing districts of Michigan, in Dickinson County, aggregating 200 square miles; the Penokee-Gogebic iron-bearing district, in Michigan and Wisconsin, about 450 square miles; the Vermilion and Mesabi iron-bearing districts of Minnesota, trending east-northeast in parallel areas along the northern boundary of the State, 1,400 square miles; the Cuyuna iron district of Minnesota, in

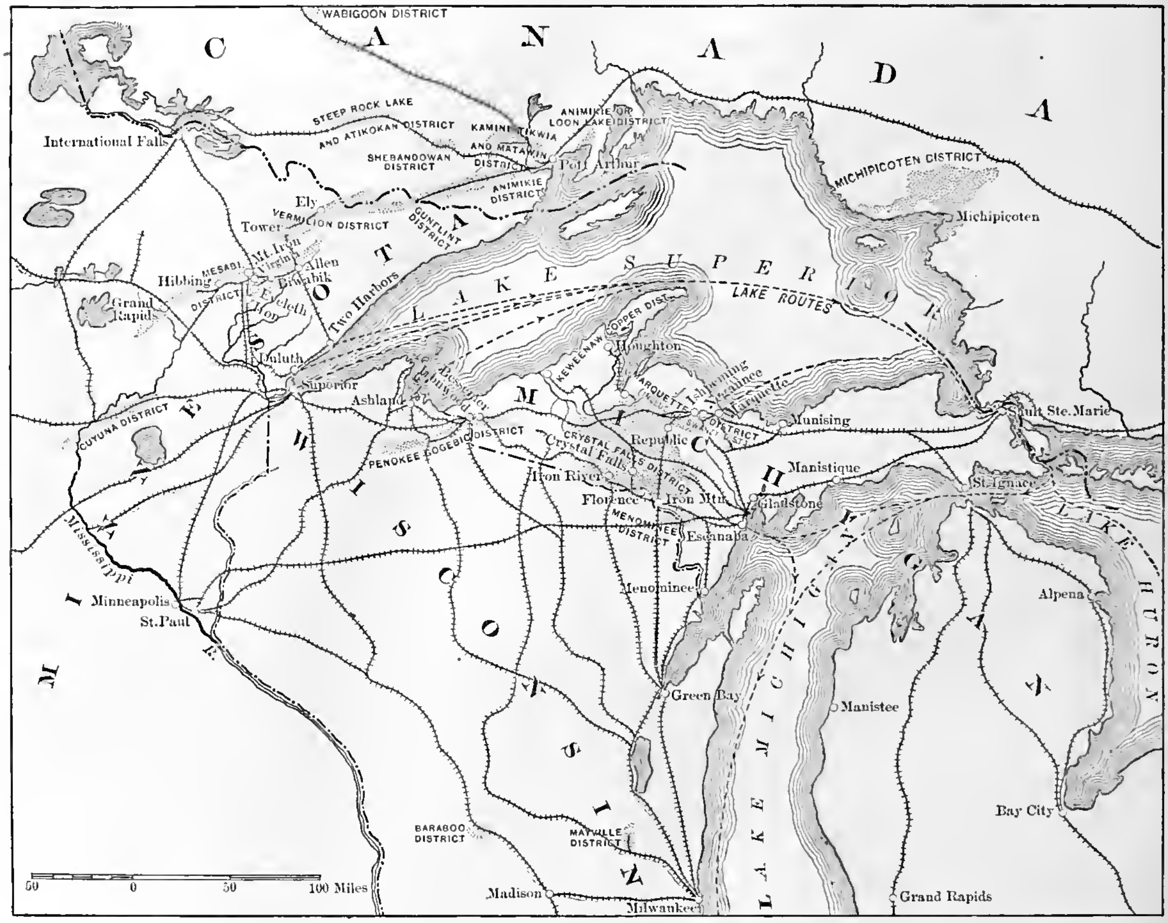

FIGURE 2.—Sketch map of Lake Superior region, showing iron districts, shipping ports, and transportation lines.

the vicinity of Brainerd, about 300 square miles; the Michipicoten district of the northeast shore of Lake Superior, aggregating 140 square miles, and others of less importance. The total area of these principal ore-bearing areas is thus less than 3 per cent of that of the entire Lake Superior region, but these districts are commercially important and the remaining portions are not; for the most part also they include a fuller succession of pre-Cambrian rocks than the intervening areas, and the detailed geologic mapping has been largely confined to them. For these reasons the term "Lake Superior region" is commonly used as a collective designation of the ore-bearing districts, notwithstanding the fact that they comprise only a small percentage of the entire Lake Superior region.

TOPOGRAPHY.[a]

RELIEF.

The principal topographic feature of the Lake Superior region is the Lake Superior basin, which has a general easterly and westerly trend. Most of the ridges and valleys in the adjacent areas lie parallel to the axis of the Lake Superior syncline, and are due to the erosion of parallel-trending folds, faults, and cleavage produced during deformations parallel to the axis of the Lake Superior basin.

The topography has been modified by glacial action. Ridges have been smoothed and rounded and some of the valleys deepened, and the features have been then masked under a varying thickness of glacial drift.

Lake Superior[b] covers about 17 per cent of the area. Its mean water level is about 602 feet, about 21 feet higher than Lakes Michigan and Huron, whose mean level is 581 feet. The basin of Lake Superior descends 978 feet below lake level, nearly 400 feet below sea level. The greatest depth in upper Lake Michigan is 870 feet, or about 289 feet below sea level.

On the several sides of Lake Superior the land rises abruptly, reaching elevations of 1,400 to 1,700 feet (locally 1,900 feet) in northern Michigan and Wisconsin on the south; 1,300 to 1,700 feet (locally 1,900 to 2,200 feet) in northern Minnesota on the northwest; and 1,100 to 1,300 feet (locally 1,700 to 2,100 feet) in Ontario on the north and northeast. The range of elevation (from a maximum of 2,230 feet in the Cook County region of Minnesota to 376 feet below sea level northeast of Keweenaw Point in Lake Superior) is 2,606 feet, but the actual observable relief is about 1,628 feet, from the level of Lake Superior to the high point in Cook County northwest of Grand Marais, Minn.

As the topographic map (fig. 4, p. 87) shows, the Lake Superior region falls into three natural divisions—the uplands, the lowlands, and the lake basins. All of the Upper Peninsula of Michigan from Marquette eastward to Sault Ste. Marie is lowland, nowhere rising more than 900 feet above sea level or 300 feet above Lake Superior. A similar very narrow lowland belt skirts the south shore of Lake Superior, with many interruptions, from Marquette westward to the head of the Lakes at Duluth and Superior. Elsewhere, except at some less important points, the upland borders the lake closely, and it includes the remainder of the Lake Superior region, lying between 1,000 and 1,700 feet (except locally) above sea level, 400 feet higher than the lake. In this upland division are situated nearly all the mining districts. Parts of Lakes Superior, Michigan, and Huron occupy the depressions.

DRAINAGE.[c]

Lake Superior is situated south of the Height of Land, near the intersection of three major drainage systems. It is near the watersheds of the Hudson Bay, the St. Lawrence River, and the Mississippi River drainage.

A large part of the Lake Superior region is tributary to Lake Superior and Lake Michigan, and hence to the St. Lawrence River drainage system. The principal streams flowing into Lake Superior are Carp, Ontonagon, Black, Brule, Bad, Nemadji, and Montreal rivers in Michigan and Wisconsin, on the south side of the lake, St. Louis River of Minnesota on the west side of the lake, and Kaministikwia and Nipigon rivers on the north side of the lake. St. Marys River, discharging from Lake Superior into Lake Huron, carries a larger volume than any other stream in the area. It has been estimated[d] to carry 86,000 cubic feet of water a second past Sault Ste. Marie.

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[a] For detailed account of topography and drainage, see Chapter IV.

[b] The general topography of this lake has been reviewed by M. W. Harrington (Nat. Geog. Mag. vol. 7, 1896, pp. 111-120), who has also studied the currents in the Great Lakes in detail (Bulletin B, Weather Bur., U. S. Dept. Agr., 1895).

[c] The physical geography of a part of this region was described in its larger aspects in 1850 by Foster and Whitney, Report on the geology and topography of a portion of the Lake Superior land district in Michigan, vol. 1, pp. 18-83.

[d] Schermerhorn, L. Y., Am. Jour. Sci., 3d ser., vol. 33, 1887, p. 282.

A number of short streams, such as Manistique, White, and Escanaba rivers, flow southward into Lake Michigan and Green Bay. Menominee River, which forms the Michigan-Wisconsin boundary, flows southeastward into Green Bay, receiving as tributaries the Paint and the Michigamme. Peshtigo and Wolf rivers drain northeastern Wisconsin. A number of small streams drain the northeastern part of the Lower Peninsula of Michigan.

Another large part of the Lake Superior region in Wisconsin and Minnesota is tributary to the Mississippi and so to the Gulf of Mexico. The principal tributaries in this area are Wisconsin, St. Croix, Black, Chippewa, Swan, and Prairie rivers.

A third large part of the Lake Superior region, in northern Minnesota and western Ontario, is tributary to Lake Winnipeg, and hence to Nelson River and Hudson Bay. This system comprises the numerous large lakes occupying a large portion of the area of northern Minnesota and western Ontario, including Lakes Rainy and Vermilion and Lake of the Woods.

The divide between the St. Lawrence and the Mississippi drainage systems extends from Portage in central Wisconsin, between Wisconsin and Fox rivers, north to the Wisconsin-Michigan boundary (fig. 4, p. 87) thence northwest and west into Minnesota, and thence north between upper Mississippi River and St. Louis River to the Giants Range. The Giants Range, extending east-northeast across the northern part of Minnesota, separates the Mississippi and the St. Lawrence systems on the southwest and southeast, respectively, from the Nelson River and Hudson Bay system on the north. The areas of these three large drainage systems within the Lake Superior region are as follows: St. Lawrence, 107,000 square miles; Mississippi, 52,000; Hudson Bay, 22,000.

As a whole the drainage of the Lake Superior region is very imperfect. The numerous lakes, swamps, waterfalls, and rapids are features of an immature drainage.

CHAPTER II. HISTORY OF LAKE SUPERIOR MINING.

THE KEWEENAW COPPER DISTRICT OF MICHIGAN (1844).[a]

The existence of copper was known to the Chippewa Indians met in the Lake Superior region by the earliest explorers. They exhibited crude ornaments of native copper but seemed to make no further use of their knowledge. There is evidence that mining was carried on at a far earlier period.

Whether the mining was done by ancestors of the aboriginal tribes discovered in possession of the Lake district by the earliest white explorers, or by some antecedent people of higher civilization, is a point that archæologists and ethnologists are still arguing. Whatever may have been the derivation or fate of that prehistoric race of copper miners vaguely termed "mound builders," it is certain that they enjoyed at least a rudimentary civilization and were successful metallurgists, for they possessed the art of tempering copper. Weapons for the chase and war and domestic utensils of good finish and style and highly tempered are dug from mounds and found in sand dunes along the southern shore of Lake Superior from time to time.[b]

The existence of native copper on Keweenaw Point was reported by La Garde in 1636, by the Jesuit missionaries in the "Relations," extending from 1632 to 1672, by Baron Le Houtan in 1689, by P. de Charlevoix in 1721, and by Jonathan Carver in 1765. The report of Captain Carver led to the formation of a mining company which actually mined copper ore in 1761 and 1762, but without commercial success. In 1771 Alexander Henry, an Englishman, began mining operations, but he desisted in 1774. The copper ores were noted in 1819 by H. L. Schoolcraft and in 1823 by Major Long, both of them conducting explorations for the Government. The first systematic survey and study of the copper ores was made by Douglass Houghton for the first Michigan Geological Survey. In 1830, in company with Gen. Lewis Cass, he first visited the copper region, and some years later began combined geologic and topographic surveying, for which, by considerable effort, he had procured support from the Michigan legislature. His first report was published in 1841.

Previous stories of mineral wealth on the southern shore of Lake Superior had been too vague and confused to interest capitalists sufficiently to venture their money in attempts at mining in a country which was then much farther from the centers of wealth and population than is Cape Nome to-day, measured by time and transportation facilities. This apathy was dispelled by Dr. Houghton's first report, which was clear and concise and bore upon its face the stamp of truth. He told the world that vast stores of copper existed upon the southern shore of Lake Superior. Pressure was brought to bear upon the Federal Government, and in 1843 an arrangement was concluded with Dr. Houghton by which he was to combine a linear survey for the United States with a topographical and geographical survey he was then making for the State of Michigan. It was necessary that the linear survey be made before mining locations could be granted by the federal authorities, as there were no boundaries other than those of nature before that time. The work was begun in 1844, and during that and the following year rapid progress was made. Dr. Houghton's career was brought to an untimely end by his accidental drowning in Keweenaw Bay in the late fall of 1845, but his work was then so far advanced that it was taken up and pushed to early completion by competent successors.[c]

The first actual copper mining at Lake Superior was done in 1844, and the first product secured was a few tons of oxide ore—not native copper—taken from a fissure vein near Copper Harbor, Keweenaw County, by the Pittsburg and Lake Superior Mining Company, which later developed the Cliff mine, nearly 20 miles to the southwest. The Minnesota mine, in Ontonagon County, was opened shortly after.[d]

The subsequent history of the copper district is one of continuous rapid growth with only minor fluctuations.

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[a] In the following history of the Keweenaw copper district the authors have drawn freely on the excellent brief account of early conditions in the Copper handbook, by Horace J. Stevens.

[b] Stevens, H. J., Copper handbook, vol. 6, 1906, p. 14.

[c] Idem, vol. 2, 1902, pp. 16–17.

[d] Idem, vol. 6, 1906, p. 17.

The following table of annual production shows, in amount and in percentage, the relation of Lake Superior shipments to those of the United States:

Annual production of Lake Superior copper district, compared with annual production of United States, 1850 to 1907.[a]

Year.	United States.	Lake Superior or Michigan district.		Year.	United States.	Lake Superior or Michigan district.		Year.	United States.	Lake Superior or Michigan district.	
		Amount.	Percentage.			Amount.	Percentage.			Amount.	Percentage.
	Long tons.	*Long tons.*			*Long tons.*	*Long tons.*			*Long tons.*	*Long tons.*	
1850	650	572	88	1871	13,000	11,942	91	1892	154,018	54,999	36
1851	900	779	86	1872	12,500	10,961	87	1893	147,033	50,270	34
1852	1,100	792	72	1873	15,500	13,433	86	1894	158,120	51,031	32
1853	2,000	1,297	65	1874	17,500	15,327	87	1895	169,917	57,737	34
1854	2,250	1,819	81	1875	18,000	16,089	89	1896	205,384	63,418	31
1855	3,000	2,593	86	1876	19,000	17,085	89	1897	220,571	63,706	29
1856	4,000	3,666	91	1877	21,000	17,422	83	1898	235,050	66,056	28
1857	4,800	4,255	88	1878	21,500	17,719	82	1899	253,870	65,603	26
1858	5,500	4,088	74	1879	23,000	19,129	83	1900	269,111	63,461	24
1859	6,300	3,985	63	1880	27,000	22,204	82	1901	268,522	69,501	26
1860	7,200	5,388	74	1881	32,000	24,363	76	1902	294,297	76,050	26
1861	7,500	6,713	89	1882	40,467	25,439	62	1903	311,582	85,848	27
1862	9,000	6,065	67	1883	51,574	26,653	51	1904	362,739	93,001	26
1863	8,500	5,797	68	1884	64,708	30,961	47	1905	402,704	102,874	25
1864	8,000	5,576	69	1885	74,052	32,209	43	1906	409,414	102,514	25
1865	8,500	6,410	75	1886	70,430	36,124	51	1907	386,655	96,480	25
1866	8,900	6,138	69	1887	81,017	33,941	42	1908	420,953	99,408	23
1867	10,000	7,824	78	1888	101,054	38,604	38	1909	502,425	103,290	20.5
1868	11,600	9,346	80	1889	101,239	39,364	38	1910	493,705	99,545	20
1869	12,500	11,886	95	1890	115,966	45,273	39				
1870	12,600	10,992	87	1891	126,839	50,992	40				

[a] Stevens, H. J., op. cit., vol. 9, 1909, p. 1594. Production for 1909 and 1910 from Engineering and Mining Journal.

For many years the district held first place as a producer of copper ore in the United States, and in total production it is still first; but in 1887 and later years, except 1891, its annual shipments have been surpassed by those of the Butte district of Montana and since 1904 by the copper districts of Arizona.

The deposits first to be developed were the transverse fissure veins, rich in mass copper, cutting across the strike of the beds in the Eagle Harbor region, at the northeast end of the district. The Cliff mine was discovered by Charles T. Jackson in 1845. Production continued in this district until 1895. It is now inactive but has been newly explored with a view to a reopening.

Next to be developed were the vein or mass-copper deposits following the trend of the Keweenaw beds in Ontonagon County, at the southwestern end of the district. The presence of copper in this district was known for many years, but systematic mining was not started until a few years after the Eagle River district was opened. The principal mines were the Minnesota (now the Michigan), the National, and the Mass. The Minnesota was discovered in 1847 by S. O. Knapp, through surface indentations of ancient workings. In one of these was found a mass of copper weighing 6 tons, together with rotted timbers on which it had been supported. The first shipment from this mine was made in 1848, and for fourteen years 70 per cent of the ore was "mass." The opening of the Minnesota mine was followed by that of the National, Mass, and other mines. The district is still actively producing, but principally from the amygdaloidal beds, mass copper at present (1908) constituting only about 25 per cent of the ore produced.

The amygdaloid deposits of the central part of the district were the next to receive attention. The first of these deposits was discovered, in 1848, on the present Pewabic location, and the second on the Isle Royal location. The Quincy had been opened in 1847 on a transverse vein, but the Quincy amygdaloid was not found until 1856, the same year that the main "Pewabic" bed was found. During 1856 the Quincy produced 13,462 pounds of copper, but it did not become profitable until 1860. In 1877 the Osceola amygdaloid was discovered, and that year the Osceola mine produced 2,744,777 pounds of copper. The Wolverine was opened before 1890 but was not profitable until 1897. The Atlantic mine was opened in 1872. The richest amygdaloid bed in the district is the "Baltic," which was first proved valuable by the Baltic mine in 1897, and a few years later was discovered on the Champion location.

The amygdaloid deposits are now the most numerous, and in 1907 produced 73.1 per cent of the total copper ore of the district, of which about 75.5 per cent came from Houghton County. A larger proportion of the production will come from the amygdaloids in the future.

The last of the principal types of deposits to be discovered were those in the Allouez conglomerate and the Calumet and Hecla conglomerate. Both conglomerates were discovered by E. J. Hulbert and associates. The Allouez conglomerate was found, in 1859, at the site of the Allouez mine, and was worked for a short time, but soon proved to be unproductive, in this locality at least. Later it was found to be productive farther south, on the Boston and Albany location, later the Peninsula and now the Franklin Junior. The Allouez conglomerate has yielded but little profit.

The site of the Calumet and Hecla was bought by Hulbert in 1860, the evidence being a number of copper-bearing conglomerate bowlders and a few depressions, such as in other parts of the district were found to indicate ancient workings. In 1869 Hulbert and his associates returned to the spot and dug through an amygdaloid into the conglomerate bed. The Calumet and Hecla paid their first dividends in 1869 and 1870. Up to January, 1910, the dividends of the Calumet and Hecla have aggregated $110,550,000 on a capital of $2,500,000.

The table below shows the relation in percentage of the annual production of the Calumet and Hecla mine, from 1867 to 1908, to the annual production of the Michigan district for the same period.

Percentage of total Michigan copper production produced by the Calumet and Hecla mine, 1867 to 1908.[a]

1867	7.5	1881	57.5	1895	61.5
1868	24.4	1882	56.0	1896	63.0
1869	46.0	1883	52.5	1897	58.0
1870	57.0	1884	58.0	1898	58.5
1871	61.0	1885	65.5	1899	61.0
1872	66.0	1886	62.5	1900	54.5
1873	62.5	1887	60.5	1901	53.5
1874	58.5	1888	58.0	1902	47.6
1875	59.5	1889	55.0	1903	39.8
1876	56.5	1890	59.0	1904	38.7
1877	60.0	1891	56.5	1905	41.2
1878	63.5	1892	46.0	1906	43.6
1879	61.0	1893	53.5	1907	37.9
1880	63.5	1894	53.5	1908	36.6

The only other mine now operating on the conglomerates is the Tamarack, opened in 1881.

COPPER MINING ON ISLE ROYAL AND ELSEWHERE.

Isle Royal is unusually rich in interesting evidences of prehistoric copper mining. The first mining of historical record was begun soon after the opening of Keweenaw Point, in 1844, culminating in 1847 and 1848 and waning in 1855, when the island was again without permanent inhabitants. Another brief period of development, from 1871 to 1883, resulted in the opening on the island of the Saginaw and Minong mines, with a combined production of less than 10,000 tons of copper. Since the nineties exploration has been going on intermittently, but without success. No mines are operating at the present time. The ores are essentially the same as those of Keweenaw Point. As mined they were low grade, probably less than 1 per cent. They occur principally in fissure veins in the traps.

The copper-bearing formation has been found elsewhere in the Lake Superior region, but the copper-mining industry has practically not extended beyond Keweenaw Point and Isle Royal. The southwestern extension of the Keweenaw district in Wisconsin and Minnesota is

[a] Calculated from data in Stevens's Copper hand book, vol. 9, 1909.

being extensively explored and opened for mining, but thus far the production has not been important. As the copper-producing area has been restricted to that of the early discoveries and as the copper-mining industry has developed evenly, it is unnecessary for our purposes to follow its history in greater detail.

MARQUETTE IRON DISTRICT (1848).

Iron was first discovered in 1844 near the site of Negaunee by the Government linear surveying party in charge of William A. Burt, himself under the direction of Douglass Houghton. The Michigan legislature having failed in 1843 to renew appropriations for the Michigan Survey, Dr. Houghton had turned to the Federal Government and had succeeded in procuring an additional allowance per mile for geologic work in connection with the linear survey of the Upper Peninsula, which had already been begun, and he himself took the contract for the linear survey in order to have the direction of the work.

In 1848 iron ore was mined by the Jackson Association (subsequently the Jackson Iron Company) and carried by team to a Catalan forge which they had constructed near Carp River. The project was not commercially successful and was closed in 1850. The Marquette Iron Company opened the Cleveland mine near the present town of Ishpeming in 1849 and carted its ore to a forge at Marquette. This also was a financial failure and was discontinued in 1854. In 1850 and again in 1852 a few tons of ore were shipped from the district to Pennsylvania for trial in Pennsylvania furnaces. The opening in 1855 of the ship canal along St. Marys River, connecting Lake Huron and Lake Superior, was followed in 1856 by the first regular shipments of iron ore from the Marquette district to the lower lakes, amounting to 6,343 tons. Up to that time the local forges had consumed about 25,000 tons of ore. The completion in 1857 of the Iron Mountain Railway (later the Houghton, Marquette and Ontonagon Railway and ultimately the Duluth, South Shore and Atlantic Railway) between Marquette and the mines gave easy transit to the lake, and 22,876 tons were shipped in 1858 and five times that amount in 1860.

From 1855 to 1862 transportation facilities were so far improved as to make it possible to get ore out, but the mines had not yet been really brought into relation with the iron market. Therefore the companies met with no real success whether they tried to make iron themselves or to send their ore down to the furnaces of Ohio and Pennsylvania. The Lehigh Valley, and not Pittsburg, was still the iron center of the United States. The war suddenly changed the whole outlook. A great demand sprang up for all kinds of iron goods, and both mining and iron making on the Upper Peninsula received a strong impetus. Shipments increased from 49,000 tons in 1861 to five times that amount in 1864, while the companies made fabulous profits. * * * The year 1865 marked a slight retrogression, but the eight years following saw a wonderful growth, the boom in iron and steel reflecting the rapid industrial development of the country, and from 1870 to 1873 registering its speculative excitement. * * * In 1863 but three mines shipped ore; in 1864, five; in 1865, seven; in 1866, nine; 1868 added four more mines, 1870 three more, while in 1872 the table of shipments increases the total number of mines by 11 to 29, and in 1873 no less than 40 are represented. The total shipments of 1866 were just below 300,000 tons; those of 1873 almost exactly four times that amount.[a]

The opening of the Republic, Michigamme, and Spurr mines in 1872 practically completed the area of the Marquette district as known at present, though a few discoveries of importance have been made within the area since that time. Exploration is still vigorous. The field for deep exploration opened by recent discoveries is a large one.

The necessary increase in means of shipment was made by the building of the Chicago and Northwestern Railway from Negaunee to Escanaba and by increase in the capacity of the docks already built at Marquette. As a result of the panic of 1873—

development work ceased, production fell off almost 25 per cent in 1874 and yet further in 1875, and the number of mines reporting shipments declined from 40 in 1873 to 33 in 1874 and to 29 in 1875. The working force of those that continued operations was largely reduced, and only five mines showed a larger output in 1874 than in 1873.[b]

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[a] Mussey, H. R., Combination in the mining industry: Studies in history, economics, and public law, Columbia Univ., vol. 23, No. 3, 1905, pp. 55, 57, 59.

[b] Idem, p. 73.

Returning prosperity brought an increase in shipments of 80 per cent between 1878 and 1882, and the number of producing mines increased from 29 in 1875 and 1877 to 48 in 1882. The following year saw a considerable depression because of overproduction, but thenceforth the production showed a general increase until 1891, with a minor depression in 1885. The years 1891 and 1893 saw another falling off in production, the latter contemporaneous with the general panic of 1893. From that time to the present there has been a general increase in production, with slight recessions in 1904 and 1906. The Lake Superior and Ishpeming Railway was constructed in 1896 to carry the ores of the Cleveland-Cliffs Iron Company from the Ishpeming district to Lake Superior.

The table of production of iron ore from the Marquette range (pp. 51–60) summarizes the development of the district.

The Swanzy district, southeast of the Marquette district proper, is reached by the Chicago and Northwestern Railway; its production is usually credited to the Marquette district. The district was first explored in 1869, and the Smith (later the Cheshire and Princeton) mine was opened in 1871. Systematic exploration by drilling, begun in 1902 by the Cleveland-Cliffs Company, greatly extended the ore reserves and determined the probable limits of the district. A largely increased production may be looked for.

MENOMINEE IRON DISTRICT (1872).

The Marquette district had been the sole producer of iron ore in the Lake Superior region for nearly thirty years when its first competitor, the Menominee district, entered the field.

The first practical discovery of iron ore in Menominee County was made by the brothers Thomas and Bartley Breen some time previous to 1867, though the veteran explorer S. C. Smith claims to have been and probably was aware of its existence in that section as early as 1855, in which year he traversed what he called a new range, south and east from Lake Michigamme to Escanaba, locating what is now the estate of the Republic Iron Company on the way. The first practical work in the way of development was done by N. P. Hulst for the Milwaukee Iron Company at the Breen and Vulcan mines in 1872, and by John L. Buell at the Quinnesec the following year.[a]

The existence of ore in shipping quantity had been demonstrated in 1874, but the distance of the district from the Great Lakes and the lack of facilities for shipment prevented its further development until the extension of the Menominee branch of the Chicago and Northwestern Railroad from Escanaba to Quinnesec. This was carried through to Iron Mountain in 1880, and thence northwest to Iron River and the Gogebic range. The Chicago, Milwaukee and St. Paul Railway entered the district in 1886 and the Wisconsin and Michigan Railway in 1903. When shipment had once started it increased much more rapidly than that of the Marquette district. The first year's output of 10,405 tons jumped to 95,221 tons the following year, to 269,609 tons the third year, and to 592,086 tons the fourth year, and reached the million mark in 1882. In 1901, 1902, and 1903 the Menominee surpassed the Marquette range in shipment, but for the most part in later years it has been producing about the same amount yearly as the Marquette district. Its total shipment to the end of 1909 is 71,212,121 tons as compared with a total of 91,838,558 tons from the Marquette district. The table (pp. 61–65) includes shipments from the outlying Florence, Iron River, and Crystal Falls districts to the northwest.

CRYSTAL FALLS, FLORENCE, AND IRON RIVER IRON DISTRICTS (1880).

The Crystal Falls, Florence, and Iron River districts may be regarded as northwesterly outliers of the Menominee range, and they are included in it in tables of production.

For a number of years after the opening of the Menominee range prospectors worked in various places, among others in the vicinity of Crystal Falls, seeking to follow the iron range west of the Menominee River. As a result of this endeavor, the deposits at Florence, Wis., and then those farther north and west at Crystal Falls, Mich., were in turn located. It was not until 1881 that sufficient exploratory work had been done at Crystal Falls to warrant a belief in the future of this iron-bearing area. In April, 1882, the Chicago and Northwestern Railway completed

[a] Swineford, A. P., Annual review of the iron mining and other industries of the Upper Peninsula for the year ending December 31, 1881; Marquette, 1882, p. 119.

its branch to Crystal Falls, and the shipment of ore began. The Amasa deposits were not exploited to any great extent until the year 1888, when the Chicago and Northwestern Railway built a branch from Crystal Falls to Amasa. The Chicago, Milwaukee and St. Paul Railway in 1893 completed a line from Channing to Sidnaw, which runs through Amasa.[a]

These districts have as a whole developed slowly as compared with the other principal iron districts of the Lake Superior country, partly because of the slightly lower grade of many of the ore bodies and partly because of the lack of exposure, making exploration difficult and costly. Consequently large areas remain to be tested underground. The increasing demand for iron ore of the lower grades has brought about a revival of exploration in this area during the last few years. This is one of the most promising fields of exploration yet remaining in the Lake Superior region, and the next few years are likely to see large developments.

GOGEBIC IRON DISTRICT (1884).

The Gogebic range of Michigan and its extension, the Penokee range of Wisconsin, sometimes referred to together as the Penokee-Gogebic district, were long known to explorers and had been mapped by the geologists of the Michigan and Wisconsin surveys prior to their opening in 1884. The first recorded notice of their discovery appears on the plats of the township surveys. It is remarkable that subsequent discoveries have been restricted to the areas first determined by the geologic mapping. Early exploration was largely confined to the well-exposed magnetic portions of the formation at the west end of the range, which have been less productive than the central, less well exposed portions of the iron-bearing formation. In 1884 the first shipment of 1,022 tons was made from the Colby mine to Marquette. In the following year the shipment reached 119,860 tons, owing to good transportation facilities and to the remarkable speculation which in 1886 and 1887 led to the formation of mining companies in this district with a nominal capital exceeding $1,000,000,000. The inevitable collapse in the fall of 1887 took the savings of smaller investors and many mines were closed down, but the stronger companies weathered the storm and in spite of the speculative failure the production of ore steadily increased until 1890, when for a period of several years the shipments reflected the depressed and unstable conditions which affected the Lake Superior region as a whole. In the autumn of 1885 the Milwaukee, Lake Shore and Western Railway (subsequently part of the Chicago and Northwestern) was finished from the mines to Ashland.

The Wisconsin Central Railway crossed the range at Penokee Gap in 1873, connecting with Ashland, and in 1887 extended a branch to the center of the district. The Duluth, South Shore and Atlantic Railway already paralleled the range on the north at the time of its discovery and afforded easy connection with the lake.

VERMILION IRON DISTRICT (1885).

J. M. Clements describes the opening of the Vermilion district, in Minnesota, as follows:[b]

The first mention of the occurrence of iron ore in the Vermilion district was made by J. G. Norwood, who observed it during his explorations in 1850 and published a statement concerning it in the report accompanying that of D. D. Owen.[c] The iron he observed is that which occurs near Gunflint Lake, at the extreme east end of the district, and which geologically belongs with the ores of the Mesabi range. In this part of the Vermilion district the ores have never been exploited to any extent and are at present of little commercial importance.

Interest in what is now known as the Vermilion iron-bearing district was aroused in the sixties by the reported occurrence of gold in the vicinity of Vermilion Lake. There was considerable excitement for several years and a small rush to the district. Shafts were sunk and stamp mills were erected, the machinery having been packed in from Duluth over the Vermilion trail. A town site was laid out near Pike River, at the southwest extremity of Vermilion Lake, and some buildings were erected. In all a good deal of money was fruitlessly expended, as no gold deposits of any importance were found.

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[a] Clements, J. M., and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, p. 175.
[b] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 213-215.
[c] A report of the geological survey of Wisconsin, Iowa, and Minnesota, 1852, p. 417.

Some time after this, in 1875, the first exploration for iron ore in this district was taken up by Mr. George R. Stuntz, accompanied by Mr. John Mallman, who began to prospect the iron formation and iron ore exposed on Lee Hill, southwest of the Bay of Vermilion Lake, which is now known as Stuntz Bay, named after Mr. Stuntz. The ore deposits on Soudan Hill were then discovered. In 1880 Prof. A. H. Chester examined the Vermilion Lake iron formation for private parties and Mr. Bailey Willis studied it for the Census Office. Systematic and extensive efforts were made in the late seventies and the early eighties to develop the iron ores. By this time the Minnesota Iron Company had been organized and all of the properties which at that time were known to contain ore and great stretches of country which were in the continuation of the ore range had been purchased, the company owning over 20,000 acres of land on the Vermilion range proper and in the vicinity of the good harbor on Lake Superior known now as Two Harbors. On August 1, 1884, the Duluth and Iron Range Railroad was completed from Two Harbors to Tower, near Vermilion Lake. This road was 72 miles long. At a later date it was connected with Duluth, 25 miles away. During the first year (1884) 62,124 tons of ore were shipped, some of this having come from the stock piles which had been growing during the years of development preceding the opening of the railroad.

Prospectors were busy in the years prior to the opening of the railroad in prospecting the district to the east of Tower, and in 1883 outcrops of ore were found by Mr. H. R. Harvey in sec. 27, T. 63 N., R. 12 W., near the present town of Ely. The body of iron ore indicated by these outcrops was further tested in 1885–6 and led to the opening up of the great deposits at Ely on which are now working the Chandler, Pioneer, Zenith, Sibley, and Savoy mines. During 1888 there were shipped from the Chandler mine 54,612 tons of high-grade ore.

From this time on the development of the range was rapid and steady, as is shown by the annual increase in the shipments of ore.

The Vermilion range was thus opened at about the same time as the Gogebic range, but its mines, in contrast to those of the Gogebic, were from the start in the hands of a strong company, which controlled the railroad and prevented active competition. To quote from Mussey:

A comparison of the output of the two ranges by years discloses an interesting contrast between centralized control backed by adequate capital in the Vermilion district and competitive exploitation based on small undertakings and insufficient funds in the Gogebic district. The Gogebic district, which was not really opened up till 1885, in the second year following produced more than a million tons; the Vermilion, though opened a year earlier, did not reach the million mark till 1892, when the Gogebic produced almost three millions, only to fall off to less than half that amount the next year. Production on the Gogebic moves upward by leaps and starts, one season rising to excess, the next sinking back to deficiency; the output of the Vermilion, on the other hand, climbs with a regularity that is surprising, when one considers the variable conditions of the market in which it had to be sold.[a]

MESABI IRON DISTRICT (1891).

ACCOUNTS OF THE DISTRICT BEFORE ITS OPENING.

In penetrating the vast wilderness north and west of the Great Lakes country, the early explorers were compelled for the most part to stick close to the waterways, for the nature of the country made travel for long distances exceedingly arduous by any other method than canoeing. Three of the canoe routes to the country northwest of Lake Superior cross the Giants or Mesabi Range[b] and its eastward continuation. Mississippi River and its tributaries, Prairie and Swan rivers, touch the western portion of the district. Embarrass Lake, tributary to St. Louis River, and thence to Lake Superior and the St. Lawrence, crosses the Giants Range near its east-central portion. Gunflint Lake, one of a chain of lakes tributary to Rainy River and Nelson River and thence to Hudson Bay, lies far to the east, on a continuation of what is now known as the Mesabi district. Hence the first published references to the Mesabi district concern the parts of the district immediately adjacent to these canoe routes. Brief descriptions of Pokegama Falls on Mississippi River and of adjacent areas were made by Z. M. Pike in 1810, by James Allen and Henry R. Schoolcraft in 1832, and by J. N. Nicollet in 1841. In 1841 also Nicollet published his map of the hydrographic basin of the upper Mississippi, on which the Giants or Mesabi Range, called "Missabay Heights," was for the first time delineated,

[a] Mussey, H. R., Combination in the mining industry: Studies in history, economics, and public law, Columbia Univ., vol. 23, No. 3, pp. 90–91.

[b] The name "Mesabi" has been variously spelled and applied with various limits to the ridges of this district, and the use of the same term to denote the iron-bearing district as such has added to the confusion. The spelling "Mesabi" has been adopted by the United States Geographic Board. It has become usual, for the sake of clearness, to speak of the main topographic feature as the Giants Range. In this report the terms are definitely distinguished, Mesabi range being applied only to the iron-bearing district that occupies a linear belt of low sloping land at the base of the Giants Range.

by hachures, although very imperfectly. In 1852 J. G. Norwood reported the occurrence of iron-bearing rocks at Gunflint Lake and mentioned granite and gneiss seen in crossing the range at Embarrass Lake. In 1866 Charles Whittlesey reported on explorations made in northern Minnesota during the years 1848, 1859, and 1864. He mentioned Pokegama Falls and made vague reference to the granitic rocks of the range. "Mesabi Range" was used in an indefinite way to cover what are now known as the Giants and Vermilion ranges. In 1866, also, Henry H. Eames, the first state geologist of Minnesota, reported granite and gneiss seen on a trip across the range at Embarrass Lake. In describing the ranges of the northern part of the State, including the "Missabi Wasju," he stated that they appear to be traversed by metal-bearing veins. Presumably, however, this statement refers mainly to the Vermilion range. In a second report, published the same year, Mr. Eames is more explicit, and, referring to the general elevated area of the northern part of the State, including the Giants Range, states: "In this region are found also immense bodies of the ores of iron, both magnetic and hematitic, occurring in dikes and associated with the rock in which it is found; in some of these formations iron enters so largely into its composition as to affect the magnetic needle." Pokegama Falls and Prairie River Falls were visited, and at the latter place the presence of "iron ore" was noted. These reports of Eames contain the first references to iron ore in the Mesabi district proper, although iron-bearing rocks had been noted by Norwood in 1852 at Gunflint Lake.

From this time on desultory exploration work was done in certain portions of the district. It was confined for the most part to the area west of Birch Lake, in Rs. 12, 13, and 14 W., and to the vicinity of Prairie River. No published accounts of the earlier portion of this exploratory work are to be found.

The first examination of the Giants Range by a mining expert with particular reference to the occurrence of iron ore in workable deposits, noted in print, was made in 1875 by A. H. Chester, of Hamilton College, New York. Reaching the Giants Range at Embarrass Lake, he worked eastward toward Birch Lake. In his report (published in 1884) he called attention to the magnetic character of the iron in this area and to the fact that the alternating iron layers are not thick or continuous. The percentage 44.68 was given as a fair average of iron in the rocks of this part of the district. In general, one gathers the impression that he was not favorably impressed with the economic prospects of this area. Between the time of Chester's examination of the range, in 1875, and the publication of his report, in 1884, N. H. Winchell, state geologist of Minnesota, briefly noticed the Mesabi district in two of his reports. In 1879 he told of the occurrence of iron ore in R. 14 W. and published analyses. In 1881 he told of a trip from Embarrass Lake east to range 14 and noted the magnetic character of the iron-bearing formation in range 14, as well as its similarity to the formation at Gunflint Lake. Indeed, the iron-bearing formation in range 14 was called the "Gunflint beds." In 1883 Irving called the iron-bearing rock series in the Mesabi district Animikie, a term which had been applied to similar rocks at Thunder Bay and westward to Gunflint Lake, and correlated the Animikie rocks with the original Huronian rocks of the north shore of Lake Huron and with the iron-bearing formation and associated rocks of the Penokee-Gogebic iron range of Michigan and Wisconsin. From this time on the term Animikie is much used in the literature on the Mesabi range to designate the iron-bearing formation and associated rocks. In 1884, in the same volume in which Chester's report was published, N. H. Winchell discussed the age of the Mesabi rocks, assigning them to the "Taconic," then regarded as Lower Cambrian, and, following Irving, correlated them with the iron-bearing rocks of the Penokee-Gogebic district. In the late eighties a number of other reports on the district were issued by the Minnesota Survey, but they contain no important points not noted in reports above cited. This brings us to the opening of the district for mining.

OPENING AND DEVELOPMENT.

Since the late sixties there had been more or less exploration, particularly along the eastern portion of the district, from Embarrass Lake to Birch Lake, and the presence of iron-bearing rocks had been recognized and discussed in the reports mentioned above. However, not a single deposit of iron ore of such size and character as to warrant mining had been revealed. In fact, the range had been "turned down" by many mining men who had examined it. This was largely because of the fact that they confined their attention principally to the eastern, magnetic end of the range, where exposures of the iron-bearing formation are numerous. Even up to the present time no ore has been found there in quantity. Yet the impression was gradually developing that iron ore in large quantity was to be found in this district, and a few prospectors were working diligently.

Among the more persistent of the Mesabi range explorers were the Merritts—Lon Merritt, Alfred Merritt, L. J. Merritt, C. C. Merritt, T. B. Merritt, A. R. Merritt, J. E. Merritt, and W. J. Merritt—of Duluth, Minn. Their faith in the range was the first to be rewarded. On November 16, 1890, one of their test-pit crews, in charge of J. A. Nichols, of Duluth, struck iron ore in the NW. ¼ sec. 3, T. 58 N., R. 18 W., just north of what is now known as the Mountain Iron mine. This was followed in 1891 by the discovery of ore in the area now covered by the Biwabik and Cincinnati mines. John McCaskill, an explorer, observed iron ore clinging to the roots of an upturned tree on what is now the Biwabik property. Test pitting by the Merritts, in charge of W. J. Merritt, led to the discovery of the Biwabik in August, 1891. The Cincinnati mine was opened the same fall. The Hale, Kanawha, and Canton mines were opened in the spring of 1892.

The discovery of ore near the sites of the present towns of Virginia, Eveleth, McKinley, and Hibbing followed in rapid succession. The excitement following the first discovery of ore at Mountain Iron was greatly augmented by each succeeding find, and in 1891 and 1892 there was the inevitable rush of explorers.

Up to October, 1892, there were two railways touching the range—the Duluth and Iron Range, crossing the range at Mesaba station on its way to the Vermilion range, and the old Duluth and Winnipeg (now the Great Northern), reaching the range at Grand Rapids. Both these places were far removed from the exploring centers. Most of the explorers went through Mesaba station. Reaching this place by rail, they were compelled to travel 12 to 50 miles to the west along "tote roads" which were all but impassable. The time, money, and energy needed to conduct even modest explorations at this time can be appreciated only by those who have experienced the difficulties of inland travel in the Lake Superior region away from railways. The stories of this "toting" period contain the usual records of misfortunes, lucky strikes, and enterprise incidental to a mining boom.

The railways were not long in getting into the field. In October, 1892, two lines were put in operation. The Duluth, Missabe and Northern Railway was built to connect the Mountain Iron mine with the old Duluth and Winnipeg Railway (now the Eastern Railway of Minnesota, a part of the Great Northern system) at Stony Brook Junction, and later was extended to Duluth. Almost immediately after the connection with Mountain Iron a branch was sent out to Biwabik. About the same time the Duluth and Iron Range Railroad sent out a branch from its main line to the group of mines at Biwabik. Very soon thereafter both railways got into Virginia. Hibbing was reached by the Duluth, Missabe and Northern in 1893. Eveleth was reached by the Duluth and Iron Range in 1894 and by the Duluth, Missabe and Northern very soon thereafter. The Mississippi and Northern (Eastern Railway of Minnesota) about the same time projected a spur from Swan River to the Hibbing district.

With the advent of railways the development of the range went on by leaps and bounds. This marvelous development has continued to the present time. The only considerable check occurred during the period of general financial depression which the country underwent in 1894, 1895, and 1896. Almost an untouched wilderness in 1890, the district is to-day the greatest producer of iron ore in the world. The rapidity of the development of the mining industry of the district, carrying with it all the prosperity of the range, can not be better told than by the table of shipments from the district (pp. 65–68).

The development of the Mesabi range eastward toward the magnetic portions of the iron-bearing formation has been less satisfactory than that to the west. A small amount of ore was opened up at the Spring mine, formerly the site of the Mallman mine, leading to the construction of a spur railway, and minor discoveries not yet exploited have been reported from places farther east. Also certain ore deposits have been developed in the vicinity of the town of Mesaba, near the Iron Range Railway track. The last-named deposits mark about the eastern limit of the principal mining operations.

The most noteworthy developments of the district in late years have been the exploration and exploitation of the ores in the western part of the district, which, because of their content of loose quartz grains, giving them the name "sandy taconite," were long regarded as worthless. As a result of elaborate experiments in washing tests it was found possible to utilize these ores, and mining operations are now being conducted and planned on an enormous scale. Since 1900 several towns have sprung up in what was before a wilderness. The town of Coleraine, built by fiat of the Oliver Iron Mining Company, is an example of what may be accomplished in a short time by large capital intelligently expended by a single group of individuals working on a uniform plan. The railways have followed up and made possible much of the development of the western Mesabi district. It is reached by spurs from both the Duluth, Missabe and Northern and the Great Northern railways, leaving the main lines south of Hibbing.

Still more recent has been the extension of the district by exploration for 12 miles or more west of Pokegama Lake, near Mississippi River. The ores have been found to be lean but probably merchantable. The iron-bearing formation pinches out at the southwest end of the district, the overlying slate coming into contact with the underlying quartzite. This part of the district, together with magnetic belts farther west, particularly the one running through Leech Lake, the east end of which comes within 12 miles of the Mesabi district, affords interesting possibilities for exploration, which will be adequately undertaken.

CUYUNA IRON DISTRICT (1903).

The development of the Cuyuna, the newest of the Lake Superior iron districts, in the same geologic group as the Mesabi district, is unique in a way. The other iron ranges of the Lake Superior region were all discovered through more or less conspicuous surface indications of ore bodies. Outcrops of the ore or of iron-bearing rocks existed. There are no rock outcrops in the Cuyuna district, the drift mantle being 80 to 350 feet thick, and the first discovery of magnetic iron-bearing rocks in this region was made with the dip needle by Cuyler Adams, about 1895.

The dip needle was the sole factor used in the subsequent tracing of the ore formations by Cuyler Adams and afterward by others, preparatory to drilling, from the time of the first discovery of magnetic iron-bearing formations until 1907, when more or less indiscriminate drilling began.

The first drilling was done in 1903 at a point just south of Deerwood, Minn., by Cuyler Adams, and has continued in greatly increasing amount to the present time, some 2,000 drill holes and two shafts having been put down, resulting in the discovery of a number of ore deposits. (See pp. 216–219.) The distribution of the ore bodies and the limits of the district are yet very imperfectly known.

Extension of magnetic surveys to the west and north have shown isolated magnetic belts at several places, some of them beyond the western boundary of Minnesota. The distribution of some of these belts is shown on the general map. Underground exploration of these belts has just begun. The next few years will see rapid exploration of the Cuyuna range and the country to the north and west.

For some time before the drilling began, geologists had suspected the existence of iron-bearing formation in the Cuyuna district. The general geologic map of Minnesota, published by the Minnesota Geological and Natural History Survey in 1901, showed this area as occupied by a southwestern extension of the slates and quartzites of the Mesabi district. In 1903 C. K. Leith published a sketch showing the hypothetical extension to the southwest of the iron-bearing formation of the Mesabi district through the since discovered Cuyuna district. A similar view of the geologic possibilities was held by W. N. Merriam, geologist for the United States Steel Corporation.

The Northern Pacific Railway extends throughout the length of the Cuyuna district and affords easy access to the ores. It also runs near some of the magnetic belts west and northwest of the Cuyuna district. The Minneapolis, St. Paul and Sault Ste. Marie Railway passes the district on the southeast and in 1910 completed a spur into the district. For both railways the lake port will be Superior.

BARABOO IRON DISTRICT (1903).

The discovery of ore in the outlying and relatively small Baraboo district, in Wisconsin, was not made until 1903. The quartzite ranges here conspicuously exposed had long been recognized as Huronian, and suggestion had been made that iron-bearing rocks might be associated with them. In fact, for several years the Chicago and Northwestern Railway had quarried small amounts of paint rock within a few feet of what is now known as the Illinois mine. Because of the covering of Cambrian sandstone and glacial deposits the ore deposits themselves escaped detection until drilling was, in 1900, begun by W. G. La Rue in the vicinity of the Illinois mine near North Freedom. Since that time, as a result of almost uninterrupted exploration, ore deposits have been found at various places in the Baraboo syncline. Only three shafts have been sunk and ore has been shipped from only one, the Illinois mine. The development of the district has not been rapid because of the relatively low grade of ore, the considerable cost of mining, and the great expense of deep drilling, although these factors have been partly offset by lower freight rates to Chicago. Both mining and exploration in the Baraboo district are in their infancy.

LESS IMPORTANT DEVELOPMENTS.

CLINTON IRON ORES OF DODGE COUNTY, WIS. (1849).

There is no record of the first discovery of the Clinton iron ores in Dodge County, Wis., for they are exposed at the surface in accessible country. Ore was first mined from them in 1849. The ores have been partly used in local charcoal furnaces at Mayville and Iron Ridge and partly shipped to Milwaukee, Chicago, and adjacent points. Because of their low percentage of iron, high phosphorus, and moderate quantity, they have not figured largely in Lake Superior production.

PALEOZOIC IRON ORES IN WESTERN WISCONSIN (1857).

Small hematite deposits scattered through the driftless portion of the Cambrian sandstone area north of Wisconsin River, in Wisconsin, were opened up about the time of the discovery of the Marquette district. In 1857 a charcoal furnace was built at Ironton, in Sauk County, to use these ores. Another was built at Cazenovia, in Richland County, in 1876, and torn down in 1879. None of these ores has been mined since 1880. Records of production are not available, but before 1873 about 25,000 tons of ore was mined from these deposits.

Farther north, at Spring Valley, in Pierce County, Wis., brown-ore deposits associated with Ordovician limestone were opened about 1890, and a charcoal furnace was built to use these ores in 1893. At a later period coke supplanted charcoal as a fuel.

IRON ORES OF THE NORTH SHORE OF LAKE SUPERIOR (1900).

Since the opening of the Lake Superior region for mining the north shore has been more or less explored and a considerable number of iron-bearing belts have been located in the territory extending from the Lake of the Woods beyond Michipicoten. Only three ore bodies have been found. The best known of these is the Helen ore body, which was discovered in 1897 in the

Michipicoten district, on the northeast side of Lake Superior. This district was connected with Lake Superior by the building of the Algoma Central and Hudson Bay Railway (12 miles) in 1899 and began shipment in 1900.

Discovery of the Helen mine led to rather vigorous exploration in the many known iron-bearing belts in the immediately adjacent territory, in some places by drilling, but without conspicuous success. A small body of ore was found at the Josephine mine, a few miles northeast of the Helen mine.

The Atikokan ore deposit was discovered in 1889, was explored by tunnel and drilling in 1898 and 1899, and became accessible for mining when the Canadian Northern Railway passed it in 1901. Utilization of the ore has been restricted by its high sulphur content. A furnace has been constructed at Port Arthur on Lake Superior for the purpose of utilizing this ore, but thus far little has been actually mined and smelted.

At Steep Rock Lake a small body of ore was discovered in 1901 by the Oliver Iron Mining Company. No ore has yet been mined.

The presence of an iron-bearing formation in the Animikie group in the vicinity of Port Arthur and at points lying east and west of that place for several miles was noted by the earliest visitors to this region. A considerable amount of more or less desultory exploration has shown that the formation as a whole is lean and unmarketable. At Loon Lake, about 25 miles east of Port Arthur, vigorous explorations begun in 1901–2 disclosed a few thin layers of lean ore of considerable horizontal extent, which may be mined in the future.

In general the results of exploration for iron ore on the north shore of Lake Superior have been disappointing. The returns have not been proportionately so large for money expended as they have been on the south shore, partly owing to the fact that the iron-bearing formations are mainly of the Keewatin series, which on the south shore are found to have smaller quantities of iron ore than those of the upper Huronian (Animikie group). On the other hand, exploration has been slight relative to the extent of the known iron-bearing formation and the large and not easily accessible areas open for exploration; moreover, the exploration has been largely confined to the surface. Future exploration and mining in this territory will be greater than that which has already been done.

SILVER MINING ON THE NORTH SHORE OF LAKE SUPERIOR (1868).

One of the interesting incidents in the development of the Lake Superior region was the discovery in 1868 of silver ore on Silver Islet, near Thunder Cape, on the northwest coast of Lake Superior. Before the mine closed in 1884 it had yielded about $3,250,000 worth of silver. The island is so small that it was necessary to inclose parts of the vein by a cofferdam to prevent the inflow of the lake.

This development was followed by active exploration of a number of silver veins in the Animikie group to the west. The principal mines were the Shuniah, Rabbit Mountain, and Silver Mountain groups, which have yielded approximately $1,885,000 worth of silver, but which are not now active.

LAKE SUPERIOR GOLD MINING (1882).

Still another less important phase of mining development in the Lake Superior region has been the production of small quantities of gold. Between 1882 and 1897 the Ropes gold mine in the Marquette district of Michigan produced about $650,000 worth of gold. On the Ontario side of the lake approximately $2,250,000 worth of gold has been mined, principally in the Rainy Lake district, which was opened in the early nineties and reached its greatest development in 1899. At present the production of gold in the Lake Superior region is practically nil, but exploration continues active, and from time to time considerable sums are spent in opening up mines and building mills on low-grade gold deposits.

GENERAL REMARKS.

INDUSTRIAL CHANGES.

The foregoing chronologic account of the opening of the Lake Superior mining industry gives no adequate idea of the magnitude and difficulty of the work and the forces involved. The bare statement that a district "had been known to explorers for many years prior to its opening" but poorly expresses the persistent hunt of many explorers for many years at the expense of money and bodily fatigue through a wilderness difficult to reach and superlatively difficult to penetrate and explore. Since the opening of the first mine in the region there has been no time in which such men have not been vigorously prosecuting the search. Surface exploration has been followed in favorable localities by test pitting and drilling at enormous expense. In the Vermilion district $2,000,000 is probably a conservative estimate of the amount spent in exploration with the drill, much the largest proportion of it entirely without success. In the Mesabi district 30,000 test pits and drill holes have been sunk in exploration of the range. The total expenditure on preliminary underground exploration in the Lake Superior region is probably not less than $22,000,000. (See p. 485.)

Since the advent of large capital into the region exploration has been systematized and now often includes, as a preliminary or accompanying step, the complete geologic, topographic, and magnetic mapping of the areas to be explored.

The early development of the Lake Superior iron mining district, from the opening of the Marquette range to 1873, was for the most part accomplished by small companies and small capital. The period from 1873 to 1892 was marked by the presence of larger companies with moderate capital; and since 1892 mines have been operated by strong companies with large capital. This increase in capital has been accompanied by combination of the mining companies.

At present considerably more than half of the Lake Superior iron-ore reserve is controlled by the Oliver Iron Mining Company, the mining branch of the United States Steel Corporation. The Minnesota tax commission's report for 1908 credits the Oliver Company with 76.6 per cent of the reserve of iron ore for Minnesota.[a] It is not clear that the company's dominance in Michigan is so great as this, but in view of the fact that the Minnesota reserve is so far in excess of that in Michigan it is not likely that the Oliver Company's percentage of the Lake Superior reserve is far short of that given for Minnesota.

SMELTING.

The Lake Superior iron mines were opened at the time when anthracite and coke first began to be largely used in the smelting of iron. Before that time the fuel used in local furnaces was largely charcoal. Charcoal was surpassed in amount by anthracite in 1855 and by coke in 1869. More anthracite than coke was used until 1875, but since then coke has gradually but almost completely replaced anthracite for smelting. The use of anthracite and coke made possible both a large increase and a centralization in pig-iron production, and the growth of the Lake Superior iron-mining industry is practically concurrent with the increased use of these substances instead of charcoal. Since the opening of the Lake Superior region much the larger part of its output has been used in coke and anthracite furnaces of the lower lake region.

The smelting of iron ore within the Lake Superior region itself has been thus far on a relatively small but still considerable scale. Detailed figures are not available, but it is roughly estimated that about 3 per cent of the total production has been locally smelted. Several small forges were built in the Marquette district of Michigan in the decade before the first shipment was made to the lower Lakes. Since then about 25 charcoal furnaces, most of them now abandoned, have been built in the Upper Peninsula of Michigan, also one at Ashland, Wis., and several in the northern part of the Lower Peninsula of Michigan, using almost entirely Lake Superior ores.

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[a] First biennial report of the Minnesota tax commission to the governor and legislature of the State of Minnesota, St. Paul, 1908, p. 122.

In addition several small furnaces in Wisconsin, built principally for the use of local ores, have used small amounts of Lake Superior ores. Coke furnaces have been established at Duluth, Minn., and at Sault Ste. Marie, Ontario, and several of the charcoal furnaces, on account of the depletion of the charcoal supply and the increase in the availibility of coke, have substituted coke as fuel. Milwaukee, Chicago, Detroit, and adjacent points have of course been large users of iron ore in coke furnaces, but these lake ports are outside of the region. In 1908[a] there were in operation a coke furnace at Duluth, Minn., three in Wisconsin outside of Milwaukee, five charcoal furnaces in the Upper Peninsula of Michigan, three furnaces in the northern part of the Lower Peninsula of Michigan, and the steel plant at Sault Ste. Marie, Ontario. The largest plant yet projected for the local use of iron is to be built for steel making in West Duluth by the United States Steel Corporation; it may be in operation in 1912.

In recent years there has been an attempt to recover by-products from the charcoal burned, the first notable project being the Cleveland-Cliffs furnace at Presque Isle, in the Marquette district. This plant is most elaborately equipped for the recovery, as by-products, of wood alcohol and creosote. The Lake Superior Iron and Chemical Company, at Ashland, Wis., also has a well-equipped by-product plant. The Zenith furnace at Duluth has been rebuilt on a large scale to recover by-products from coke. At present it is supplying gas to the city of Duluth. The steel plant now planned at Duluth by the United States Steel Corporation will utilize the gases as fuel.

With increase of population directly tributary to the Great Lakes it is very likely that the local smelting of the ores will increase. The depletion of the timber will probably compel increased use of coke instead of charcoal. Peat, which is found locally in large quantities, may be considered as a possible fuel for the future.

INFLUENCE OF PHYSIOGRAPHY ON INDUSTRIAL DEVELOPMENT.

One of the principal relations between the physiography and history of the industrial Lake Superior region seems sufficiently distinct to be summarized in a few words. The early stages of development were closely controlled by conditions of accessibility. The early explorers, traders, and prospectors were confined to the lake and river shores and to country easily accessible from them. When mining and lumbering began there was also a distinct localization of these industries in accessible places. With the growth of the industry and the introduction of railways the influence of physiography on the local distribution of activity gradually became less marked, until at present this distribution is but little affected by the configuration of the surface and drainage. The situation of ore deposits has of course localized the mining development. Favorable conditions of access, though advantage has been taken of them, have been subordinate factors. An iron deposit would be utilized whether it was in a swamp or on a mountain, whether easily accessible or not. In other words, increased demand for the raw materials of the Lake Superior region, due to general commercial conditions and the westward movement and increase of population, has gradually overridden and more or less obliterated the natural physiographic channels of development.

The relation of the Great Lakes to cheapness of water transportation and of the simple topography of the region to ease of railway construction to any mineral-producing district continues to be an important physiographic influence and one that is unusual in a mining district.

[a] Map of the United States showing location of blast furnaces in 1908, compiled by W. T. Thom from Swank's Iron and steel works directory for 1908: Mineral Resources U. S. for 1908, pt. 1, U. S. Geol. Survey, 1910, Pl. II.

PRODUCTION OF IRON ORE.

The production of iron ore from the several producing ranges of the Lake Superior region since their opening is given in the following table, compiled principally from the Iron Trade Review. The figures refer mainly to shipments rather than to production. The figures of the United States Geological Survey do not go back far enough for the purposes of this table. The facts of the table are graphically expressed in figure 3.

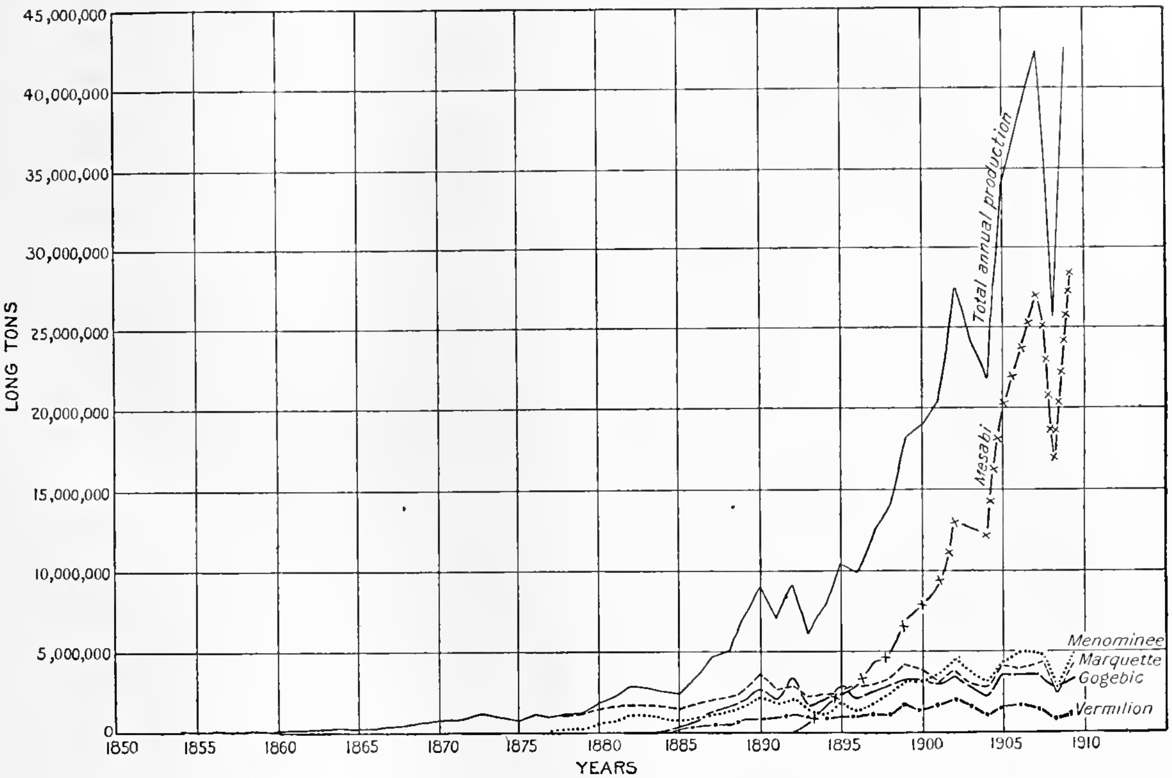

FIGURE 3.—Diagram showing annual production of iron ore in Lake Superior region since the opening of the region.

Table of Lake Superior iron-ore shipments from the earliest shipment to date.[a]

Gogebic Range.

[Gross tons.]

Name of mine.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
Ada. (Included in Ironton.)									
Anvil				10,075	24,676	47,000	45,690	73	42,090
Ashland		6,741	74,015	175,563	174,183	257,915	435,949	267,439	231,896
Atlantic				1,369					
Aurora [b]		5,422	94,553	159,252	179,937	199,865	246,695	83,554	319,482
Bessemer			4,788	16,101					
Blue Jacket				1,799					
Brotherton			8,880	21,721	40,639	53,267	80,486	46,574	130,833
Carey (and Superior)			2,697	29,763		56,542	152,878	131,896	119,676
Castile									
Chicago									
Colby [c]	1,022	84,302	257,432	258,518	285,880	136,833	193,038	9,619	69,968
Davis (Wisconsin)							1,497		21,754
Eureka							23,794	13,907	10,655
Federal							21,150	6,778	8,515
First National				1,997					
Geneva									

[a] Figures for 1893–1909, inclusive, from Supplement to the Iron Trade Review, vol. 46, No. 9, March 3, 1910. Figures for previous years compiled from the annual tables published by the Iron Trade Review and from "Annual review of the iron mining and other industries of the Upper Peninsula for the year ending December, 1880," by A. P. Swineford.

[b] Under Norrie group after 1904.

[c] Includes Tilden prior to 1891.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Gogebic Range—Continued.

[Gross tons.]

Name of mine.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
Germania (Harmony)	......	5,468	19,734	61,714	53,918	103,169	52,000	22,383	4,283
Hennepin	......	......	......	......	28,721	76,545	63,903	15,759	......
Imperial. (See Federal.)									
Iron Belt	......	......	......	......	30,000	51,551	110,368	1,506	161,635
Iron Chief	......	......	9,950	2,249	......	......	......	......	......
Iron Chief No. 2	......	......	551	......	......	......	......	......	......
Iron King. (See Newport.)									
Ironton	......	......	18,424	24,762	......	8,635	6,247	300	......
Jack Pot	......	......	......	......	......	......	......	......	3,944
Kakagon (now Cary)	......	......	18,497	52,179	1,228	......	......	......	......
Meteor (Comet)	......	......	......	......	......	......	2,882	10,144	54,779
Mikado	......	......	......	......	......	......	......	......	......
Montreal (Section 33)	......	......	23,013	43,989	38,015	116,094	143,691	108,684	73,409
New Davis. (See Davis.)									
Newport	......	......	20,184	75,660	69,145	36,987	71,488	105,606	165,962
Nimikon (now Cary)	......	......	4,105	23,217	1,313	......	......	......	......
Norrie group [a]	......	15,419	124,844	237,254	412,196	674,394	906,728	758,572	985,216
Ottawa (Odanah)	......	......	13,714	30,475	5,412	13,354	1,065	......	6,711
Pabst [b]	......	1,103	17,979	19,906	49,976	116,376	172,060	130,226	113,245
Palms	......	......	......	1,414	9,725	35,245	50,604	32,227	102,382
Pence	......	......	......	......	26,687	574	......	......	......
Pike	......	......	......	......	......	......	......	......	......
Puritan (Ruby)	......	......	16,388	45,000	3,058	9,472	11,694	913	......
Section 33. (See Montreal.)									
Shores	......	......	......	......	......	......	......	......	......
Sparta	......	......	......	......	......	......	......	......	2,912
Sunday Lake	......	1,405	10,963	18,137	......	......	6,010	64,902	56,046
Tilden [c]	......	......	......	......	......	......	......	28,415	233,356
Trimble	......	......	10,780	12,764	2,387	......	......	......	......
Tylers Forks	......	......	......	......	......	......	10,683	......	......
Upson	......	......	......	......	......	......	......	......	......
Valley	......	......	1,878	......	......	......	......	......	......
Vaughn. (See Aurora.)									
Windsor (now Cary)	......	......	......	......	......	14,576	37,210	97	53,242
Wisconsin. (See Davis.)									
Yale (West Colby)	......	......	......	......	......	......	......	......	......
	1,022	119,860	753,369	1,324,878	1,437,096	2,008,394	2,847,810	1,839,574	2,971,991

Name of mine.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Ada. (Included in Ironton.)									
Anvil	......	13,297	68,064	57,483	......	5,037	......	......	1,101
Ashland	66,067	83,020	126,096	91,149	111,625	123,208	154,615	232,961	286,399
Atlantic	......	......	70,989	60,727	50,307	38,058	19,964	135,955	190,135
Aurora [d]	179,028	203,152	245,883	187,169	166,122	133,076	170,369	193,111	223,747
Bessemer	......	......	......	......	......	......	......	......	......
Blue Jacket	......	......	......	......	......	......	......	......	......
Brotherton	18,905	47,148	40,567	50,490	46,186	73,198	78,858	89,804	103,109
Cary (and Superior)	28,578	47,156	52,349	38,821	37,308	43,162	62,524	125,496	179,374
Castile	......	......	......	......	......	......	......	......	......
Chicago	......	......	......	504	......	......	......	633	......
Colby [e]	59,346	32,616	......	48,492	22,921	152,875	103,239	32,572	23,475
Davis (Wisconsin)	15,210	......	10,253	......	......	......	5,029	3,569	......
Eureka	31,385	18,329	26,105	4,544	......	......	......	......	......
Federal	......	......	......	......	......	......	......	......	......
First National	......	......	......	......	......	......	......	......	......
Geneva	......	......	......	......	......	......	......	......	......
Germania (Harmony)	7,964	......	......	......	1,015	......	1,255	986	10,358
Hennepin	......	......	......	......	......	......	......	7,728	21,475
Imperial. (See Federal.)									
Iron Belt	23,976	45,109	148,228	81,351	96,763	58,418	105,934	54,664	43,883
Iron Chief	......	......	......	......	......	......	......	......	......
Iron Chief No. 2	......	......	......	......	......	......	......	......	......
Iron King. (See Newport.)									
Ironton	......	......	......	......	......	......	7,977	25,047	......
Jack Pot	1,651	......	......	......	1,265	......	......	33,893	19,988
Kakagon (now Cary)	......	......	......	......	......	......	......	......	......
Meteor (Comet)	9,604	11,782	......	......	......	......	332	7,844	34,140
Mikado	......	......	4,788	......	11,397	......	10,324	1,090	91,846
Montreal (Section 33)	34,299	46,037	138,882	131,531	191,106	270,776	153,307	107,524	72,945
New Davis. (See Davis.)									
Newport	109,718	150,392	157,821	142,369	150,979	196,953	263,711	217,201	190,448
Nimikon (now Cary)	......	......	......	......	......	......	......	......	......
Norrie group [a]	472,062	621,608	738,480	329,068	604,281	700,990	714,669	666,389	660,965
Ottawa (Odanah)	3,956	2,437	......	......	......	......	......	......	......
Pabst [b]	104,510	206,074	219,960	68,984	220,496	223,891	263,869	239,242	198,686
Palms	2,658	37,911	46,965	114,108	207,153	175,925	154,705	139,658	7,603
Pence	......	......	......	13,185	120	......	......	......	......
Pike	......	......	......	......	......	......	......	3,434	6,346
Puritan (Ruby)	......	......	......	......	......	......	......	......	21,788
Section 33. (See Montreal.)									
Shores	......	......	......	12,196	16,102	15,691	11,819	......	......
Sparta	......	......	1,950	......	......	......	......	......	......
Sunday Lake	22,876	34,323	20,970	89,441	45,815	......	12,526	74,097	89,997
Tilden [c]	135,118	209,077	418,188	250,205	276,890	287,203	500,830	481,909	446,670

[a] Includes Aurora after 1904 and Pabst after 1901.
[b] Under Norrie group after 1901.
[c] Under Colby prior to 1891.
[d] Under Norrie group after 1904.
[e] Includes Tilden prior to 1891.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Gogebic Range—Continued.

[Gross tons.]

Name of mine.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Trimble									
Tylers Forks									
Upson									
Valley									
Vaughn. (See Aurora.)									
Windsor (now Cary)	2,474		11,438	28,154	385			488	841
Wisconsin. (See Davis.)									
Yale (West Colby)									12,836
	1,329,385	1,809,468	2,547,976	1,799,971	2,258,236	2,498,461	2,795,856	2,875,295	2,938,155

Name of mine.	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Ada. (Included in Ironton.)									
Anvil	135,502	11,309	45,595	82,118	79,493	39,495	35,937	22,927	766,962
Ashland	301,824	274,138	344,102	409,131	341,841	298,056	259,611	259,612	5,387,156
Atlantic	190,213	148,385	77,224	208,039	97,689	91,759	41,465	124,845	1,547,123
Aurora [a]	402,981	355,365	212,920						3,961,683
Bessemer									20,889
Blue Jacket									1,799
Brotherton	53,255	94,986	84,870	137,351	147,281	104,224	96,776	103,090	1,752,498
Cary (and Superior)	136,895	89,221	61,860	146,414	216,992	209,407	96,358	224,251	2,289,618
Castile					2,108	6,157		26,982	35,247
Chicago	44,625	22,965							68,727
Colby [b]	22,526	54,915	81,141	83,736	113,001	94,480	58,305	170,095	2,450,347
Davis (Wisconsin)	31,530	734	11,225	3,160					103,961
Eureka					37,525	57,904	122,324	115,662	462,134
Federal									36,443
First National									1,997
Geneva		7,108							7,108
Germania (Harmony)	20,502	2,246	23,364	2,973	9,436	19,319		152	422,239
Hennepin	36,383	862		2,589	5,768				259,733
Imperial. (See Federal.)									
Iron Belt	79,121	25,353			3,227	17,347	2,508	44,560	1,185,502
Iron Chief									12,199
Iron Chief No. 2									551
Iron King. (See Newport.)									
Ironton	8,555	16,875	23,197	41,314	106,158	190,968	92,932	277,594	848,985
Jack Pot	102	31,709	6,538						99,090
Kakagon (now Cary)									71,904
Meteor (Comet)	19,117	6,156	59,587						216,367
Mikado	98,834	108,709	25,611	140,740	154,043	163,891	86,617	99,195	997,085
Montreal (Section 33)	136,354	93,139	163,021	107,854	139,202	159,763	177,006	191,611	2,861,252
New Davis. (See Davis.)									
Newport	141,571	279,905	171,931	438,023	549,745	551,496	579,390	1,008,354	5,845,039
Nimikon (now Cary)									28,635
Norrie group [c]	1,080,032	790,346	618,638	1,527,128	1,245,997	1,109,085	773,243	977,054	17,744,658
Ottawa (Odanah)	26,141	87,929	30,420	21,986	57,219	46,424	33,893	100,223	481,359
Pabst [d]									2,366,583
Palms	32,113	60,800	53,718	13,953	5,622				1,284,489
Pence									40,566
Pike	6,343	115		11,161	17,934	24,922	6,303	22,174	98,732
Puritan (Ruby)			1,259						109,572
Section 33. (See Montreal.)									
Shores									55,808
Sparta									4,862
Sunday Lake	144,630	91,383	50,625	79,209	86,879	101,899	111,130	93,712	1,306,975
Tilden [e]	468,672	211,534	204,581	188,104	169,697	312,496	111,184	154,506	5,088,635
Trimble									25,931
Tylers Forks									10,683
Upson	11,065	310							11,375
Valley									1,878
Vaughn. (See Aurora.)									
Windsor (now Cary)									148,905
Wisconsin. (See Davis.)									
Yale (West Colby)	26,043	46,211	46,860	60,224	56,657	38,010	14,874	71,458	373,173
	3,654,929	2,912,708	2,398,287	3,705,207	3,643,514	3,637,102	2,699,856	4,088,057	60,896,457

Marquette Range.

Name of mine.	Years unknown.	1854.	1855.	1856.	1857.	1858.	1859.	1860.	1861.	1862.
American (Sterling)										
Ames										
Austin										
Barnum [f]										
Bay State										
Bessemer. (See Lillie.)										
Bessie										
Beaufort (Ohio)										

[a] Under Norrie group after 1904.
[b] Includes Tilden prior to 1891.
[c] Includes Aurora after 1904 and Pabst after 1901.
[d] Under Norrie group after 1901.
[e] Under Colby prior to 1891.
[f] Under Iron Cliffs, 1890-1895; under Cleveland-Cliffs group after 1895.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	Years unknown.	1854.	1855.	1856.	1857.	1858.	1859.	1860.	1861.	1862.
Blue. (See Queen group.)										
Boston										
Braastad, Mitchell										
Braastad, Winthrop										
Breitung Hematite No. 2										
Buffalo[a]										
Cambria										
Champion										
Cheshire. (See Princeton.)										
Chester. (See Rolling Mill.)										
Chicago										
Cleveland[b]		3,000	1,449	6,343	13,204	7,909	15,787	40,091	11,795	40,364
Cleveland Hematite. (Included under Cleveland.)										
Cleveland-Cliffs group[c]										
Columbia (Kloman)										
Curry										
Dalliba (Phenix)										
Detroit										
Dexter										
Dey										
East Champion										
East New York										
Edison										
Edwards. (See Samson.)										
Empire										
Erie										
Etna										
Fitch										
Foster[d]										
Foxdale										
Gibson										
Goodrich										
Grand Rapids (Davis)										
Green Bay. (See Bay State.)										
Hartford										
Hortense (North Champion)										
Home (P. and L. S.) (now Volunteer)										
Humboldt (Washington)										
Imperial										
Indiana. (See Bay State.)										
Iron Cliffs[e]										
Iron Mountain										
Jackson	30,000				12,442	10,309	28,377	41,295	12,919	46,096
Keystone. (See East Champion.)										
Lake Angeline										
Lake Superior						4,658	24,668	33,015	25,195	37,709
Lillie										
Lucy (McComber)										
Maas										
Magnetic (stock pile)										
Manganese (Negaunee)										
Marquette[f]										
Mary Charlotte										
Mesabi's Friend										
Michigamme[e]										
Miller										
Milwaukee										
Mitchell										
Moore										
National										
Negaunee										
Negaunee Construction Works										
New York (York)										
New York Hematite										
North Champion. (See Hortense.)										
North Republic										
Nonpareil (St. Lawrence)										
Northwest										
Norwood										
Ogden										
Pascoe										
Pendill										
Palmer										
Palmer (Cascade). (See Volunteer.)										
Pioneer										
Pittsburg and Lake Angeline. (See under Lake Angeline.)										
Platt										
Portland										
Primrose										
Prince of Wales[a]										
Princeton (Swanzey or Cheshire)										
Quartz										
Queen[a]										

[a] Under Queen group after 1890.
[b] Under Cleveland-Cliffs group after 1883.
[c] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.
[d] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[e] Under Cleveland-Cliffs group after 1895.
[f] Under Winthrop after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	Years unknown.	1854.	1855.	1856.	1857.	1858.	1859.	1860.	1861.	1862.
Queen group [a]										
Republic										
Republic Reduction Co.										
Richards										
Richmond										
Riverside										
Rolling Mill										
Saginaw										
Salisbury [b]										
Sam Mitchell. (See Mitchell.)										
Samson (Argyle)										
Schadt										
Section 12										
Smith. (See Princeton.)										
South Buffalo [c]										
Spurr										
Star West (Wheat)										
St. Lawrence. (See Nonpareil.)										
Stegmiller										
Sterling. (See American.)										
Stephenson										
Taylor										
Teal Lake. (See Cambria.)										
Titan										
Volunteer (see also Home)										
Washington										
Webster										
West Republic										
Wetmore										
Wheeling										
Winthrop [d]										
Wheat. (See Star West.)										
	30,000	3,000	1,449	6,343	25,646	22,876	68,832	114,401	49,909	124,169

Name of mine.	1863.	1864.	1865.	1866.	1867.	1868.	1869.	1870.	1871.	1872.
American (Sterling)										
Ames										
Austin										
Barnum [e]						14,385	33,484	44,793	45,939	38,381
Bay State										
Bessemer. (See Lillie.)										
Bessie										
Beaufort (Ohio)										
Blue. (See Queen group.)										
Boston										
Braastad {Mitchell										197
Braastad {Winthrop								3,469	11,088	14,239
Breitung Hematite No. 2										
Buffalo [c]										
Cambria										
Champion						6,255	21,535	73,161	67,588	68,408
Cheshire. (See Princeton.)										
Chester. (See Rolling Mill.)										
Chicago										
Cleveland [f]	46,842	44,959	33,355	42,680	75,864	102,112	106,133	132,884	142,658	151,724
Cleveland Hematite. (Included under Cleveland.)										
Cleveland-Cliffs group [g]										
Columbia (Kloman)										
Curry										
Dalliba (Phenix)										
Detroit										
Dexter										
Dey										
East Champion										
East New York										
Edison										
Edwards. (See Samson).										
Empire										
Erie										
Etna										
Fitch										
Foster [b]						6,000	14,540	23,458	13,532	18,684
Foxdale										
Gibson										
Goodrich										
Grand Rapids (Davis)										
Green Bay. (See Bay State.)										
Hartford										

[a] Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
[b] Under Iron Cliffs, 1891–1895; under Cleveland-Cliffs group after 1895.
[c] Under Queen group after 1890.
[d] Prior to 1890, see Braastad; includes Marquette after 1892.
[e] Under Iron Cliffs, 1890–1895; under Cleveland-Cliffs group after 1895.
[f] Under Cleveland-Cliffs group after 1883.
[g] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1863.	1864.	1865.	1866.	1867.	1868.	1869.	1870.	1871.	1872.
Hortense (North Champion)										
Home (P. and L. S.) (now Volunteer)										1,160
Humboldt (Washington)			4,782	15,150	25,440	35,757	58,402	79,762	48,725	38,841
Imperial										
Indiana. (See Bay State.)										
Iron Cliffs *a*										
Iron Mountain										
Jackson	77,237	83,905	65,505	92,287	127,491	130,524	125,908	127,642	132,297	119,910
Keystone. (See East Champion.)										
Lake Angeline		19,500	20,151	24,073	46,607	27,651	35,432	53,467	33,645	35,221
Lake Superior	78,976	86,763	50,201	68,002	119,935	105,745	131,343	166,582	158,047	185,070
Lillie										
Lucy (McComber)								4,866	15,942	24,153
Maas										
Magnetic (stock pile)										
Manganese (Negaunee)										
Marquette *b*										
Mary Charlotte										
Mesabi's Friend										
Michigamme *a*										141
Miller										
Milwaukee										
Mitchell										
Moore										
National										
Negaunee										
Negaunee Construction Works										
New York (York)		8,000	12,214	33,761	43,302	45,665	71,456	94,809	76,381	68,950
New York Hematite								1,809	2,921	9,925
North Champion. (See Hortense.)										
North Republic										
Nonpareil (St. Lawrence)										
Northwest										
Norwood										
Ogden										
Pascoe										
Pendill										
Palmer										
Palmer (Cascade). (See Volunteer.)										
Pioneer										
Pittsburg and Lake Angeline. (See under Lake Angeline.)										
Platt										
Portland										
Primrose										
Prince of Wales *c*										
Princeton (Swanzey or Cheshire)										13,445
Quartz										
Queen *c*										
Queen group *d*										
Republic										11,025
Republic Reduction Co.										
Richards										
Richmond										
Riverside										
Rolling Mill									236	6,772
Saginaw										18,503
Salisbury *e*										545
Sam Mitchell. (See Mitchell.)										
Samson (Argyle)				2,843	4,928	17,360	19,151	24,232	26,437	28,380
Schadt										
Section 12										
Smith. (See Princeton.)										
South Buffalo *c*										
Spurr										
Star West (Wheat)										
St. Lawrence. (See Nonpareil.)										
Stegmiller										
Sterling. (See American.)										
Stephenson										
Taylor										
Teal Lake. (See Cambria.)										
Titan										
Volunteer (see also Home)									4,171	39,495
Washington										
Webster										
West Republic										
Wetmore										
Wheeling										
Winthrop *f*										
Wheat. (See Star West.)										
	203,055	243,127	186,208	278,796	443,567	491,454	617,444	830,934	779,607	893,169

a Under Cleveland-Cliffs group after 1895.
b Under Winthrop after 1892.
c Under Queen group after 1890.
d Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
e Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
f Prior to 1890, see Braastad; includes Marquette after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1873.	1874.	1875.	1876.	1877.	1878.	1879.	1880.	1881.	1882.
American (Sterling)								797	4,702	8,006
Ames										
Austin										
Barnum [a]	48,076	41,403	43,209	37,632	37,909	26,680	24,015	24,522	27,883	41,778
Bay State				8,583			3,336	2,268	583	1,236
Bessemer. (See Lillie.)										
Bessie										
Beaufort (Ohio)										5,532
Blue. (See Queen group.)										
Boston								6,478	14,824	18,245
Braastad Mitchell	8,658	7,549		5,596	3,898	4,259	11,131	13,279	21,146	33,396
Braastad Winthrop	33,456	7,549	7,502	27,236	12,549	23,740	26,595	45,247	43,630	23,005
Breitung Hematite No. 2										
Buffalo [b]										
Cambria		2,610		6,329	10,083	3,754	6,724	6,958	19,246	64,545
Champion	72,782	47,097	56,877	66,002	70,883	73,464	94,027	112,401	145,427	159,009
Cheshire. (See Princeton.)										
Chester. (See Rolling Mill.)										
Chicago							949	2,415	5,531	
Cleveland [c]	133,265	105,858	129,881	146,393	152,188	152,737	131,167	212,748	198,569	206,120
Cleveland Hematite. (Included under Cleveland.)										
Cleveland-Cliffs group [d]										
Columbia (Kloman)	21,065	35,088	8,059					6,663	11,158	12,066
Curry										
Dalliba (Phenix)									10,986	44,836
Detroit										5,402
Dexter										
Dey										
East Champion	10,426	5,227	3,346	7,715	14,495	5,401	4,029	10,217	3,408	4,002
East New York										
Edison										
Edwards. (See Samson.)										
Empire										
Erie										2,731
Etna										
Fitch										
Foster [e]	18,107	4,719	847	125			4,804	1,122	3,011	11,648
Foxdale										
Gibson										
Goodrich				[f] 6,338	503	7,547	3,992	11,131	10,245	9,998
Grand Rapids (Davis)										
Green Bay. (See Bay State.)										
Hartford										
Hortense (North Champion)										
Home (P. and L. S.) (now Volunteer)	21,498	1,362				1,225	492	285		
Humboldt (Washington)	38,014	27,890	9,642	3,333	16,545	23,921	18,204	14,726	26,302	43,463
Imperial										
Indiana. (See Bay State.)										
Iron Cliffs [g]										
Iron Mountain										
Jackson	130,131	105,600	90,568	98,480	80,340	83,121	103,219	120,620	118,939	96,830
Keystone. (See East Champion.)										
Lake Angeline	43,933	31,526	26,370	22,539	19,112	28,161	25,321	14,928	18,060	14,326
Lake Superior	158,078	114,074	129,339	111,766	127,349	109,674	173,938	204,094	262,235	296,509
Lillie				5,945	10,127	8,506	22,380	18,347	16,748	27,494
Lucy (McComber)	38,969	2,642	10,407	17,276	19,691	30,180	28,962	31,206	28,051	40,406
Maas										
Magnetic (stock pile)										
Manganese (Negaunee)										
Marquette [h]										
Mary Charlotte										
Mesabi's Friend										
Michigamme [g]	29,107	45,294	44,763	70,074	28,238	58,622	56,970	52,766	57,272	43,712
Miller										
Milwaukee							941	13,142	31,635	40,891
Mitchell										
Moore										
National						4,191	33,310	29,351	24,833	23,366
Negaunee										
Negaunee Construction Works										1,177
New York (York)	70,882	77,017	70,103	58,863	55,581	21,903	57,528	58,512	50,074	56,806
New York Hematite	6,629		987	556	3,307	4,547	2,609	2,192		2,105
North Champion. (See Hortense.)										
North Republic										
Nonpareil (St. Lawrence)										9,998
Northwest										
Norwood										
Ogden										
Pascoe										18,880
Pendill						4,000	12,549	3,959	13,586	9,987
Palmer										
Palmer (Cascade). (See Volunteer.)										
Pioneer										
Pittsburg and Lake Angeline. (See under Lake Angeline.)										

[a] Under Iron Cliffs, 1890-1895; under Cleveland-Cliffs group after 1895.
[b] Under Queen group after 1890.
[c] Under Cleveland-Cliffs group after 1883.
[d] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.
[e] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[f] Includes shipments for prior years.
[g] Under Cleveland-Cliffs group after 1895.
[h] Under Winthrop after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1873.	1874.	1875.	1876.	1877.	1878.	1879.	1880.	1881.	1882.
Platt										
Portland										
Primrose										
Prince of Wales [a]										
Princeton (Swanzey or Cheshire)	9,328		187	225	8,434	16,924	17,985	13,202	15,011	31,498
Quartz										
Queen [a]										
Queen group [b]										
Republic	105,453	122,639	119,726	120,095	165,836	176,221	135,231	235,387	233,786	235,109
Republic Reduction Co										
Richards										
Richmond										
Riverside										
Rolling Mill	11,319	16,643	37,806	53,265	38,121	30,773	10,039	15,172	1,668	163
Saginaw	37,138	45,486	55,318	56,979	44,005	54,097	43,396	35,059	30,793	16,276
Salisbury [c]	11,023	6,730	4,571	20,510	37,869	52,155	39,293	21,457	43,690	42,243
Sam Mitchell. (See Mitchell.)										
Samson (Argyle)	38,968	2,849	12,804	19,330	10,419	10,351	5,455		4,584	12,421
Schadt										
Section 12							5,027	330	13,243	3,287
Smith. (See Princeton.)										
South Buffalo [a]										
Spurr	31,933	42,068	23,094	20,276	22,801	2,225	1,409		2,746	8,873
Star West (Wheat)	1,091	2,139					851	3,323	9,040	9,554
St. Lawrence. (See Nonpareil.)										
Stegmiller										
Sterling. (See American.)										
Stephenson										
Taylor								1,110	10,559	15,146
Teal Lake. (See Cambria.)										
Titan										1,778
Volunteer (see also Home)	28,920	18,198	4,071	15,324	20,211	4,704	24,141	38,596	39,276	41,456
Washington										
Webster										4,443
West Republic									7,354	27,865
Wetmore										1,777
Wheeling										
Winthrop [d]										
Wheat. (See Star West.)										
	1,158,249	919,257	889,477	1,006,785	1,010,494	1,023,083	1,130,019	1,384,010	1,579,834	1,829,394

Name of mine.	1883.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
American (Sterling)	3,618	2,916			1,483	13,699	20,032	21,000	21,604	15,076
Ames										
Austin										
Barnum [e]	62,752	69,408	47,458	52,975	16,123	10,211	12,835			
Bay State	631									
Bessemer. (See Lillie.)										
Bessie									847	
Beaufort (Ohio)	18,976	18,360	17,166	17,354	12,829					
Blue. (See Queen group.)										
Boston	20,190	2,218								
Braastad {Mitchell				7,017	16,419	4,091				
Braastad {Winthrop	50,143	73,144	53,913	58,743	74,067	86,789	155,341			
Breitung Hematite No. 2										
Buffalo [a]				10,860	24,686	30,801	50,919	100,464		
Cambria	47,508	59,742	50,796	58,784	41,130	57,861	72,780	80,359	34,662	41,549
Champion	104,960	210,180	173,915	137,593	146,330	174,680	215,098	223,442	133,413	109,979
Cheshire. (See Princeton.)										
Chester. (See Rolling Mill.)										
Chicago	117									
Cleveland [f]	218,219									
Cleveland Hematite. (Included under Cleveland.)										
Cleveland-Cliffs group [g]		225,674	218,757	203,664	207,441	184,316	274,048	331,713	221,788	310,907
Columbia (Kloman)	714									
Curry							16,671			
Dalliba (Phenix)	1,687				1,605					
Detroit	12,314	3,809	19,125	39,400	26,099	18,500	10,112	6,080		
Dexter	4,878	16,202	750			1,821	3,895	9,136	5,448	13,000
Dey		2,709								
East Champion	5,039						2,697			
East New York						13,694	29,739	36,431	50,293	35,175
Edison							893			
Edwards. (See Samson.)										
Empire										
Erie	5,405									
Etna	1,091									
Fitch								16,550	15,093	
Foster [c]	10,029	9,675	9,643					21,949		
Foxdale										

[a] Under Queen group after 1890.
[b] Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
[c] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[d] Prior to 1890, see Braastad; includes Marquette after 1892.
[e] Under Iron Cliffs, 1890-1895; under Cleveland-Cliffs group after 1895.
[f] Under Cleveland-Cliffs group after 1883.
[g] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1883.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
Gibson			1,515	12,142	2,700					
Goodrich										
Grand Rapids (Davis)					1,200	11,611	20,058	26,426	9,362	22,823
Green Bay. (See Bay State.)										
Hartford							566			5,678
Hortense (North Champion)					886	5,685	7,757	16,246		
Home (P. and L. S.) (now Volunteer)										
Humboldt (Washington)	31,866	23,763	11,766	20,207	19,873	11,655	15,866	23,259	19,879	4,571
Imperial								38,460	18,552	7,194
Indiana. (See Bay State.)										
Iron Cliffs [a]					87,346	78,520	134,616	188,776	278,270	289,395
Iron Mountain					393					
Jackson	71,278	83,251	68,657	89,370	109,906	101,909	128,891	124,682	92,979	92,567
Keystone. (See East Champion.)										
Lake Angeline	27,259	86,922	111,051	131,731	191,120	223,600	229,070	261,680	241,605	287,517
Lake Superior	200,799	204,796	226,040	267,622	302,909	240,225	288,784	318,321	308,831	366,715
Lillie	4,614	2,683	708	3,957	23,041	32,692	33,916	31,812	19,551	29,005
Lucy (McComber)	14,676				12,139	22,276	32,982	43,483	27,683	26,326
Maas										
Magnetic (stock pile)										
Manganese (Negaunee)	397	1,484	3,111	1,367						
Marquette [b]				5,229	20,441	7,060	70,128	23,692	16,802	9,555
Mary Charlotte										
Mesabi's Friend										
Michigamme [a]	42,533	25,935	12,373	48,790	58,726	36,448	56,999	80,777	23,169	1,894
Miller										
Milwaukee	805	25,991	38,465	46,693	50,490	48,908	52,727	24,763		
Mitchell				8,823	8,411	546				
Moore										
National	21,178	13,987								
Negaunee					5,259	45,304	78,318	76,488	64,218	85,846
Negaunee Construction Works	10,394	43		1,094						
New York (York)	1,517	1,677			5,128		12,844	2,422		11,220
New York Hematite										
North Champion. (See Hortense.)										
North Republic						289				
Nonpareil (St. Lawrence)	11,961				1,436					
Northwest										1,687
Norwood					2,200	3,553				
Ogden										
Pascoe		12,605	18,249	10,072						
Pendill	318	1,594								
Palmer										
Palmer (Cascade). (See Volunteer.)										
Pioneer				5,140	1,203	9,066				
Pittsburg and Lake Angeline. (See under Lake Angeline.)										
Platt										2,676
Portland										
Primrose										
Prince of Wales [c]								32,415		
Princeton (Swanzey or Cheshire)	13,730	3,557		8,328	2,842				7,301	29,403
Quartz							491			
Queen [c]						5,527	66,122	109,217		
Queen group [d]									479,509	379,719
Republic	152,565	277,757	250,835	241,161	220,624	235,062	287,390	220,065	191,127	167,991
Republic Reduction Co					87	21,050	22,122	3,915		
Richards					1,374					
Richmond										
Riverside						5,622	3,712		6,783	
Rolling Mill	1,528	1,820	3,437	4,403	1,058	402				
Saginaw	9,108	946							4,320	
Salisbury [e]	17,028	26,629	29,503	51,667	48,304	74,947	72,449	85,798		
Sam Mitchell. (See Mitchell.)										
Samson (Argyle)	15,700	1,334		1,133		4,512	2,796	1,218		600
Schadt										
Section 12										
Smith. (See Princeton.)										
South Buffalo [c]					4,964	24,706	69,359	146,383		
Spurr	9,067			752						
Star West (Wheat)	6,625	6,824	9,200	15,867	17,538	4,987	7,997	15,141	4,412	
St. Lawrence. (See Nonpareil.)										
Stegmiller										
Sterling. (See American.)										
Stephenson										
Taylor	6,155									
Teal Lake. (See Cambria.)										
Titan	13,128	19,411	23,340	13,865	16,003	2,846				
Volunteer (see also Home)	19,414	11,748	5,679	24,034	47,486	56,321	60,156	141,524	92,699	127,130
Washington										
Webster		934		6,229	2,054		448			
West Republic	30,734	19,623	12,700	10,558	12,872	9,861	1,510			
Wetmore	2,777	4,585	5,887	10,756	3,335	2,074	19,679			
Wheeling		4,098	6,383		74					
Winthrop [f]								109,576	122,042	191,658
Wheat. (See Star West.)										
	1,305,425	1,558,034	1,430,422	1,627,380	1,851,634	1,923,727	2,642,813	2,993,664	2,512,242	2,666,856

[a] Under Cleveland-Cliffs group after 1895.
[b] Under Winthrop after 1892.
[c] Under Queen group after 1890.
[d] Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
[e] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[f] Prior to 1890, see Braastad; includes Marquette after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.	1902.
American (Sterling)										
Ames	1,103	5,195								
Austin										
Barnum [a]										
Bay State										
Bessemer. (See Lillie.)										
Bessie										5,007
Beaufort (Ohio)								1,583	4,338	59,781
Blue. (See Queen group.)										
Boston				587						
Braastad: Mitchell										
Braastad: Winthrop										
Breitung Hematite No. 2										
Buffalo [b]										
Cambria	30,445	47,218	41,656	95,086	110,648	102,623	124,930	80,432	68,907	63,976
Champion	61,648	42,788	100,398	113,375	141,728	163,190	215,074	113,743	99,026	205,721
Cheshire. (See Princeton.)										
Chester. (See Rolling Mill.)										
Chicago										
Cleveland [c]										
Cleveland Hematite. (Included under Cleveland.)										
Cleveland-Cliffs group [d]	218,105	143,706	221,153	513,119	718,408	869,482	1,011,048	881,021	860,484	1,104,864
Columbia (Kloman)										
Curry										
Dalliba (Phenix)										
Detroit										
Dexter	7,833	21,740	13,752	18,903	1,154					
Dey										
East Champion										
East New York	911							27,987	31,696	38,761
Edison										
Edwards. (See Samson.)										
Empire										
Erie										
Etna										
Fitch			174							
Foster [e]										
Foxdale									4,647	15,015
Gibson										
Goodrich										
Grand Rapids (Davis)	352	12,073	6,764	67						
Green Bay. (See Bay State.)										
Hartford	6,513	940		1,532						7,440
Hortense (North Champion)										
Home (P. and L. S.) (now Volunteer)										
Humboldt (Washington)				2,297						
Imperial							23,235	62,321		
Indiana. (See Bay State.)										
Iron Cliffs [f]	130,812	253,760	259,042							
Iron Mountain										
Jackson	51,009	32,288	42,186	80,710	79,102	55,012	88,230	31,714	38,271	15,449
Keystone (See East Champion.)										
Lake Angeline	351,973	355,453	313,555	342,251	489,685	460,333	464,988	389,128	481,574	304,125
Lake Superior	329,610	344,758	342,439	459,576	376,761	686,563	682,595	709,143	635,642	832,796
Lillie	68,861	78,388	54,285	107,532	112,781	211,023	196,200	114,990	98,788	79,919
Lucy (McComber)	21,964				10,033	11,846				
Maas										
Magnetic (stock pile)										
Manganese (Negaunee)										
Marquette [g]										
Mary Charlotte										
Mesabi's Friend			5,503	10,540						
Michigamme [f]	935	1,610	3,214							
Miller										
Milwaukee										
Mitchell										
Moore								4,648	37,655	
National										
Negaunee	69,732	132,581	90,682	175,394	182,169	191,330	195,573	126,829	234,713	204,286
Negaunee Construction Works										
New York (York)	25,000	21,487					6,642	3,327		
New York Hematite										
North Champion. (See Hortense.)										
North Republic										
Nonpareil (St. Lawrence)										
Northwest										
Norwood										
Ogden					986					
Pascoe										
Pendill										
Palmer				1,041						
Palmer (Cascade). (See Volunteer.)										
Pioneer										
Pittsburg and Lake Angeline. (See under Lake Angeline.)										

[a] Under Iron Cliffs, 1890-1895; under Cleveland-Cliffs group after 1895.
[b] Under Queen group after 1890.
[c] Under Cleveland-Cliffs group after 1883.
[d] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.
[e] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[f] Under Cleveland-Cliffs group after 1895.
[g] Under Winthrop after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.	1902.
Platt	5,448	41,226	13,198	11,296						
Portland										
Primrose				6,040						
Prince of Wales[a]										
Princeton (Swanzey or Cheshire)	19,096		6,593			25,247	55,802	75,037	67,051	118,048
Quartz										
Queen[a]										
Queen group[b]	120,673	252,469	204,957	323,057	242,293	61,022	342,978	398,298	400,845	418,044
Republic	64,195	105,719	174,027	127,360	124,342	140,312	137,085	130,126	104,604	157,646
Republic Reduction Co.										
Richards					6,887					
Richmond				1,088	4,630	24,464	4,613	51,303	54,181	50,041
Riverside	43									
Rolling Mill					3,975			22,585	22,815	24,874
Saginaw										
Salisbury[c]										
Sam Mitchell. (See Mitchell.)										
Samson (Argyle)										
Schadt			1,261							
Section 12										
Smith. (See Princeton.)										
South Buffalo[a]										
Spurr										
Star West (Wheat)		5,550	51,207	9,658	942		6,716	15,987		
St. Lawrence. (See Nonpareil.)										
Stegmiller										
Sterling. (See American.)										
Stephenson										
Taylor										
Teal Lake. (See Cambria.)										
Titan										
Volunteer (see also Home)	69,561	26,946	32,672	53,216	1,617		29,983	47,578		32,736
Washington										
Webster								20,797		
West Republic										
Wetmore										
Wheeling										
Winthrop[d]	180,071	134,365	119,120	150,496	106,894	122,592	171,318	148,945	109	129,496
Wheat. (See Star West.)										
	1,835,893	2,060,260	2,097,838	2,604,221	2,715,035	3,125,039	3,757,010	3,457,522	3,245,346	3,868,025

Name of mine.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
American (Sterling)				419	13,764	23,222	90,001	240,339
Ames								6,298
Austin					195,950	111,229	125,858	433,037
Barnum[e]								801,851
Bay State								16,637
Bessemer. (See Lillie.)								
Bessie	29,718		21,879	1,646				59,097
Beaufort (Ohio)	134,648	25,781	38,306		78,029	61,035	72,987	566,705
Blue. (See Queen group.)								
Boston								62,542
Braastad {Mitchell								136,636
Braastad {Winthrop								831,445
Breitung Hematite No. 2	7,854	9,869		38,671	59,667	55,849	129,673	301,583
Buffalo[a]								217,730
Cambria	41,168	84,852	81,791	40,628	135,145	85,977	136,815	2,037,717
Champion	74,238	174	64,680	115,007	107,577	313	11,199	4,394,385
Cheshire. (See Princeton.)								
Chester. (See Rolling Mill.)								
Chicago								9,012
Cleveland[f]								2,806,298
Cleveland Hematite. (Included under Cleveland.)								
Cleveland-Cliffs group[g]	810,845	743,263	1,288,416	1,330,944	1,030,928	438,379	877,433	15,239,906
Columbia (Kloman)								94,813
Curry								16,671
Dalliba (Phenix)								59,114
Detroit								140,841
Dexter								118,512
Dey								2,709
East Champion								76,002
East New York	22,523	7,299	33,095					327,604
Edison								893
Edwards. (See Samson.)								
Empire					40,565	53,537	108,993	203,095
Erie								8,136
Etna								1,091
Fitch								31,817
Foster[c]								171,893
Foxdale	5,053	3,429	3,303					31,447
Gibson								16,357

[a] Under Queen group after 1890.
[b] Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
[c] Under Iron Cliffs, 1891-1895; under Cleveland-Cliffs group after 1895.
[d] Prior to 1890, see Braastad; includes Marquette after 1892.
[e] Under Iron Cliffs, 1890-1895; under Cleveland-Cliffs group after 1895.
[f] Under Cleveland-Cliffs group after 1883.
[g] Includes Cleveland after 1883; includes Barnum, Foster, Iron Cliffs, Michigamme, and Salisbury after 1895.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Marquette Range—Continued.

[Gross tons.]

Name of mine.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Goodrich								49,754
Grand Rapids (Davis)								110,736
Green Bay. (See Bay State.)								
Hartford	26,085	179,980	322,209	364,801	328,161	278,366	250,680	1,766,951
Hortense (North Champion)								30,574
Home (P. and L. S.) (now Volunteer)								26,022
Humboldt (Washington)								713,961
Imperial		727	1,661	5,076	55,756	48,231	115,478	376,691
Indiana. (See Bay State.)								
Iron Cliffs [a]								1,700,537
Iron Mountain								393
Jackson	5,409		33,180	5,066	61,345		11,000	3,885,513
Keystone. (See East Champion.)								
Lake Angeline	310,950	262,486	374,183	269,116	283,373	220,410	280,298	8,285,460
Lake Superior	604,829	590,339	727,378	635,671	674,066	261,955	349,435	14,931,563
Lillie	77,454	63,209	9,868	32,781	80,545	8,632	61,708	1,748,490
Lucy (McComber)				85		1,115	1,672	519,031
Maas					32,378	29,036	159,197	220,611
Magnetic (stock pile)				292				292
Manganese (Negaunee)								6,359
Marquette [b]								152,907
Mary Charlotte	34,303	48,885	221,738	257,088	155,633	99,104	240,433	1,057,184
Mesabi's Friend								16,043
Michigamme [a]								880,362
Miller								
Milwaukee								375,451
Mitchell						11,539		29,319
Moore		25,828						68,131
National								150,216
Negaunee	224,665	145,132	239,554	253,448	196,170	232,219	312,217	3,662,127
Negaunee Construction Works								12,708
New York (York)								1,123,071
New York Hematite								37,587
North Champion. (See Hortense.)								
North Republic								289
Nonpareil (St. Lawrence)								23,395
Northwest								1,687
Norwood								5,753
Ogden								986
Pascoe								59,806
Pendill								45,993
Palmer				13,131				14,172
Palmer (Cascade). (See Volunteer.)								
Pioneer								15,409
Pittsburg and Lake Angeline. (See under Lake Angeline.)								
Platt								73,844
Portland							79,652	79,652
Primrose								6,040
Prince of Wales [c]								32,415
Princeton (Swanzey or Cheshire)	84,223	76,461	129,079	166,894	177,863	36,033	42,934	1,271,761
Quartz								491
Queen [c]								180,866
Queen group [d]	254,658	311,479	253,377	221,096	309,917	104,098	237,509	5,315,998
Republic	155,415	124,506	150,699	177,220	170,554	67,999	176,575	6,193,469
Republic Reduction Co								47,174
Richards								8,261
Richmond	55,593	68,134	86,129	89,563	35,156	60,994	102,566	688,455
Riverside								16,160
Rolling Mill	6,786		28,766		49,204	52,147	133,139	578,916
Saginaw								451,424
Salisbury [e]								686,411
Sam Mitchell. (See Mitchell.)								
Samson (Argyle)								267,805
Schadt								1,261
Section 12								21,887
Smith. (See Princeton.)								
South Buffalo [c]								245,412
Spurr								165,244
Star West (Wheat)								204,649
St. Lawrence. (See Nonpareil.)								
Stegmiller							39,869	39,869
Sterling. (See American.)								
Stephenson					6,305	52,588	64,075	122,968
Taylor								32,970
Teal Lake. (See Cambria.)								
Titan								90,371
Volunteer (see also Home)	7,395	71,870	106,281	38,544	10,022			1,393,175
Washington						20,625	44,716	65,341
Webster								34,905
West Republic								133,077
Wetmore								50,870
Wheeling								10,555
Winthrop [f]	72,433							1,759,115
Wheat. (See Star West.)								
	3,040,245	2,843,703	4,215,572	4,057,187	4,388,073	2,414,632	4,256,172	91,838,558

[a] Under Cleveland-Cliffs group after 1895.
[b] Under Winthrop after 1892.
[c] Under Queen group after 1890.
[d] Includes Buffalo, Prince of Wales, Queen, and South Buffalo after 1890.
[e] Under Iron Cliffs, 1891-1895; under Cleveland Cliffs group after 1895.
[f] Prior to 1890, see Braastad; includes Marquette after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Menominee Range.

[Gross tons.]

Name of mine.	1877.	1878.	1879.	1880.	1881.	1882.	1883.	1884.	1885.
Alpha									
Antoine (Clifford)									
Aragon									
Armenia									
Baker									
Baltic									
Berkshire									
Beta									
Breen	5,812	4,796	1,463	5,359					
Brier Hill						10,593	4,388		
Bristol (Claire)									
Calumet						5,847	29,239	3,627	
Caspian									
Chapin (see also Ludington)				34,556	134,521	247,506	265,830	290,972	157,455
Chatham									
Clifford									
Columbia						15,948	4,334	6,774	
Commonwealth				9,643	97,410	115,862	21,493	34,622	42,947
Cornell				30,856	11,816				
Crystal Falls						1,341			
Cuff									
Cundy									
Curry [a]			12,803	21,851	17,534	13,374	3,676	10,079	4,897
Cyclops [a]		6,028	46,158	14,368	12,644	18,287	22,675	24,099	49,897
Delphic							3,410	508	9,880
Dober [b]									
Dunn									
Eleanor (Appleton)									
Emmett		12,397	22,474	31,136	648				
Fairbanks [c]						8,045	455		
Florence				14,143	100,501	160,155	40,232		
Fogarty									
Forest									
Genesee (Ethel)									
Gibson									
Great Western						587	22,825	20,710	
Groveland									
Half and Half									
Hamilton									
Hemlock									
Hersel									
Hiawatha									
Hilltop									
Hollister									
Hope									
Indiana						4,280	4,362	636	2,739
Iron River [d]						29,115	100,369	52,584	55,693
James									
Keel Ridge				11,496	19,511	23,425	5,033		
Kimball									
Lamont (Monitor)									
Lee Peck [e]									
Lincoln									
Loretta									
Ludington [f]				8,816	3,374	52,152	102,632	101,165	124,194
Manganate									
Mansfield									
Mastodon						3,477	18,577	18,187	11,737
McDonald									
Metropolitan						23,854	36,643	27,577	
Michigan Exploration Co									
Millie (Hewitt)					4,352	9,500	7,516	7,927	4,627
Monongahela									
Munro									
Nanaimo						2,480	29,221	37,620	
Northwestern							7,202	10,004	
Norway [a]		7,276	73,519	198,165	137,077	165,547	114,836	71,710	67,741
Paint River (see also Fairbanks)						6,515	5,973	11,652	2,373
Penn Iron Mining Co. [g]									
Perry							3,138		
Pewabic (see also Walpole)									
Quinnesec		25,925	41,954	52,436	43,711	44,240	21,676	16,995	14,110
Riverton (see also Dober and Iron River) [h]									
Saginaw (Perkins)			13,465	49,196	60,406	73,648	76,514	38,120	18,020
Selden									
Sheridan									
Shelden & Shafer (Union). (See Columbia.)									
South Mastodon									
Stephenson			798	23,089	10,856				
Sturgeon River									
Tobin									
Verona									

[a] Under Penn Iron Mining Co. after 1892.
[b] Under Riverton after 1900.
[c] Included in Paint River after 1893.
[d] Under Riverton after 1892.
[e] Cherry Valley ore.
[f] Included in Chapin after 1894.
[g] Includes Curry, Cyclops, Norway, and Vulcan prior to 1893.
[h] Includes Iron River after 1892; includes Dober after 1900.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Menominee Range—Continued.

[Gross tons.]

Name of mine.	1877.	1878.	1879.	1880.	1881.	1882.	1883.	1884.	1885.
Vivian									
Vulcan [a]	4,593	38,799	56,975	86,976	85,274	94,042	79,874	101,722	124,125
Walpole [b]									
Youngs									
Youngstown						6,198	15,292	8,344	
Zimmerman									
	10,405	95,221	269,609	592,086	739,635	1,136,018	1,047,415	895,634	690,435

Name of mine.	1886.	1887.	1888.	1889.	1890.	1891.	1892.	1893.	1894.
Alpha									
Antoine (Clifford)									
Aragon				1,745	46,609	96,829	167,948	127,901	138,209
Armenia				50,275	26,649				
Baker									
Baltic									
Berkshire									
Beta	1,585	1,226				1,400			
Breen									
Brier Hill									
Bristol (Claire)							57,352	9,612	
Calumet									
Caspian									
Chapin (see also Ludington)	198,871	335,128	290,871	518,990	742,843	488,749	660,052	489,134	235,895
Chatham									
Clifford									
Columbia	14,282	2,377	10,936	11,385	60,133	70,770	57,682	22,426	10,300
Commonwealth	51,189	56,609	61,818	108,515	116,786	134,982	249,113	151,291	174,921
Cornell	4,566	2,064							
Crystal Falls					3,974				
Cuff									
Cundy									
Curry [a]			5,376	28,722	72,162	100,681	125,773		
Cyclops [a]	37,189	14,297	14,693	6,101	7,361	10,599	1,697		
Delphic	17,648	2,272							
Dober [c]									
Dunn		24,677	118,096	151,828	156,963	162,721	133,666	58,590	24,538
Eleanor (Appleton)							4,377	5,618	
Emmett									
Fairbanks [d]									
Florence	8,210	79,399	142,585	196,269	218,570	48,806	48,246	9,634	2,726
Fogarty									
Forest									
Genesee (Ethel)									
Gibson							[e] 16,357		
Great Western	22,267	23,239	21,860	38,454	72,546	62,464	87,487	661	
Groveland						1,049			
Half and Half				5,961	1,496	67			
Hamilton	872	600	8,801	8,347	17,072	58,197	2,183		
Hemlock						35,531	65,459	11,323	
Hersel					955				
Hiawatha								1,683	
Hilltop									
Hollister					2,020	1,057	1,021		
Hope							15,543	2,275	
Indiana	5,854								
Iron River [f]	78,591	83,018	110,000	179,238	155,458	59,345	1,176		
James									
Keel Ridge							5,997	3,298	
Kimball									
Lamont (Monitor)				12,348	31,139	26,226	42,819	13,777	2,600
Lee Peck [g]							2,844		
Lincoln						1,813	26,019	8,757	
Loretta								8,131	55,983
Ludington [h]	74,454	101,653	61,883	116,297	97,355	141,303	15,777	109	354
Manganate					6,844				
Mansfield					18,303	49,836	69,259	69,558	
Mastodon	41,640	48,792	51,463	63,511	66,526	45,370	9,150	23,485	
McDonald									
Metropolitan	6,393	9,070	3,490						
Michigan Exploration Co								505	77
Millie (Hewitt)	5,517	1,163	11,124	12,274	39,232	5,889	6,780		13,062
Monongahela									
Munro									
Nanaimo	5,400	30,460	5,744		3,441	13,200			
Northwestern									
Norway [a]	93,878	95,726	87,260	68,044	61,717	4,089	44,767		
Paint River (see also Fairbanks)	13,933	10,240	12,506	32,700	62,654	45,435	18,390		
Penn Iron Mining Co. [i]								280,450	175,274

[a] Under Penn Iron Mining Co. after 1892.
[b] Included in Pewabic after 1891.
[c] Under Riverton after 1900.
[d] Included in Paint River after 1893.
[e] Includes shipments for prior years.
[f] Under Riverton after 1892.
[g] Cherry Valley ore.
[h] Included in Chapin after 1894.
[i] Includes Curry, Cyclops, Norway, and Vulcan prior to 1893.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Menominee Range—Continued.

[Gross tons.]

Name of mine.	1886.	1887.	1888.	1889.	1890.	1891.	1892.	1893.	1894.
Perry									
Pewabic (see also Walpole)					26,991	64,507	115,273	165,745	304,010
Quinnesec	13,442	6,585	2,249						
Riverton (see also Dober and Iron River) [a]									
Saginaw (Perkins)	12,852	10,834	16,684	12,354	11,971				
Selden	790	1,302							
Sheridan				1,102	505	7,137	45,745	2,234	
Shelden & Shafer (Union). (See Columbia.)									
South Mastodon			2,722	4,005	1,476				
Stephenson	1,018	3,589							
Sturgeon River		6,829	7,800	4,775					
Tobin									
Verona									
Vivian									
Vulcan [b]	143,930	205,036	129,541	153,900	104,996	78,967	179,904		
Walpole [c]		1,740	900	9,614	2,940	3,895			
Youngs									
Youngstown	25,635	34,418	12,699		44,460	3,705			
Zimmerman									
	880,036	1,193,343	1,191,101	1,796,754	2,282,237	1,824,619	2,277,856	1,466,197	1,137,949

Name of mine.	1895.	1896.	1897.	1898.	1899.	1900.	1901.	1902.
Alpha								
Antoine (Clifford)	27,931	110,821	98,847	104,510	93,025	119,940	63,429	110,993
Aragon	183,296	95,809	149,594	295,821	337,807	404,645	477,212	646,203
Armenia	2,045						18,750	100,864
Baker								
Baltic							17,326	64,664
Berkshire								
Beta								
Breen								
Brier Hill								
Bristol (Claire)					80,915	51,639	36,593	129,035
Calumet								
Caspian								
Chapin (see also Ludington)	618,589	420,318	643,402	724,768	940,513	929,937	929,701	956,812
Chatham								
Clifford								
Columbia	70,867	87,202	24,623	14,199	126,290	97,531	19,963	186,798
Commonwealth	208,880	93,707	98,283	250,687	117,295	53,342	77,799	112,704
Cornell								
Crystal Falls	13,037	44,526	95,210	128,233	147,346	197,770	230,614	195,555
Cuff					20,210	38,209		
Cundy		3,395	41,942	76,877	100,902	141,148	178,800	183,052
Curry [b]								
Cyclops [b]								
Delphic		52						
Doher [d]				5,009	10,980	49,203		
Dunn	90,885	47,081	31,062	49,381	7,458			2,816
Eleanor (Appleton)	2,107							
Emmett								
Fairbanks [e]								
Florence	22,820	35,136	37,594	93,663	74,235	35,756	15,395	130,798
Fogarty								
Forest								
Genesee (Ethel)								14,455
Gibson								
Great Western		14,643		33,851	43,316	98,550	123,261	42,470
Groveland							11,444	7,599
Half and Half								
Hamilton								
Hemlock	949	94,645	96,032	69,865	110,269	72,413	149,966	123,331
Hersel								
Hiawatha	1,201					11,008	20,355	74,596
Hilltop					3,496	6,410	2,503	
Hollister								
Hope								3,373
Indiana								
Iron River [f]								
James								
Keel Ridge	19,441				4,900			
Kimball								
Lamont (Monitor)					67,652	31,323		47,267
Lee Peck [g]								
Lincoln					43,622	72,959	19,727	7,747
Loretta	53,160	34,334	54,104	68,447	64,824	61,219	54,985	128,300
Ludington [h]								
Manganate								
Mansfield			37,182	60,739	86,607	90,155	74,113	31,181
Mastodon	23,733	60						
McDonald								

[a] Includes Iron River after 1892; includes Dober after 1900.
[b] Under Penn Iron Mining Co. after 1892.
[c] Included in Pewabic after 1891.
[d] Under Riverton after 1900.
[e] Included in Paint River after 1893.
[f] Under Riverton after 1892.
[g] Cherry Valley ore.
[h] Included in Chapin after 1894.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Menominee Range—Continued.

[Gross tons.]

Name of mine.	1895.	1896.	1897.	1898.	1899.	1900.	1901.	1902.
Metropolitan								
Michigan Exploration Co	1,071		216					53,272
Millie (Hewitt)	10,924	21,815	10,374	17,430	15,194	14,922	12,133	25,935
Monongahela							2,397	
Munro								
Nanaimo								
Northwestern								1,324
Norway [a]								
Paint River (see also Fairbanks)						1,316		10,383
Penn Iron Mining Co. [b]	290,622	179,917	237,886	223,713	229,651	197,606	358,126	273,443
Perry								
Pewabic (see also Walpole)	262,551	273,587	279,855	305,072	530,129	374,043	507,786	530,291
Quinnesec	761				11,050	25,967	66,383	62,531
Riverton (see also Dober and Iron River) [c]					2,262	71,004	119,860	215,850
Saginaw (Perkins)	2,161							
Selden								
Sheridan	16,754	3,419	146		31,104	8,063		
Shelden & Shafer (Union). (See Columbia.)								
South Mastodon								
Stephenson								
Sturgeon River								
Tobin							18,957	55,238
Verona						5,143	11,475	43,245
Vivian								40,384
Vulcan [a]								
Walpole [d]								
Youngs								
Youngstown	13		661					
Zimmerman								
	1,923,798	1,560,467	1,937,013	2,522,265	3,301,052	3,261,221	3,619,053	4,612,509

Name of mine.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Alpha	1,370							1,370
Antoine (Clifford)	107,886	81,164	138,395	195,855	100,996			1,353,792
Aragon	522,035	374,944	423,698	431,000	441,636	226,354	246,984	5,836,279
Armenia	31,901	16,577		27,882	36,665			311,608
Baker							45,003	45,003
Baltic	123,236	151,114	133,246	186,495	189,119	129,037	174,426	1,168,663
Berkshire						3,440	34,295	37,735
Beta								4,211
Breen			16,625	21,004	20,366			75,425
Brier Hill								14,981
Bristol (Claire)	246,581	132,420	210,388	298,031	345,676	190,300	396,825	2,185,367
Calumet				15,773	51,646	15,222		121,354
Caspian	2,088	4,242	10,248	80,875	138,867	102,628	189,023	527,971
Chapin (see also Ludington)	704,051	541,324	902,628	943,425	855,308	391,620	587,647	16,182,416
Chatham					14,883	45,826	68,730	129,439
Clifford							103,626	103,626
Columbia			27,883					942,703
Commonwealth	5,051	1,617	8,085	6,346			50,787	2,511,784
Cornell								49,302
Crystal Falls	117,096	180,983	152,255	111,871	114,158	296	986	1,735,251
Cuff								58,419
Cundy	111,851					1,410	5,512	844,889
Curry [a]								416,928
Cyclops [a]								286,093
Delphic								33,770
Dober [e]								65,192
Dunn	5,365		21,051	91,476	141,992	8,829	193,396	1,521,871
Eleanor (Appleton)			1,819	3,121	1,677			18,719
Emmett								66,655
Fairbanks [f]								8,500
Florence	95,877	153,452	233,858	169,459	178,955	140,354	231,191	2,718,019
Fogarty					7,949	32,560	77,356	117,865
Forest		11,988						11,988
Genesee (Ethel)	61,694	132,380	77,370	80,971	38,984		65,585	471,439
Gibson						4,548	36,246	57,151
Great Western	100,751	68,318	191,265	311,218	234,492	124,246	112,747	1,872,228
Groveland	1,294	4,737			13,913	9,123	24,933	74,092
Half and Half								7,524
Hamilton								96,072
Hemlock	79,420	136,232	124,450	106,437	117,181	83,834	112,481	1,589,818
Hersel								955
Hiawatha	53,828	38,288	9,704	20		138,190	136,739	485,612
Hilltop				7,820				20,229
Hollister					6,371	10,671	25,842	46,982
Hope	7,339							28,530
Indiana								17,871
Iron River [g]								904,587
James					2,360	59,760	90,851	152,971
Keel Ridge								93,101
Kimball					16,224			16,224

[a] Under Penn Iron Mining Co. after 1892.
[b] Includes Curry, Cyclops, Norway, and Vulcan prior to 1893.
[c] Includes Iron River after 1892; includes Dober after 1900.
[d] Included in Pewabic after 1891.
[e] Under Riverton after 1900.
[f] Included in Paint River after 1893.
[g] Under Riverton after 1892.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Menominee Range—Continued.

[Gross tons.]

Name of mine.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Lamont (Monitor)	43,736	29,393	74,991	89,980	42,090			555,341
Lee Peck [a]								2,844
Lincoln	15,606	17,577	19,539	5,890	714		1,657	241,627
Loretta	87,939	54,720	118,738	140,390	99,779	13,354	96,613	1,195,020
Ludington [b]								1,001,518
Manganate								6,844
Mansfield	51,440	79,163	38,584		183,532	41,633	118,713	1,102,998
Mastodon								425,708
McDonald							1,144	1,144
Metropolitan								107,027
Michigan Exploration Co			58,088	146	39,819	603		153,797
Millie (Hewitt)	40,860			36,815	18,691	3,322	10,887	368,265
Monongahela	6,913							9,310
Munro	8,739	32,332	92,183	47,454	46,834	27,773	23,241	278,556
Nanaimo		9,086	91,238	91,792	53,778	305		373,765
Northwestern	17,280							35,810
Norway [c]								1,291,352
Paint River (see also Fairbanks)	9,863	11,257	11,973	28,321	75,805			371,289
Penn Iron Mining Co. [d]	343,543	141,948	423,244	496,582	381,128	176,211	428,004	4,837,348
Perry								3,138
Pewabic (see also Walpole)	489,175	372,791	533,413	493,891	457,796	365,341	465,453	6,917,700
Quinnesec	49,708	33					3,147	502,903
Riverton (see also Dober and Iron River) [e]	97,633	81,543	82,611	161,701	90,358	47,073	171,200	1,141,098
Saginaw (Perkins)				21,017	26,080	38,669	19,994	501,985
Selden								2,092
Sheridan								116,299
Shelden & Shafer (Union). (See Columbia.)								
South Mastodon								8,203
Stephenson								39,350
Sturgeon River								19,404
Tobin	45,386	113,669	166,529	235,867	237,781	161,642	359,668	1,394,737
Verona	50,910	20,202						130,975
Vivian	12,122	81,354	90,426	122,577	48,493	10,056		405,412
Vulcan [c]								1,668,654
Walpole [f]								19,089
Youngs			10,926	47,583	92,632	70,094	154,150	375,385
Youngstown								151,425
Zimmerman						1,832	10,303	12,135
	3,749,567	3,074,848	4,495,451	5,109,088	4,964,728	2,679,156	4,875,385	71,212,121

Mesabi Range.

Name of mine.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Adams				59,141	234,562	170,738	390,860	720,474	777,346	829,118
Adriatic										
Agnew										
Ajax (Kanawha)								14,963	64,218	41,300
Albany										
Alberta										
Alexander										
Auburn			108,210	376,970	131,478	175,263	235,630	385,992	263,692	427,510
Bessemer										
Biwabik		151,500	90,048	247,069	242,565	427,464	383,180	553,836	924,868	410,074
Bray										
Brunt										
Burt										
Canisteo										
Canton		24,416	213,853	359,020	16,261			99,498		
Cass										
Chisholm										34,573
Cincinnati		26,372		17,187	57,324	32,912		246		
Clark									63,071	199,566
Columbia										15,627
Commodore		65,137	7,213		22,063	60,798	80,494	152,947	278,416	35,546
Corsica										26,838
Crosby										
Croxton										
Cyprus										
Day							18,651	1,975		
Diamond										
Duluth		37,626					112,155	165,435	128,587	150,024
Elba							564	9,547	121,707	224,630
Euclid										
Fayal				136,601	248,645	642,939	575,933	1,072,257	1,252,504	1,656,973
Forest										
Fowler										
Franklin		46,617	223,399	286,423	231,086	30,128	200,400	60,000	168,524	39,299
Franz										
Genoa					17,136	309,514	279,677	276,559	253,651	332,022
Gilbert										

[a] Cherry Valley ore.
[b] Included in Chapin after 1894.
[c] Under Penn Iron Mining Co. after 1892.
[d] Includes Curry, Cyclops, Norway, and Vulcan prior to 1893.
[e] Includes Iron River after 1892; includes Dober after 1900.
[f] Included in Pewabic after 1891.

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Mesabi Range—Continued.

[Gross tons.]

Name of mine.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Glen										
Grant										
Hanna										
Hartley										
Hawkins										
Hector (Hale)		3,616	24,167	31,004	70,006	13,728		18,807	32,901	30,929
Higgins No. 2										
Hobart										
Holland										
Holman										
Hull										
Hull-Rust										
Iroquois										
Jennings										
Jordon										
Kellogg										
Kinney										
Knox										
La Belle										
Lake Superior group				58,123	67,659	259,912	135,404	154,326	284,023	594,761
Larkin (Tesora)										
La Rue										
Laura										
Leetonia										
Léonard										
Lincoln										
Longyear										
McKinley										
Mahoning				117,884	167,245	519,892	520,751	750,341	911,021	765,872
Malta								28,615	65,346	126,299
Mariska										
Mayas										
Miller										
Minnewas		13,858	2,140							
Minorca										
Mohawk										
Monica										
Monroe										
Morris										
Morrow										
Mountain Iron (and Rath and Aetna)	4,245	121,463	573,440	371,274	159,744	773,538	650,955	1,137,970	1,001,324	1,058,160
Myers										
Nassau										
Onondaga										
Pearce										
Pearson										
Penobscot						11,933	29,652	85,619	146,641	221,080
Perkins										
Pettit										
Pillsbury							99,691	106,487	101,032	120,723
Roberts						18,614		57,847	41,965	42,756
Rust										
Sauntry-Alpena								53,004	68,500	328,739
Scranton										
Sellers				47,433	153,037		112,765	174,867	56,280	34,918
Seville										
Sharon										56,810
Shenango										
Sliver										
Sparta						66,722	226,156	237,143	202,144	156,426
Spring										
Spruce (Cloquet)			5,628	47,700	96,280	12,215		1,621	101,675	279,515
St. Clair										
St. Paul										
Stephens										
Stevenson									56,031	666,273
Susquehanna										
Sweeney										
Syracuse										
Tener										
Troy										
Union									8,297	93,109
Utica										
Victoria										
Virginia group		123,015	544,954	622,712	955,739	749,499	560,848	293,651	417,473	5,420
Wacoutah										
Webb										
Williams (North Cincinnati)				3,046	11,249			12,357	18,238	
Wills										
Winnifred										
Yates										
Yawkey										
	4,245	613,620	1,793,052	2,781,587	2,882,079	4,275,809	4,613,766	6,626,384	7,809,535	9,004,890

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Mesabi Range—Continued.

[Gross tons.]

Name of mine.	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Adams	1,242,923	1,109,750	940,105	1,140,984	1,238,350	1,136,513	765,592	1,829,372	12,585,828
Adriatic					3,294	70,187	108,129	107,317	288,927
Agnew	45,582	108,847	96,435	44,651	163,260	149,084	164,486	151,536	923,881
Ajax (Kanawha)	24,829	23,932	912	28,439	9,057				207,650
Albany		109,608	153,433	241,186	356,371	437,521	64,860	368,057	1,731,036
Alberta						31,032	51,143		82,175
Alexander				15,073	60,547	120,332	35,747		231,699
Auburn	38,283								2,143,028
Bessemer			86,303	112,630	131,791	78,012	120,350	227,767	756,853
Biwabik	623,127	807,511	647,614	1,092,987	807,374	803,750	365,781	542,821	9,121,569
Bray								65,514	65,514
Brunt					75,401	178,935	636	14,212	269,184
Burt				1,860,452	1,376,875	1,501,272	1,460,998	1,660,101	7,859,698
Cauisteo						5,454	2,760	85,505	93,719
Canton									713,048
Cass		50,155	29,554	59,552	65,961	36,121			241,343
Chisholm	200,629	168,831	130,732	231,296	379,156	258,793	228,386	314,597	1,946,993
Cincinnati				965	1,373	6,369	4,790	4,537	152,075
Clark	350,799	300,492	256,873	358,091	274,394	319,983	334,594	484,512	2,942,375
Columbia				1,360					16,987
Commodore	65,833	20,436	249	146,901	263,401	477,203	116,069	409,148	2,201,854
Corsica	59,292	34,043	30,131		100,606	172,226	77,674	135,366	636,176
Crosby					115,373	227,265	152,084	183,470	678,192
Croxton	18,594	100,297	348	130,228	162,533	349,853	154,868	159,038	1,075,759
Cyprus		121,818	244,343	235,351	192,114	260,948	115,745	107,685	1,278,034
Day	106,516	107,781	84,530						319,453
Diamond						171			171
Duluth	150,220	150,053	149,819	142,172	158,336	93,120	149,185	150,501	1,737,233
Elba	207,454	93,616	123,425	125,724	255,580	134,488	147,916	224,202	1,668,853
Euclid								82,627	82,627
Fayal	1,919,172	1,460,601	975,102	1,358,922	1,634,853	1,878,812	1,439,879	1,879,357	18,132,550
Forest			85,280	99,785	41,647	4,840	2,420	6,304	240,276
Fowler						34,014	21,511	99,892	155,417
Franklin	111,085	92,019	65,528		66,935	30,926	8,246	51,393	1,712,008
Franz			62,884	70,210	11,068	907			145,069
Genoa	399,719	303,700	244,150	281,081	179,468	108,610			2,985,287
Gilbert						100,178	336,927	783,683	1,220,788
Glen	23,875	171,705	280,412	287,835	279,421	205,426	272,142	396,591	1,917,410
Grant	51,946	18,928	44,413	49,227					164,514
Hanna								238,873	238,873
Hartley						334,646	55,462		390,108
Hawkins	5,892	107,905	99,055	202,070	294,588	270,984	248,246	316,783	1,545,523
Hector (Hale)	54,289			4,990	37,221	65,952		30,726	418,336
Higgins No. 2			35,286	238,598	341,319	173,439		322,504	1,111,146
Hobart					975	7,339			8,314
Holland				158,484	95,472	16,908			270,864
Holman						8,068	1,682	391,157	400,907
Hull				233,065	282,592	157,366	163,020		836,043
Hull-Rust					1,690,311	2,900,493	2,926,683	3,039,911	10,557,398
Iroquois		17,562	50,215	61,109	190,971	254,329	151,071	152,510	877,767
Jennings					84,715	99,812	18,313	10,477	213,317
Jordon	147,931	190,024	97,474	185,854	110,768	61,996	118,529	12,754	925,330
Kellogg							31,331	165,458	196,789
Kinney		32,352	6,225	89,161	57,691	145,989	176,510	287,421	795,349
Knox								7,464	7,464
La Belle	70,753	48,298	89,554	78,597	50,466	56,146	51,638	27,216	472,668
Lake Superior group	766,311	1,226,066	1,415,884						4,962,469
Larkin (Tesora)					12,001	22,040	14,030	46,651	94,722
La Rue		53,335	105,170	197,192	175,670	301,522	79,313	365,543	1,277,745
Laura	16,453	79,286	3,778	27,207	138,001	149,410	176,725	178,110	768,970
Leetonia	28,784	200,163	228,536	352,004	308,989	301,368	289,490	553,162	2,262,496
Leonard		10,591	151,952	297,011	254,368	137,316		6,857	858,095
Lincoln	87,908	279,399	153,822	275,777	367,192	297,870	379,219	303,066	2,144,253
Longyear	22,788	81,604	221	16,778					121,391
McKinley						17,706	1,399	89,981	109,086
Mahoning	1,038,645	1,009,446	706,325	1,011,661	1,274,232	1,564,332	611,592	1,561,893	12,531,132
Malta	222,640	11,675	66,641	139,853	115,763	82,065	93,072	92,356	1,044,325
Mariska						137	30,226	77,690	108,053
Mayas					107,244	113,521			220,765
Miller				118,520	234,071	279,453	224,321	277,119	1,133,484
Minnewas							525		16,523
Minorca	35,499	115,886	121,739	117,653	155,541	154,661	80,330	119,154	900,463
Mohawk					92,715	128,870	119,439	216,291	557,315
Monica								7,614	7,614
Monroe				13,730	310,839	156,809		147,521	628,899
Morris				1,070,937	1,809,743	2,076,388	528,154	1,831,187	7,316,409
Morrow	35,571	49,409	33,012	60,725	64,073	34,935	1,571		279,296
Mountain Iron (and Rath and Aetna)	1,617,772	1,348,714	1,168,855	2,495,089	2,563,111	1,973,519	206,698		17,198,871
Myers				188,568	228,451	153,770	150,249	193,698	914,736
Nassau						19,172		11,940	31,112
Onondaga						521	30,887	59,389	90,797
Pearce	54,884	50,204	235		65,862	71,645			242,830
Pearson								68,683	68,683
Penobscot	209,531	1,615							706,071
Perkins								59,029	59,029
Pettit	17,278	52,706	27,088	140,239	82,757	36,071	57,140	83,548	496,830
Pillsbury	238,122	229,133		161,924	33,546	489,718	59,889		1,640,265
Roberts	28,972								190,154
Rust				272,114	284,517	213,355	227,079		997,065
Sauntry-Alpena	249,837								700,140
Scranton			1,168						1,168
Sellers	193,428	251,631	207,990	261,501	241,031	155,060	354,780	626,169	2,870,890
Seville								23,585	23,585

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Mesabi Range—Continued

[Gross tons.]

Name of mine.	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Sharon	224,526	48,199							329,535
Shenango			51,712	213,097	383,717	387,093	461,887	831,099	2,328,605
Sliver							49,291	256,073	305,364
Sparta	227,444	40,458	59,692	27,777	235				1,241,197
Spring						15,257	20,516		35,773
Spruce (Cloquet)	543,203	587,153	589,319	606,295	674,602	610,457	430,633	579,903	5,166,199
St. Clair		6,148	26,748	61,792					94,688
St. Paul					24,230	113,200			137,430
Stephens		87,055		367,764					454,819
Stevenson	1,434,681	1,014,582	1,652,021	1,428,614	1,041,500	1,142,977	516,770	1,030,742	9,984,191
Susquehanna					20,984	137,207	182,352	243,049	583,592
Sweeney							7,579		7,579
Syracuse								5,509	5,509
Tener				58,136	174,309	190,903	174,033	256,384	853,765
Troy		15,099	12,759	87,584	146,849	100,730	40,283	86,520	489,824
Union	103,522	91,496			20,691	61,825	20,937		399,877
Utica	9,009	156,180	120,697	185,944	268,281	304,864	57,194	201,480	1,353,649
Victoria					64,820	90,090	21,310	113,305	289,525
Virginia group	5,131	5,866	5,395	402,224	5,674	1,015,717	661,329	1,843,450	8,218,097
Wacoutah					6,766	158,692		60,966	226,424
Webb				71,235	165,604	113,334	19,610		369,783
Williams (North Cincinnati)					17,685	35,267			97,842
Wills	12,158			4,550				3,440	20,148
Winnifred		39,179	81,686		3,415	94,867	61,341	84,614	365,102
Yates			53,179	58,174	265,289	210,726	86,308	5,362	679,038
Yawkey						15,453	84,446	45,790	145,689
	13,342,840	12,892,542	12,156,008	20,158,699	23,819,029	27,495,708	17,257,350	28,176,281	195,703,424

Vermilion Range.

Name of mine.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
Chandler					54,612	306,220	336,002	373,969	651,655
Pioneer						3,144	12,012	3,079	2,651
Savoy									
Sibley									
Soudan (Minnesota)	62,124	225,484	304,396	394,252	457,341	535,318	532,000	517,570	498,353
Zenith									14,991
	62,124	225,484	304,396	394,252	511,953	844,682	880,014	894,618	1,167,650

Name of mine.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Chandler	435,930	558,050	605,024	471,545	438,365	715,919	808,359	644,801	627,379
Pioneer			40,054	149,073	207,103	123,183	339,897	450,794	678,310
Savoy							81,022	170,446	212,008
Sibley							5,169	4,670	
Soudan (Minnesota)	370,303	390,463	432,760	448,707	592,196	426,040	457,732	325,020	208,284
Zenith	14,388			18,765	40,817		79,323	60,089	60,082
	820,621	948,513	1,077,838	1,088,090	1,278,481	1,265,142	1,771,502	1,655,820	1,786,063

Name of mine.	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Chandler	645,786	460,548	422,162	365,739	318,990	245,684	50,639		9,537,378
Pioneer	673,863	596,735	505,432	653,682	766,853	830,700	477,506	477,226	6,991,297
Savoy	243,937	169,616	74,866	91,775	106,933	43,320	82,521	83,167	1,359,611
Sibley	78,304	113,595	122,783	251,170	271,496	226,835	127,544	151,009	1,352,575
Soudan (Minnesota)	275,168	175,114	70,713	205,002	146,503	102,977	53,070	74,862	8,281,752
Zenith	167,205	161,091	86,557	109,818	181,580	235,751	50,264	321,951	1,602,672
	2,084,263	1,676,699	1,282,513	1,677,186	1,792,355	1,685,267	841,544	1,108,215	29,125,285

Miscellaneous (in Wisconsin).

Name of mine.	1892.	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Illinois										
Iron Ridge										
Mayville	9,044	7,925	10,511	16,472	13,144	10,546	18,151	19,731	20,986	22,400
	9,044	7,925	10,511	16,472	13,144	10,546	18,151	19,731	20,986	22,400

Table of Lake Superior iron-ore shipments from the earliest shipment to date—Continued.

Miscellaneous (in Wisconsin)—Continued.

[Gross tons.]

Name of mine.	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Illinois			47,922	71,413	67,118	72,180	51,108		309,741
Iron Ridge		17,913	19,558	39,978	61,624	3,966		15,955	158,994
Mayville	23,338	18,836	26,562	20,610	15,847	19,644	71,341	66,804	411,892
	23,338	36,749	94,042	132,001	144,589	95,790	122,449	82,759	880,627

Summary.

	Years unknown.	1854.	1855.	1856.	1857.	1858.	1859.	1860.	1861.	1862.
Gogebic range										
Marquette range	30,000	3,000	1,449	6,343	25,646	22,876	68,832	114,401	49,909	124,169
Menominee range										
Mesabi range										
Vermilion range										
Miscellaneous (in Wisconsin)										
Grand total	30,000	3,000	1,449	6,343	25,646	22,876	68,832	114,401	49,909	124,169

	1863.	1864.	1865.	1866.	1867.	1868.	1869.	1870.	1871.	1872.
Gogebic range										
Marquette range	203,055	243,127	186,208	278,796	443,567	491,454	617,444	830,934	779,607	893,169
Menominee range										
Mesabi range										
Vermilion range										
Miscellaneous (in Wisconsin)										
Grand total	203,055	243,127	186,208	278,796	443,567	491,454	617,444	830,934	779,607	893,169

	1873.	1874.	1875.	1876.	1877.	1878.	1879.	1880.	1881.	1882.
Gogebic range										
Marquette range	1,158,249	919,257	889,477	1,006,785	1,010,494	1,023,083	1,130,019	1,384,010	1,579,834	1,829,394
Menominee range					10,405	95,221	269,609	592,086	739,635	1,136,018
Mesabi range										
Vermilion range										
Miscellaneous (in Wisconsin)										
Grand total	1,158,249	919,257	889,477	1,006,785	1,020,899	1,118,304	1,399,628	1,976,096	2,319,469	2,965,412

	1883.	1884.	1885.	1886.	1887.	1888.	1889.	1890.	1891.	1892.
Gogebic range		1,022	119,860	753,369	1,324,878	1,437,096	2,008,394	2,847,810	1,839,574	2,971,991
Marquette range	1,305,425	1,558,034	1,430,422	1,627,380	1,851,634	1,923,727	2,642,813	2,993,664	2,512,242	2,666,856
Menominee range	1,047,415	895,634	690,435	880,006	1,193,343	1,191,101	1,796,754	2,282,237	1,824,619	2,277,856
Mesabi range										4,245
Vermilion range		62,124	225,484	304,396	394,252	511,953	844,682	880,014	894,618	1,167,650
Miscellaneous (in Wisconsin)										9,044
Grand total	2,352,840	2,516,814	2,466,201	3,565,151	4,764,107	5,063,877	7,292,643	9,003,725	7,071,053	9,097,642

	1893.	1894.	1895.	1896.	1897.	1898.	1899.	1900.	1901.
Gogebic range	1,329,385	1,809,468	2,547,976	1,799,971	2,258,236	2,498,461	2,795,856	2,875,295	2,938,155
Marquette range	1,835,893	2,060,260	2,097,838	2,604,221	2,715,035	3,125,039	3,757,010	3,457,522	3,245,346
Menominee range	1,466,197	1,137,949	1,923,798	1,560,467	1,937,013	2,522,265	3,301,052	3,261,221	3,619,053
Mesabi range	613,620	1,793,052	2,781,587	2,882,079	4,275,809	4,613,766	6,626,384	7,809,535	9,004,890
Vermilion range	820,621	948,513	1,077,838	1,088,090	1,278,481	1,265,142	1,771,502	1,655,820	1,786,063
Miscellaneous (in Wisconsin)	7,925	10,511	16,472	13,144	10,546	18,151	19,731	20,986	22,400
Grand total	6,073,641	7,759,753	10,445,509	9,947,972	12,475,120	14,042,824	18,271,535	19,080,379	20,615,907

	1902.	1903.	1904.	1905.	1906.	1907.	1908.	1909.	Total.
Gogebic range	3,654,929	2,012,708	2,398,287	3,705,207	3,643,514	3,637,102	2,699,856	4,088,057	60,896,457
Marquette range	3,868,025	3,040,245	2,843,703	4,215,572	4,057,187	4,388,073	2,414,632	4,256,172	91,838,558
Menominee range	4,612,509	3,749,567	3,074,848	4,495,451	5,109,088	4,964,728	2,679,156	4,875,385	71,212,121
Mesabi range	13,342,840	12,892,542	12,156,008	20,158,699	23,819,029	27,495,708	17,257,350	28,176,281	195,703,424
Vermilion range	2,084,263	1,676,699	1,282,513	1,677,186	1,792,355	1,685,267	841,544	1,108,215	29,125,285
Miscellaneous (in Wisconsin)	23,338	36,749	94,042	132,001	144,589	95,790	122,449	82,759	880,627
Grand total	27,585,904	24,308,510	21,849,401	34,384,116	38,565,762	42,266,668	26,014,987	42,586,869	449,656,472

CHAPTER III. HISTORY OF GEOLOGIC WORK IN THE LAKE SUPERIOR REGION.

GENERAL STATEMENT.

The Lake Superior region is among the first in which detailed study and mapping of the ancient crystalline complex have been extended over large areas; it has had special attention because of the magnitude of the mining industry and the commercial importance in mining of a correct understanding of geologic structure. Without the mines, expenditure for geologic work upon so large a scale would scarcely have been undertaken in a district so inaccessible. The increase of knowledge concerning the geology of the region has closely followed the development of mining.

The earlier geologic work in the Lake Superior region was of a most general nature and was necessarily confined to the shores of Lake Superior and to parts immediately accessible from canoe routes tributary to Lake Superior. The great distances and the difficulties of travel made detailed mapping impracticable over large areas in the interior. Numerous important observations were made which have subsequently been found to be of value, but these were in the main fragmentary. Detailed geologic work has been for the most part confined to the ore-bearing areas and was not begun until these areas had been located or opened for mining.

WORK OF INDIVIDUALS.

On the Canadian shore of Lake Superior and in adjacent territory the geologic work has been of a somewhat general nature except in one or two localities. This is so largely because no ore-bearing districts have been discovered in this part of the region of sufficient commercial importance to warrant large expenditures for geologic work. The geologists who have contributed most to the knowledge of this portion of the district are Bigsby (1825, 1852, 1854), Bayfield (1829, 1845), Logan (1847, 1852, 1863), Murray (1847, 1863), Macfarlane (1866, 1868, 1869, 1879), Robert Bell (1870, 1872–1878, 1883, 1890), Selwyn (1873, 1883, 1885, 1890), G. M. Dawson (1875), Lawson (1886, 1888, 1890, 1891, 1893, 1896), H. L. Smyth (1891), Pumpelly (1891), W. H. C. Smith (1892, 1893), Coleman (1895–1902, 1906, 1907, 1909), Willmott (1898, 1901, 1902), Van Hise (1898, 1900), McInnes (1899, 1902, 1903), Parks (1898, 1902, 1903), Clements (1900), Miller (1903), W. N. Smith (1905), Burwash (1905), J. M. Bell (1905), and Moore (1907, 1909). All were in the service of the Canadian government or of the Canadian Geological Survey except Coleman, Willmott, J. M. Bell, Burwash, and Moore, who represented the Ontario Bureau of Mines, and Pumpelly, H. L. Smyth, Van Hise, Clements, and W. N. Smith, American geologists. The principal detailed mapping has been that in the Lake of the Woods and Rainy Lake district by Lawson (1886–1888), that in the Steep Rock Lake region by Pumpelly and Smyth (1891), and that in the Michipicoten iron district by Coleman, Willmott (1898), Burwash (1905), and J. M. Bell (1905). Closely related is the extremely important work of Logan and Murray (1863) in the original Huronian district east of Lake Superior and north of Lake Huron.

In the United States portion of the Lake Superior region early general observations were made by explorers sent out by the United States Government. Schoolcraft visited the south shore of Lake Superior and ascended St. Louis River (1821, 1854). Owen (1847, 1851, 1852) visited particularly the west end of Lake Superior and the upper Mississippi and its tributaries. Norwood (1852) ascended Montreal and St. Louis rivers. Whittlesey (1852, 1876) explored northern Wisconsin and northern Minnesota. Whitney (1854, 1856, 1857) visited nearly all parts of the Lake Superior shore. Houghton (1840–1841) made general observations on the Lake Superior region as a whole.

However, much the larger part of the early geologic exploration was confined to the regions now known as the Marquette iron and Keweenaw copper districts, the extension of the Keweenaw district into the Gogebic district, and adjacent parts of the Upper Peninsula. The first important detailed report on the Keweenaw copper district was that of Douglass Houghton, of the Michigan Geological Survey, in 1841, based on work done several years before. This report led directly to the opening of the Keweenaw copper district. He was followed by Whitney (1847–1850), Foster (1848, 1850), Jackson (1849, 1850), and Agassiz (1850, 1867). Subsequent geologic work on Keweenaw Point of great importance was that of Brooks and Pumpelly (1872, 1873), Marvine (1873), Rominger (1873), and others, for the Michigan Geological Survey. Field study leading to the preparation of a monograph on the copper-bearing rocks of Lake Superior was begun by Irving prior to 1880 for the Wisconsin Geological Survey and completed in 1882 for the United States Geological Survey. This volume [a] has remained the standard reference book on the district to the present time, though contributions of much value have been made by Hubbard, Lane, Seaman, and others.

The extension of Houghton's work in the copper district and that of Burt, his assistant, led directly to the discovery and opening of the Marquette iron-bearing district in 1848. The important early geologic work in this district was done by Burt (1850), Foster and Whitney (1851), Kimball (1865), and Credner (1869), all in the service of the United States Government. Later followed the important contributions of the geologists of the Michigan Geological Survey—Brooks (1873, 1876), Wright (1879, 1880), Rominger (1873, 1881), and others. Wadsworth's contributions to the geology of the Marquette and Keweenaw districts (1880, 1881, 1884, 1890, 1891) have been the subject of much controversy.

After the opening of the Keweenaw and Marquette districts geologic mapping began to be extended to the south and west through the Upper Peninsula of Michigan and northern Wisconsin. Particularly noteworthy are the reports of the Michigan Geological Survey on the general geology of the Upper Peninsula of Michigan, but particularly of the Marquette, Menominee, and Gogebic districts, by Brooks (1873, 1876), Wright (1879, 1880), Rominger (1881, 1895), and Alexander Winchell (1888). The Menominee range in its Wisconsin extension was reported on by Wright (1880) and Brooks (1880) for the Wisconsin Survey, and Fulton (1888). The Penokee district and adjacent territory in northern Wisconsin was described by the geologists of the Wisconsin Survey—Lapham (1860), Whittlesey (1863), Irving (1874, 1877, 1880), Sweet (1876), Chamberlin (1878), and Wright (1880). Early general observations in northern Wisconsin were contributed by Percival (1856), Daniels (1858), Lapham (1860), Hall (1861–62), Irving (1872–1874, 1877, 1878, 1880, 1882, 1883), Murrish (1873), Eaton (1873), Wright (1873), Chamberlin (1877, 1878, 1880, 1882, 1883), Strong (1880), Sweet (1880, 1882), and Van Hise (1884).

The detailed geologic work by the United States Geological Survey leading up to the preparation of the series of monographs on the iron-bearing districts of Michigan and Wisconsin was begun in the Gogebic district by R. D. Irving and C. R. Van Hise in 1884. On the completion of work there detailed work was taken up in the Marquette district, 1888 to 1895, by Van Hise, Bayley, Merriam, Smyth, and others, and a monographic report [b] was issued in 1895; similar work was done in the Crystal Falls district from 1893 to 1898 by Van Hise, Bayley, Clements, Smyth, Merriam, and others, and a monograph [c] was issued in 1899; and the Menominee district was examined by Van Hise, Bayley, Clements, Weidman, and others, and a monograph [d] was issued in 1904. Since the completion of the work in the Menominee district in 1900 the United States Geological Survey has been devoting its attention to Minnesota, although a small amount of general work has been done in Michigan and Wisconsin. While the United States Geological Survey has been mapping the districts of the Upper Peninsula, the Michigan Geological Survey has given relatively less attention to this area than it had previously,

[a] Mon. U. S. Geol. Survey, vol. 5, 1883.
[b] Idem, vol. 28, 1895, 608 pp., 35 pls., and atlas.
[c] Idem, vol. 36, 1899, 512 pp., 53 pls.
[d] Idem, vol. 46, 1904, 513 pp., 43 pls.

but during this period it has issued important reports on the districts of Keweenaw Point, Porcupine Mountains, and Isle Royal by Hubbard, Lane, Wright, and others. Lane and Seaman in 1909 and 1910 published an interesting summary of their views on Michigan geology. In 1909 and 1910 R. C. Allen, successor to Mr. Lane as state geologist, mapped and reported on the Iron River district of Michigan and then took up the mapping of the region between the Iron River district and Lake Gogebic.

The Wisconsin Geological Survey, after the completion of the work of Irving, Chamberlin, Wright, and others, was discontinued in 1883. The new Wisconsin Geological and Natural History Survey, established in 1897, has been engaged continuously through Weidman in mapping the crystalline rocks of north-central Wisconsin and the outlying areas, including the Baraboo iron district. Hobbs and Leith (1907) mapped the volcanic rocks of Fox River in central Wisconsin. In 1910 W. O. Hotchkiss, for the Wisconsin Geological and Natural History Survey, took up the detailed mapping of the Florence iron-bearing district of northeastern Wisconsin, and F. T. Thwaites, for the same organization, examined in detail the Keweenawan and Cambrian sandstones on the southwestern shore of Lake Superior, with a view of ascertaining their relations.

In Minnesota early work of a most general nature was done by Owen (1851, 1852), Schoolcraft (1821, 1854), Norwood (1847, 1852), Eames (1866), and Whittlesey (1866, 1876). The Minnesota shore and the Gunflint Lake areas were examined in detail by Irving and assistants in 1880. The Minnesota Survey began its study of the crystalline rocks of northern Minnesota in 1872 and continued it until 1901. The men engaged in this work were N. H. Winchell, Alexander N. Winchell, H. V. Winchell, U. S. Grant, J. E. Spurr, and others. A number of special reports were issued, but the final general account appeared in volumes 4, 5, and 6 of the Minnesota Survey, published, respectively, in 1899, 1900, and 1901. The Minnesota Survey was then discontinued. The work of the United States Geological Survey in Minnesota was begun in the Vermilion district in 1896 by Van Hise, Clements, Bayley, and Leith, and a monographic report[a] was issued in 1903. Upon the completion of this work in 1899 work was taken up in the Mesabi district by Leith under direction of C. R. Van Hise, and the monograph[b] on this district was issued in 1903. Since that time no detailed mapping has been done in the Minnesota region by the United States Geological Survey, but many general observations have been made. Geologic work in Minnesota for commercial purposes has been done by Merriam and Sebenius in the Vermilion and Mesabi districts and by Leith, Zapffe, and Adams in the Cuyuna district.

Detailed summaries of the work of all the men above mentioned and others will be found in the United States Geological Survey monographs on the several Lake Superior districts, and in Bulletin 360 of the United States Geological Survey, on the pre-Cambrian geology of North America. Only such names and reports have been mentioned here as seem necessary to a general sketch of the history of geologic knowledge in the region. A number of the men named have contributed, in addition to the reports specifically mentioned, valuable information on the geology of the Lake Superior region in general.

GROWTH OF GEOLOGIC KNOWLEDGE.

An attempt has been made in Bulletin 360 (cited above) to sum up the salient features of the history of the development of geologic knowledge concerning the Lake Superior region. This summary will not be repeated here. It shows how the present knowledge of the district has resulted from a long series of approximations, in general successively more adequate owing to gradual accumulation of facts, improvement of means of studying them, and general advance in knowledge of geologic principles. Needless but perhaps inevitable confusion has resulted locally from duplication of geologic terms by different geologic observers and from varying inferences drawn by different men from the same set of facts. It is indeed curious to note how differently truth is revealed to different observers. A chronologic series of geologic maps of the Marquette district shows how it is possible in the development of geologic knowledge gradually

[a] Mon. U. S. Geol. Survey, vol. 45, 1903, 463 pp., 13 pls., and atlas.

[b] Idem, vol. 43, 1903, 316 pp., 33 pls.

to make closer approximations to actual conditions. It also illustrates well the fact, sometimes lost sight of, that a geologic map represents an approximation to the truth, limited in its accuracy and adequacy by the general stage of advancement of the science, and perhaps falling short of this limit if the map maker does not fairly represent that advance. The maps published with this monograph are closer approximations to the truth than the maps previously published. These maps in turn will be superseded by better approximations as facts accumulate and geologic knowledge advances. It is hoped that the user of these maps will measure them by their advance over preexisting maps rather than by the distance they fall short of the ideally perfect map.

In the geologic literature on the Lake Superior region a progressive change may be noted from the fragmentary descriptions of earlier writers to more elaborate descriptions accompanied by attempts at stratigraphic and structural classification and the development of better principles for that purpose, and in turn a change to better understanding of the principles of correlation of the rocks, based on better knowledge of these rocks and of the conditions of the formation of rocks of this kind. The work on ore deposits similarly began with fragmentary descriptions, followed by fuller descriptions and attempts at lithologic and structural classification, then by hypotheses on the origin of the ore, which gradually gave way to accepted theories based on qualitative evidence. The present monograph is believed to mark a further development in the same direction by transferring the theories of origin of the ore more largely from a qualitative to a quantitative basis.

Mention of names in connection with the general tendencies outlined above would lead to endless detail, but the tendencies may be noted in terms of years and organizations. Before 1870 the geologic work was fragmentary, descriptive, and as a whole unorganized, though work of exceptional merit was done by individuals. The period from 1870 to 1880 was marked by the better organized efforts of the Michigan and Wisconsin geological surveys, with corresponding improvements in the organization of geologic knowledge of the parts of the Lake Superior region studied, affording the first real contribution to the stratigraphic and structural geology of the region. Then the kinds of geologic work really began which are now followed in the Lake Superior region. In the early eighties the United States Geological Survey took up the study of the district, its first reports being based largely on information previously gathered by Irving and other members of the Wisconsin and other State geological surveys. Since its entrance into the region the United States Geological Survey has studied the problem more continuously than the state surveys, over a larger area, and with a uniform plan, with the result that its publications since the early eighties mark the principal steps in the advancement of knowledge of the region. This is said without disparagement of contemporaneous work by the Michigan, Wisconsin, Minnesota, Ontario, and Canadian surveys, which have issued reports on different phases of the problem, but for reasons mentioned above these reports for the most part have been more limited in their scope than those of the United States Geological Survey. In recent years the Wisconsin Geological Survey has again taken up the mapping of the crystalline rocks of northern Wisconsin with thoroughness and with good results. The Michigan Geological Survey also has now taken up work in the Upper Peninsula of Michigan, on the iron-bearing district of Iron River and on the copper-bearing series, which is rapidly advancing our knowledge. It is to be hoped that all local organizations will continue to develop. Even though they do, however, there will still be need for attention to the region by the United States Geological Survey, because its field of work is broader and it is in better position to take up general correlation and structural problems common to the district.

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The following bibliography comprises references to literature on the geology of the region arranged first by districts and then by date. Reports on districts and mines that do not refer primarily to the geology are not here included. Also no reference is made in the following list to literature dealing with the physical geography or with the Pleistocene geology of this region. All references to these subjects will be found as footnotes in Chapters IV and XVI.

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CHAPTER IV. PHYSICAL GEOGRAPHY OF THE LAKE SUPERIOR REGION.

By Lawrence Martin.

TOPOGRAPHIC PROVINCES.

The Lake Superior region as described in this report includes three topographic provinces (fig. 5)—(1) the Lake Superior highlands, a peneplain with hilly upland and lowland subdivisions; (2) a series of lowland plains surrounding the peneplain on the east, south, and west; and (3) the deep basin of Lake Superior embraced between parts of the highland and the lowland. These three topographic provinces are in various stages of development and preservation, depending on the underlying rock structure, the process by which they are being modified, and the length of their period of development. The first consists essentially of Archean and Algonkian rocks; the second of Cambrian and other early Paleozoic rocks and of Cretaceous rocks; the third is a present seat of rock deposition, and probably includes rocks of all ages represented in the other provinces, in addition to the glacial drift of the Quaternary, which also partly mantles the rocks in the first province and almost completely buries those of the second.

The peneplain highland was worn down from former lofty mountains.[a] Diastrophism (warping, folding, and faulting) has notably modified the peneplain, tilting its borders and introducing the deep basin of Lake Superior. (See Pl. II.) Subsequent deposition of early Paleozoic and Cretaceous rocks in the Lake Superior basin and about the margin of the peneplain (see fig. 5) has been followed by the exhuming of fossil topography and the production of a belted plain with alternate uplands and lowlands in the region of horizontal and gently tilted post-Algonkian rocks. Continental glaciation has slightly modified the relief and completely altered the soil and drainage of the region (Chapter XVI, pp. 427–459).

THE LAKE SUPERIOR HIGHLANDS.

TOPOGRAPHIC DEVELOPMENT.

The highlands about Lake Superior fall into two classes—(1) those underlain by coarse-grained homogeneous rocks, chiefly igneous, of both Archean and Algonkian age, and (2) those underlain by banded (both areally and structurally) alternating weak and resistant tilted rocks, chiefly sediments and lavas of Algonkian age. The areas of homogeneous igneous rocks still preserve plateaus or high plains of slight relief, diversified only by monadnocks and by some valleys of greater than normal depth; the areas including belts of sediments have narrow plateaus, monoclinal ridges, and mesas isolated among broader intermediate lowlands.

It is possible that the whole highland area was reduced to a peneplain, now represented by the plateau surfaces, the crests of some of the higher monoclinal ridges, and the tabular surfaces of the higher mesas, none of the adjacent lowland areas having been down-warped or down-faulted or excavated when the peneplain was most nearly perfected.

[a] Van Hise, C. R., Science, new ser., vol. 4, 1896, pp. 57–59 and 217–220; Weidman, Samuel, Jour. Geology, vol. 11, 1903, pp. 289–313; Wilson, A. W. G., Jour. Geology, vol. 11, 1903, pp. 615–667; Weidman, Samuel, Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 592–603 and 385–395.

Diastrophism during post-Algonkian time, by changing the altitude of the peneplain with reference to base-level, enabled denudation to reattack this peneplain. Stream erosion was renewed actively along the fault escarpments, possibly being delayed in areas that had been submerged and buried by Paleozoic sediments (p. 116). This renewal of cutting was weak or not yet active at all in regions remote from the escarpments (here also possibly being delayed in the buried and protected parts), but was strongest in the areas of banded Algonkian rocks, especially those near the steeper slopes. In these areas of banded rocks the remnants of the original peneplain surface are small and scattered, being largest where the vertical beds resisted erosion best, smaller where gentle tilting made development of monoclinal ridges and intermediate valleys possible, and of least extent where horizontal beds allowed the opening of broad lowlands with only isolated mesas, as in the Thunder Bay region, or with protruding reexposed knobs, like the Baraboo range of Wisconsin and knobs north and east of it (figs. 53, 54, pp. 359, 360). The lowlands developed at several points may be incipient stages of a peneplain of a later generation, developed with respect to a much lower base-level.

The older peneplain surface is found at various altitudes, some of which are shown in the following table:

Altitude of different parts of the Lake Superior highlands.

Locality.	Average height above sea level.[a]	Highest hill.	Lowest valley.
	Feet.	*Feet.*	*Feet.*
Southeast of Michipicoten	1,500—1,600	....	....
Near Michipicoten	*1,200—1,400	1,700	± 1,100
Northwest of Michipicoten	*1,206—1,400	2,120	....
Near Heron Bay	*1,100—1,300	....	....
North of Lake Superior	* 900—1,050	....	....
West of Lake Nipigon	*1.250—1,500	....	....
Thunder Bay and Hunters Island region	*1,400—1,700	....	....
Rainy Lake and Lake of the Woods region	*1,200—1,400	1,700	1,072
Gunflint Lake	1,800—2,000	2,232	1,547
Vermilion district	1,600—1,700	1,910	1,300
Mesabi district	1,400—1,500	1,920	1,400
Gabbro plateau	1,400—1,700	2,320	± 1,400
Northern Wisconsin	*1,400—1,500	1,900	1,400
Keweenaw Point	About 1,350	1,469	....
Marquette district	1,400—1,600	*1,950	± 1,300
Crystal Falls district	1,400—1,600	1,900	1,120
Menominee district	1,200—1,400	1,570	800
North-central Wisconsin	1,300—1,500	1,940	1,100
Edge of Potsdam sandstone	*About 1,000	....	....

[a] Altitudes marked with an asterisk are accurate approximations based upon railway grades, etc. All other altitudes are averaged from accurate topographic maps.

It will be noted (figs. 4 and 5) that the general peneplain surface lies between 1,000 and 1,700 feet, though it is a trifle lower locally, and rises in monadnocks to exceptional heights of a little more than 2,300 feet. The maximum relief of the peneplain proper (excluding the basin of Lake Superior) is less than 1,450 feet (900 to 2,320), and these extremes are many miles apart. The maximum local relief of any part of the peneplain at the time of its greatest perfection may be quite safely placed between 400 and 500 feet, and the average relief would be much less, perhaps 100 to 200 feet.

The present differences of elevation in the peneplain remnants might be explained as inherited, for the writer does not conceive of peneplains as approaching at all closely to a plane or perfectly base-leveled surface. Possibly the peneplain in the Lake Superior region when most nearly perfect stood at levels perhaps corresponding to present elevations of 1,400 feet in central Wisconsin, 1,350 feet on Keweenaw Point, 1,600 feet in northeastern Minnesota, and 1,400 feet northeast of Lake Superior in Canada, etc. Because there was upon the well-developed peneplain a series of old streams whose valleys lay at lower levels than the low intermediate ridges and at slightly different levels with reference to one another, the surface beveled back smoothly up the stream courses and the lines dividing parallel drainage systems. As we do not know where these ancient trunk streams were, we must regard the various preserved peneplain fragments merely as parts of a lowland worn down where mountains had been; and

RELIEF MAP OF THE LAKE SUPERIOR REGION, SHOWING THE LARGER TOPOGRAPHIC FEATURES.

Scale, 1 inch = about 60 miles. See page 85.

it is quite unnecessary to assume warping to account for their discrepancies of level, as has been done with regard to numerous peneplains, though warping in this region is indicated on other grounds.

The chief evidence of diastrophic modification of the levels of the peneplain is the rift or graben faulting indicated by displacements and by the great escarpments and their drainage conditions. (See p. 113.) One such modification of the peneplain took place when portions of it on the site of the west half of the present Lake Superior were down faulted.

We have excellent evidence that the peneplain has been modified by warping. There are three suggestive conditions: (1) In Wisconsin the peneplain dips down under the Paleozoic cover,[a] being 1,000 feet above sea level at Grand Rapids and 500 feet at Kilbourne, or 385

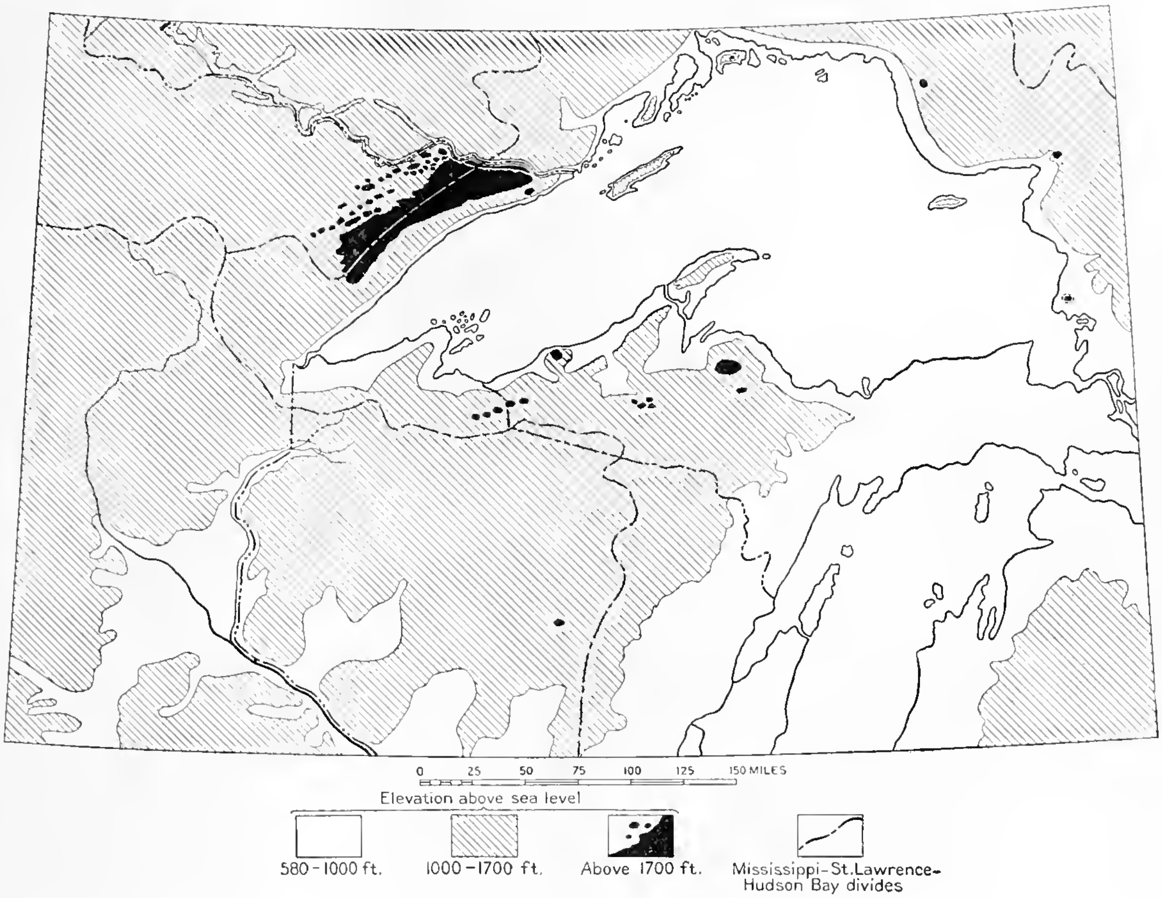


FIGURE 4.—Generalized topographic map of the Lake Superior region.

feet below the surface, one of its monadnocks rising through the Cambrian sandstone in the Baraboo range, while at Madison its surface lies 70 feet above sea level, or 810 feet below the present surface; (2) the gradients of the peneplain surface, especially in central Wisconsin, are greater than would be normal in aged rivers on a peneplain; (3) the Paleozoic rocks are in such positions as almost to prove warping, for a broad north-south post-Cambrian anticline is recognized in Wisconsin. All these suggestive conditions are corroborated by the well-established fact, to be described in the chapter on the Pleistocene, that tilting of the originally horizontal shore lines of former glacial lakes definitely proves slight recent warping of the region. The fact that such warping has been and is still taking place is adequate ground for saying that the peneplain remnants are not at their original levels.

[a] Weidman, Samuel, Jour. Geology, vol. 11, 1903, pp. 306-307; Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 392-394.

The peneplain might be conceived to represent facets of one or more earlier peneplains, but this does not seem likely unless the main peneplain is Cretaceous and parts of it represent preserved facets of a late Algonkian or early Cambrian peneplain. Earlier possible peneplain levels—in the Huronian, for example—would have been warped or folded by pre-Algonkian deformation from their original nearly horizontal position to almost any conceivable angle. The several great unconformities of the region doubtless represent peneplain stages, and the very fine material deposited after certain unconformities also suggests a low gradient of rivers and a lack of coarse sediments—conditions characteristic of a nearly base-leveled region. Some of these unconformities, now exposed by denudation, reach the surface at low angles, but it does not follow that a remnant of a lower Huronian peneplain is anywhere visible. In view

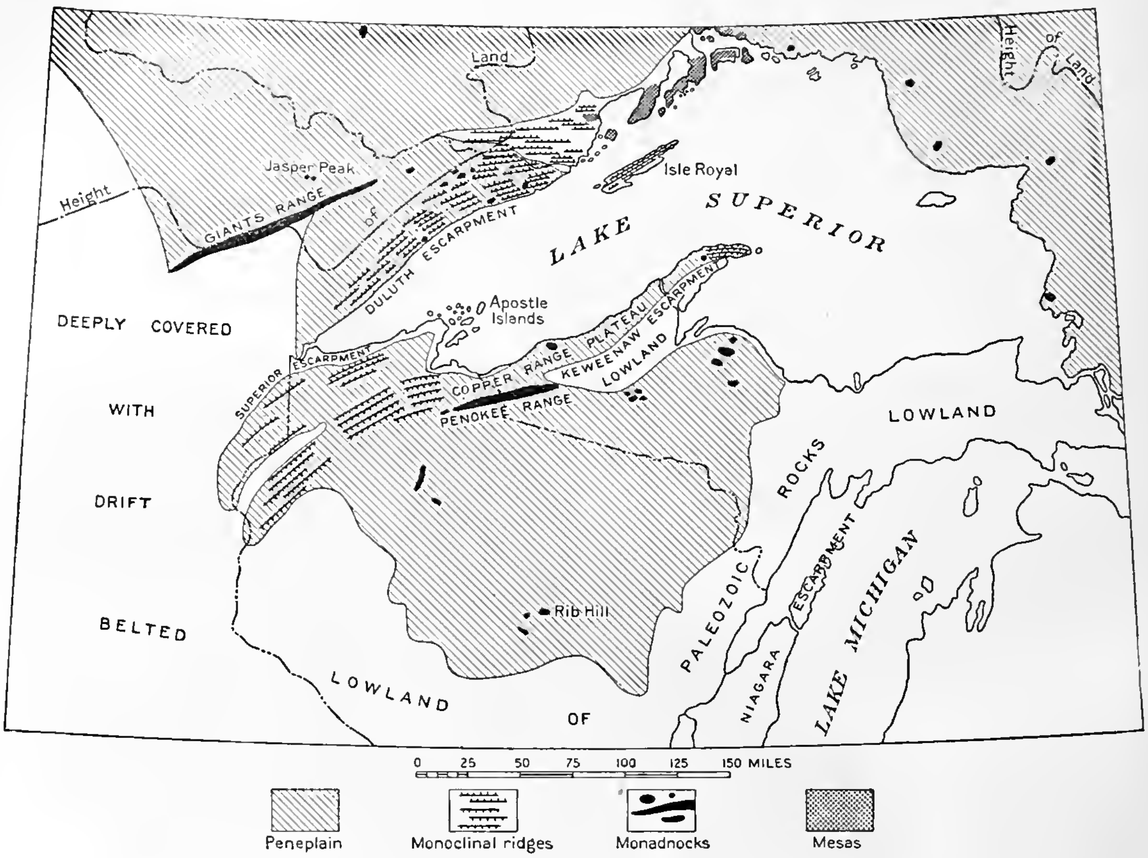


FIGURE 5.—The topographic provinces of the Lake Superior region, with some subdivisions of the peneplain.

of the tremendous pre-Cambrian base-leveling, any such surface, in the writer's opinion, should be regarded as either still buried or else long ago eroded away, unless definite evidence to the contrary can be produced. If the peneplain is not Cretaceous but a dissected late Algonkian or early Cambrian peneplain, it seems hardly likely that any facets of its surface represent earlier base-leveling.

The age of the Lake Superior peneplain, where studied in parts of the area, has been tentatively suggested by Van Hise to be Cretaceous.[a] Weidman dates the Wisconsin part of it as pre-Potsdam,[b] apparently recognizing it beneath the first Paleozoic rocks (Potsdam or Upper Cambrian) in Wisconsin. The Laurentian peneplain described by A. W. G. Wilson[c] does not include the Keweenawan areas of northeastern Minnesota, Isle Royal, northern Wisconsin, and Keweenaw Point, and therefore represents for our area merely the possibility of the several

[a] Science, new ser., vol. 4, 1896, pp. 59 and 220; Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1899–1900, pp. 333–336.
[b] Jour. Geology, vol. 11, 1903, p. 310; Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, p. 388.
[c] Jour. Geology, vol. 11, 1903, pp. 615–669.

A. PRE-CAMBRIAN PENEPLAIN IN ONTARIO, NEAR MICHIPICOTEN.

See page 89.

B. JASPER PEAK, NEAR TOWER, MINN.

A monadnock rising above the even upland of the Pre-Cambrian peneplain. See page 90.

pre-Keweenawan (Huronian and Archean) peneplains. The more specific fixing of the age of the whole Lake Superior peneplain depends largely on the age of certain escarpments and of certain faults and on the overlap of certain sediments; the trend of the evidence (see discussion of basin of Lake Superior) suggests an early origin of the peneplain, perhaps late Algonkian or early Cambrian. It is not conclusively established that a later peneplain, perhaps Cretaceous, was developed in the area, though the regions of low relief close to or within the basin of Lake Superior may be Cretaceous—as, for example, the lowlands of central Minnesota and eastern upper Michigan.

THE BROAD UPLANDS.

POSITION, RELIEF, AND SKY LINE.

The Lake Superior highlands form a broad upland cut by valleys and diversified by monadnocks and other ridges. The upland is made up chiefly of the Archean, but most of its ridges and monadnocks are composed of rocks of Algonkian age. This is so because the Archean rocks in this region are chiefly granites, greenstones, and other coarse-grained rocks, together with schists and gneisses, most of which are homogeneous over broad areas in their resistance to weathering and erosion and at present generally still preserve the peneplain developed upon them; whereas in the Algonkian areas, because of folding and faulting, the Huronian schists, gneisses, quartzites, etc., and the Keweenawan lavas usually present homogeneous resistance to weathering and erosion, not over broad areas but in narrow linear belts, so that the former peneplain is dissected in these regions to hilly uplands and lowlands with notable ridge topography. There are some exceptions, however, in the Algonkian—for example, where the homogeneous, coarse-grained Duluth gabbro of the Keweenawan northeast of Duluth and the similar granite of northern Wisconsin, which is possibly lower Huronian rather than Archean, form broad uplands.

These broad pre-Cambrian uplands stand above the adjacent relatively lower plains of the Paleozoic and Cretaceous and above the deep basin of Lake Superior at an average height of about 1,350 feet above sea level (fig. 4). Their local relief is slight. The following elevations in representative areas are taken from topographic maps:

Northeast-southwest section along the Vermilion iron range in northeastern Minnesota.

	Feet.	*Feet.*	*Feet.*	*Feet.*
Hilltops	1,620	1,660	1,800	2,120
Valley bottoms	1,380	1,360	1,480	1,760

East-west section, west of Marquette, Mich.

	Feet.	*Feet.*	*Feet.*	*Feet.*
Hilltops	1,700	1,750	1,800	1,550
Valley bottoms	1,550	1,550	1,500	1,350

East-west section in north-central Wisconsin.

	Feet.	*Feet.*	*Feet.*	*Feet.*
Hilltops	1,340	1,412	1,440	1,460
Valley bottoms	1,200	1,200	1,160	1,300

It will be seen that the average local relief here is about 240 feet. A few hills rise slightly above the general level and many valleys are cut slightly below it, but from an eminence an observer views a region of slight relief with an even sky line. (See Pl. III, *A*.)

RELATION OF ORIGINAL AND PRESENT TOPOGRAPHY.

It is of interest now to compare the present surface, which bevels indifferently across structural lines, with the surface which must have existed when most of the Archean and Algonkian rocks received their present texture and structure. The granite and similar rocks could have been made coarse grained only by cooling under a heavy mantle of overlying rock. (See fig. 11, p. 116, and cross sections on Pl. XVII, in pocket.) Evidently the surface when the granite was intruded here was far higher than the present surface. The greenstones, some of which cooled at the surface, are truncated in such positions that the original folds, if restored, would extend high above the present surface and deep into the earth (figs. 7, p. 101; 35, p. 253). Some of the gneisses and schists contain crystals and show structures such as slaty cleavage and schistosity which could have been produced only under a heavy load of overlying rock. Restoration of the missing parts of the folds, as revealed by study of the structure, shows that all the gneisses and schists are parts of the architectural scheme of an edifice entirely different from the present Lake Superior region. (See fig. 54, p. 360, and structure sections on Pls. I, VIII, XVI, and XVII, in pocket.) In all other sorts of plains besides peneplains the strata normally lie nearly horizontal, or nearly parallel to the surface of the plain. In the Lake Superior region the strata almost nowhere coincide in position with the surface, the dips at many places being almost vertical. The texture, the position, and the relations of the rocks are such as are found in existing mountainous regions. Evidently this peneplain was anciently a region of lofty mountains.[a]

MONADNOCKS.

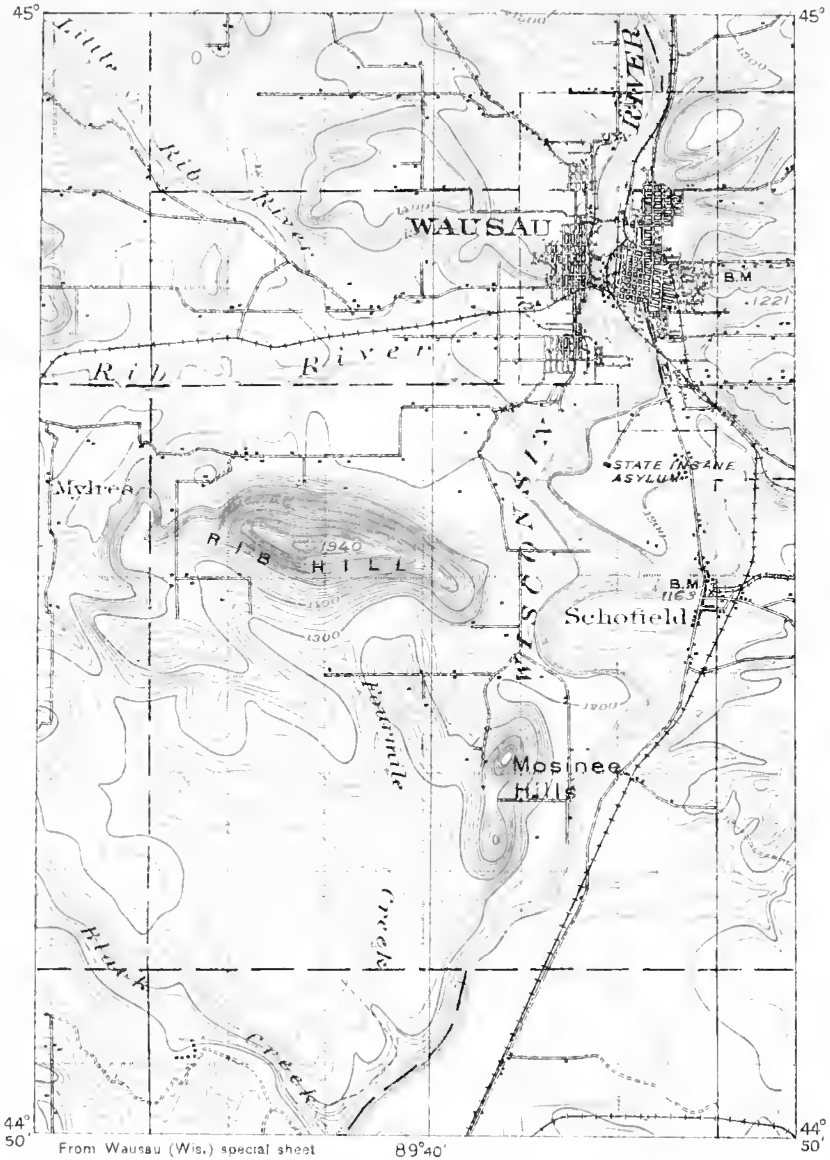
In some parts of the region knobs or monadnocks (fig. 5) rise conspicuously above the peneplain surface. None of them is of great area or of great height. In fact, many of them would not be noticeable if it were not for the evenness of the general upland surface of the region. Of these monadnocks, Jasper Peak (1,710 feet), near Tower, Minn., is a good example (Pl. III, *B*) and will be described as typical of the class. Other monadnocks are Minnesota Hill, at Soudan, Minn.; the 2,230-foot peak among the Misquah Hills in Cook County, Minn., the highest in the Lake Superior region; Eagle Mountain and Brule Mountain, in the same region; Tiptop Mountain (2,122 feet), northwest of the Michipicoten district, probably the highest in Ontario; Hematite Mountain (1,700 feet), at the Helen mine in the Michipicoten district; the Porcupine Mountains and parts of the Huron Mountains in western upper Michigan; and Rib Hill (Pl. IV, *A*) (1,942 feet), Hardwood Hill, the Mosinee Hills, and Powers Bluff in northern Wisconsin.

Jasper Peak is an oval eminence about one-half mile long from northeast to southwest and three-eighths of a mile in the shorter dimension. It rises nearly 500 feet above the valleys on either side but only 350 to 400 feet above the general upland of the region. It stands up as a monadnock because the jasper and ferruginous chert of which it is made are more resistant to denudation than the adjacent rocks. Other resistant rocks to which monadnocks of the Lake Superior region are due are the Archean gneiss in Tiptop Mountain, ferruginous chert and iron-bearing formation in Hemlock Mountain in the Michipicoten district, and Huronian quartzite in Rib Hill, Wis.[b] Various other resistant Huronian and Keweenawan formations stand up as monoclinal or other ridges. The long ridges of this character that rise high enough above their surroundings to be called monadnocks include the Giants Range of Minnesota, the Penokee Range of Wisconsin, and others which will be specifically described later.

VALLEYS IN THE PENEPLAIN.

There are, of course, general inequalities in the peneplain, but there are also valleys cut 100 to 400 feet below the general level, which may be interpreted as evidence of slight uplift after the completion of the base-leveling that produced the peneplain. In general these valleys are fairly broad and mature, and most of them are most widely opened along the areas of the weaker rocks. The original consequent drainage of this region was modified as the mountainous area was worn down, and the streams on the belts of weaker rocks naturally wore their valleys lower, received more water, and captured tributaries from the more slowly eroding streams

[a] A different opinion has been advanced by A. C. Lawson (Geol. and Nat. Hist. Survey Canada, vol. 1, new ser., 1885, p. 23cc).
[b] Van Hise, C. R., Science, new ser., vol. 4, 1896, p. 58; Weidman, Samuel, Jour. Geology, vol. 11, 1903, p. 297



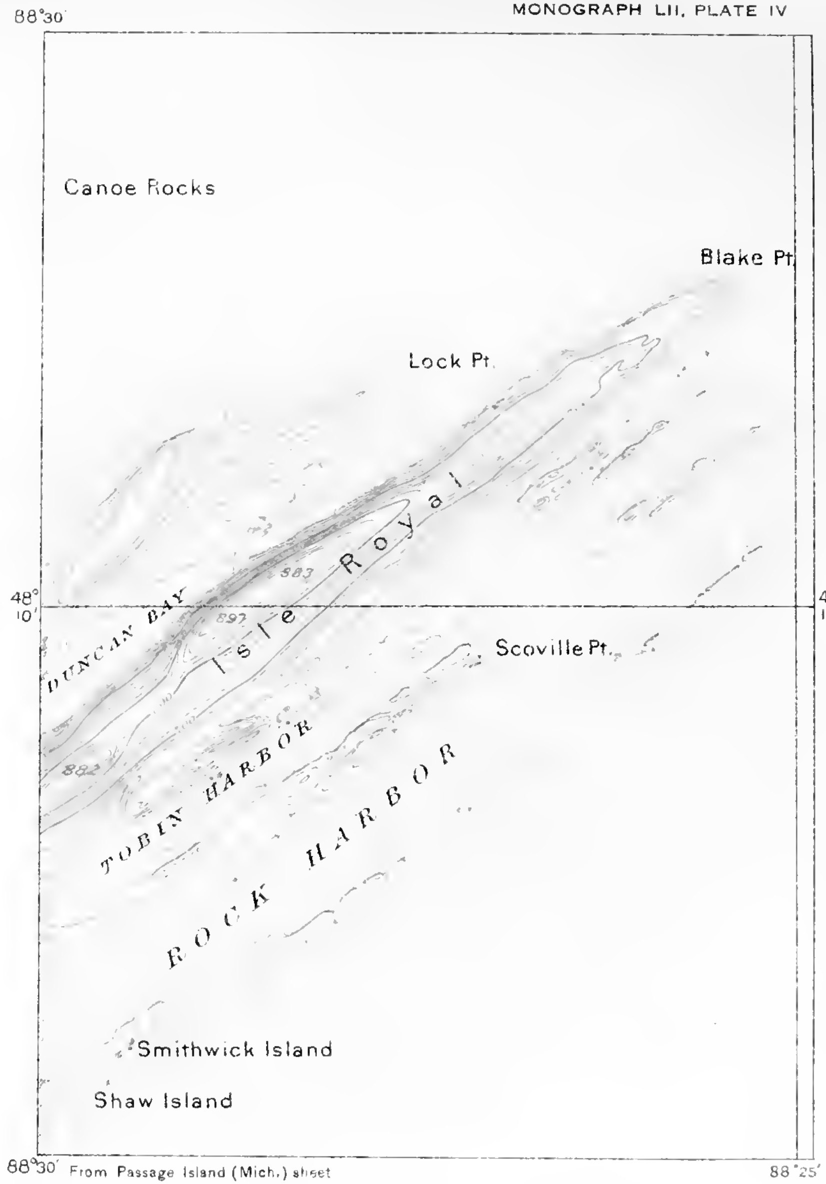
A

RIB HILL, A MONADNOCK RISING ABOVE THE PENEPLAIN IN WISCONSIN

Scale 1:125000

0 1 2 3 4 Miles

Contour interval 20 feet



B

TYPICAL MONOCLINAL RIDGE TOPOGRAPHY ISLE ROYAL, MICHIGAN

Scale 1:62500

0 1 2 Miles

Contour interval 20 feet

on the durable rocks. The stream systems are now subsequent rather than consequent—that is, they are adjusted to the weaker structures—crossing the ridges of resistant strata in narrow transverse courses and flowing in greater depressions along the longitudinal belts of weak rock. Most of the streams of the pre-Cambrian upland are in this adjusted condition; but Weidman has discussed evidences of a lack of adjustment of the stream courses in northern Wisconsin, the rivers being superposed indifferently upon weak and resistant beds because of original courses consequent upon the dip of unconformably overlying Paleozoic sediments.

SOIL AND GLACIAL TOPOGRAPHY.

A striking feature in the uplands is the absence nearly everywhere of any local or residual soil, such as would be derived from the weathering and decay of the various strata during the very long time necessary to reduce this from a mountainous region to a peneplain of slight relief. In the driftless portion of the region the ledges are deeply covered with residual soil derived from their decay. Elsewhere the soil is of a different kind from the underlying rock, with which it forms a sharp contact. It shows almost no sign of decay. It is not a residual but a transported soil, produced through erosion and deposition by the great continental ice sheet. This ice sheet removed the residual soil, brought a new and less fertile soil or left the ledges bare, displaced stream courses from the zones of weaker rock, producing many of the existing waterfalls and rapids, clogged the longitudinal subsequent valleys so as to form one class of lakes,[a] deepened some of the valleys so as to form lakes of another type, and produced numerous other effects, which are described in Chapter XVI (pp. 427–459). It is owing chiefly to this glacial invasion that the region differs from the normal peneplain type in minor topography, in drainage, and in soils.

DESCRIPTION OF DISTRICTS IN DETAIL.

The following description of the upland topography in the several districts is designed to exhibit its variations in accordance with the character of the constituent rocks. A geographic order has been adopted, starting with the part of the peneplain at the west end of Lake Superior, north of Duluth, continuing around north of Lake Superior in Ontario, and thence proceeding to the districts south of Lake Superior in upper Michigan and Wisconsin.

GABBRO PLATEAU.

The area in northeastern Minnesota underlain by the various Keweenawan gabbros, porphyries, etc., is a broad upland or plateau and forms a typical well-developed part of the peneplain. The rocks of the gabbro plateau are prevailingly coarse grained and homogeneous and hence furnish a notable exception to the linear topography commonly developed in the Algonkian. Locally they form ridges grading into the monoclinal ridge or sawtooth country to the east and north, which is mostly composed of granite or felsite or diabase rather than gabbro. The gabbro plateau surface is thus described by Grant:[b]

> In general the surface of this area is in the nature of an undulating plain. Many small elevations occur, but few which rise to a hundred feet above the surrounding country. * * * While the surface is in general one of low relief, the minor irregularities are pronounced. Steep rock hills are common, and small vertical escarpments 10 tc 20 feet in height are of frequent occurrence. Some of the water bodies, none of which are deep, stretch through considerable areas. * * * The general plainlike character of the gabbro-covered area can be ascribed to weathering, erosion, and glaciation, acting upon a surface composed of a single rock mass (the gabbro) uniform in constitution, grain, and resistance to disintegrating agents.

Clements[c] refers to it as a peneplained upland with minor irregularities due to joints, composition, etc., with irregular shallow lakes. He speaks of it as "reduced almost to base-level." In places the gabbro forms a more hilly topography.[d]

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[a] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 43–46.
[b] Grant, U. S., Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, pp. 434–435, 482, 492.
[c] Op. cit., pp. 37–38, 399–400.
[d] Grant, U. S., op. cit., pp. 399, 420, 462.

In St. Louis County, north and northeast of Duluth, the plateau topography is mild[a] (Pl. V, *A*), being largely obscured by the glacial drift. N. H. Winchell has referred to this plateau topography[b] as "very monotonous and nearly flat," with the gabbro "rising in irregular rocky domes about 10 to 30 feet above the surrounding country." Grant speaks of it in Lake and Cook counties, Minn.,[c] as a "broad undulating plateau," with a "surface which is still rough but has no marked elevations."

The areas of resistant red rock (felsites, porphyries, syenites, and granites) form monadnocks and higher ridges, among these being the Misquah Hills, one of whose summits, reaching a height of about 2,230 feet, is the highest point in Minnesota and the highest in the Lake Superior region. Other monadnocks of the resistant "red rock," including Eagle Mountain, rise to 2,100 or 2,200 feet. Certain anorthosites also form resistant knobs, such as Carlton Peak, which rises 927 feet above Lake Superior; it has been described by A. C. Lawson.[d]

The diabases generally form monoclinal ridges of the type described on page 99; they do not properly form a part of the topographic subprovince here discussed (the broad uplands) but are located upon its margins.

The whole plateau is deeply covered with glacial deposits, which conceal the ledges and the preglacial topography to some extent and have disarranged the drainage so that there are abundant lakes, swamps, and muskegs.

The east border of the plateau is the steep escarpment which descends abruptly to Lake Superior (Pl. V, *A*). The west boundary is obscured by glacial deposits, so that the topographic relationship of the Keweenawan of the plateau and the upper Huronian slates south of the Giants Range is obscure. The north boundary of the gabbro plateau, as described by Clements[e] and by Leith, is a "conspicuous northward-facing escarpment overlooking the low-lying area of Virginia slate and iron formation immediately to the north. To this the name 'Mesabi Range'[f] was first applied."[g] In places the gabbro overlies the granite and there is no intermediate lowland.

ST. LOUIS PLAIN.

West of the gabbro plateau, in the region drained by St. Louis River and its tributaries, the homogeneous upper Huronian slates form a broad plain at a lower level, extending north to the Giants Range and in most places deeply covered by glacial drift but still retaining the even peneplain topography.

VERMILION DISTRICT.[h]

In the Vermilion district, which is separated from the gabbro plateau and the slate plateau of upper St. Louis River by a great linear monadnock called the Giants Range, the peneplain topography is also well developed. Here, however, the even-featured surface bevels across Archean and Huronian rocks rather than Keweenawan gabbros. The truncated folds of conglomerates, slate, iron formation, etc., and the exposed masses of greenstone, granite, etc., indicate, however, that this was originally the heart of a lofty mountain region. (See structure profiles, Pls. I, XXVI, in pocket.) The peneplain seems to have been base-leveled and subsequently slightly uplifted, so that the streams have incised valleys, between which flat uplands and ridges rise to the peneplain level. The present topography has been described by C. R. Van Hise[i] as follows:

[a] See topographic map of Duluth quadrangle, U. S. Geol. Survey, and maps of St. Louis, Cook, and Lake counties in atlas accompanying Final Rept. Geol. and Nat. Hist. Survey Minnesota.

[b] Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, pp. 212, 265.

[c] Idem, pp. 267, 317.

[d] Bull. Geol. and Nat. Hist. Survey Minnesota No. 8, 1893, pp. 18-19.

[e] The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 399-400.

[f] The name "Giants Range" is generally applied to the high ridge area underlain by the Huronian granite, though there is a tendency to extend the name eastward to the somewhat disconnected peaks (Misquah Hills, etc.) underlain by the "red rock" (a Keweenawan granite). See footnote on p. 103.

[g] The Mesabi iron-bearing district of Minnesota, Mon. U. S. Geol. Survey, vol. 43, 1903, p. 182.

[h] A brief statement about the topography is included in each of the chapters on the iron-producing districts.

[i] Manuscript notes.

The ridges correspond in direction with the greater extent of the district. They are parallel with the major structure and also with the secondary structures, such as cleavage and schistosity. The trend of these ridges is therefore about N. 70° E., although locally they vary much from this direction.

These ridges vary in altitude somewhat rapidly in the direction of their trend, and a single ridge is usually no longer than a fraction of a mile to a few miles, ordinarily 1 or 2 miles. The slopes parallel with the trend of the ridges are comparatively gentle. The slopes transverse to the course of the ridges are steep between the ridges, the valleys being deep and many of them narrow. Also the cross section of a single ridge may be complex, so that it consists of a series of minor ridges between which are minor valleys. Though the major features of the region are undoubtedly preglacial, the action of the ice has been very important, so that the hills and bluffs are now round-topped, the slopes steep, and the valleys flat-bottomed and U-shaped. This form is, however, subordinately due to filling rather than to erosion.

Many of these valleys are occupied by lakes. The greater number of these lakes are almost exactly parallel to the trend of the ridges and are generally several times as long as broad. This is true not only of the main body of each lake but also of its arms. Characteristic lakes of this class are Long Lake, Fall Lake, Moose Lake, New Found Lake, and Knife Lake.

Where the structure of the district locally is not linear, as in the granites, the lakes also lack the linear character. As illustrating this may be cited Snowbank Lake, Gabimichigama Lake, Gull Lake, and Lake Saganaga.

From high knobs or recently burned areas may be had the best views of the topography. From a point like Jasper Peak, or Disappointment Mountain, or one of the high ridges in the neighborhood of Gunflint, an observer sees in the foreground the linear ridges, rough and partly covered by trees in various stages of growth, in the valley at his feet a lake, and along the range, if the point of view is advantageous, many lakes. From Jasper Peak he may follow nearly all the bays and arms of the largest and most complex of the lakes of the district, Vermilion Lake [Pl. VI]. However, if the observer ignores the immediate surroundings and looks farther away, he gets an idea of the more ancient topography of the region. Southward from a high point in the western part of the range his view extends over a number of ridges and valleys, and as a horizon line he sees the Giants Range north of the Mesabi district. This range in the western part of the district is composed of the Giants Range granite and in the eastern part of the district of the Keweenawan gabbro. To the north his range of vision is limited by the granitic hills of Basswood Lake.

From the various points of view he learns that, though the Vermilion district has numerous hills and bluffs not inferior in altitude to the areas north and south of the district, on the whole it is an area in which erosion has played an important rôle, the valleys being wider and deeper and containing lakes in especial abundance.

Ignoring all these minor irregularities, he is astonished at the apparent horizontality of the sky line. A few points, however, project above this sky line—for instance, Jasper Peak [Pl. III, *B*].

This impressive feature of the topography suggests very strongly that this region was at some time in the distant past nearly base-leveled; that the high projecting points were not reduced to this level; that since that ancient time a new cycle of erosion has far advanced. Into this base-leveled plain the present topography of the Vermilion district has been incised. It almost surely was mainly accomplished by river erosion in preglacial times. However, the glacial erosion has been exceedingly vigorous here. It was preeminently an area of glacial erosion and not of deposition. The hills and bluffs are almost devoid of glacial débris; even the valleys contain comparatively little as compared with moraine areas of Wisconsin and Minnesota. The present forms of topography are not typical river-sculpture forms; they are rather such forms considerably modified by glacial sculpture and glacial deposition.

J. M. Clements reviews the relation between topography and structure in this district, emphasizing many points by local examples.[a] He refers to the whole region[b] as "characterized by ridges trending N. 70°–80° E., with intervening valleys, the larger ones usually occupied by streams or lakes. In this area the topography is rugged but the range of altitude is not very great."

Clements[c] has described in detail the topography characteristic of the various Archean formations in the Vermilion district as follows:

Ely greenstone: Prominent east-west hills and ridges, or broad, low, rounded knobs and ridges.

Soudan formation (iron bearing): No great effect upon topography usually, though locally very important, as where its jaspers form prominent peaks, such as Jasper Peak, Lee and Tower hills, and other notable knobs and ridges, some of them monadnocks.

Granites of Vermilion Lake: Usually occupies hill crests or "occurs in rounded or oval hills higher than those occupied by the surrounding rocks."

Granites of Trout, Burntside, and Basswood lakes: "Does not seem to affect the topography very materially." Topography rough in detail but with no notable relief. Irregular or rounded lakes contrast strikingly with linear lakes of sedimentary areas. Has small area, possibly base-leveled in second cycle.

Granites between Moose Lake and Kawishiwi River: Exposures numerous in oval mass.

Granites of Saganaga Lake: Unemphatic topography, with low rounded hills rising to same level and suggesting rather complete peneplaining.

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[a] The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 431–436.

[b] Idem, pp. 19, 36–37.

[c] Idem, pp. 134–135, 175, 248, 259, 264, 266.

The several Huronian intrusives of smaller area also produce a typical peneplain topography in the somewhat isolated highlands of the plain of Huronian slate at the edge of the Keweenawan gabbro. Their several effects are thus described by Clements:[a]

Giants Range granite: Low rounded to oval hills, perhaps a topographic continuation, though lower, of the Giants Range north of the Mesabi iron range. Has small area, possibly base-leveled in second cycle.

Granite of Snowbank Lake: Rounded topography characteristic of glaciated granite. Stands lower topographically than might be expected from its position in center of a structural anticline.

Cacaquabic granite: Occupies prominent position, with fairly high hills.

Acid dikes: Locally form knolls and ridges.

The Huronian beds are nearly always associated with depressions or with minor ridges and the slates form a linear lowland with local ridges and knobs. Clements[b] has described the topography developed upon the lower Huronian sediments as follows:

Conglomerates and slates of Vermilion Lake area: Depressions underlying lakes, swamps, etc., or generally low land between ridges of Archean greenstone and iron formation, trending north-northeast and south-southwest.

Conglomerate, iron-bearing Agawa formation, and Knife Lake slate of Knife Lake area: Much rougher topography than in Vermilion Lake area to west. Relief of 400 feet or 600 feet including depth of lakes. Normally conglomerates form ridges and slate forms depressions. Ridges and valleys, all on comparatively small scale, trend east-northeast and west-southwest. Locally siliceous slates form sheer cliffs of 100 feet.

RAINY LAKE AND LAKE OF THE WOODS DISTRICT.

The Rainy Lake and Lake of the Woods region, north of the international boundary, is underlain chiefly by the Archean, but has subordinate linear areas of not clearly separated Huronian. A. C. Lawson has characterized the topography near the Lake of the Woods as one which, "although extremely hummocky or mammillated in its surface aspects, presents extraordinarily little variation in level. There are no great valleys or high hills. The whole country is practically a plateau of very moderate elevation above the sea for so inland a region."[c] He describes the Rainy Lake region as "remarkably flat and devoid of prominent elevations, although the surface in detail is extremely uneven and hummocky or mammillated."[d]

He regards the region as probably never having been mountainous, giving as his reasons the lack of proof that plications in general make mountains and the absence of immense valleys or gorges. His report was written, however, long before the idea was developed that the condition of moderate relief in a peneplain belongs to a later state of denudation than that of the mountains, deep gorges, etc.

Lawson[e] shows how the variously folded weak and resistant beds form minor ridges and valleys on the land, or peninsulas and bays and islands where lake waters wrap around an irregular series of valleys and hillocks produced by subaerial erosion previous to the formation of the lakes. Near Rainy Lake elevations average only 100 to 200 feet, though certain exceptional ridges and knobs, which seem to be monadnocks held up on resistant schists, gneisses, and granites, rise 300 to 500 feet above lake level, the highest being Kishkutena Ridge, approximately 1,700 feet above sea level and visible for long distances. The lakes average less than 50 feet deep, the greatest depth found being 165 feet.

HUNTERS ISLAND AND THUNDER BAY REGION.

East of the regions described by Lawson lies the region of Hunters Island and Thunder Bay. W. H. C. Smith[f] and William McInnes[g] have described the topography as belonging to the same sorts and having the same relationships as that to the west. The greenstones,

[a] The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 354, 361, 364, 370.

[b] Idem, pp. 36, 278, 299.

[c] Geology of the Lake of the Woods region: Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1885, new ser., vol. 1, 1886, Rept. CC, p. 22.

[d] Geology of the Rainy Lake region: Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1887-88, vol. 3, new ser., 1889, Rept. F, p. 10.

[e] Op. cit., vol. 1, Rept. CC, pp. 15-25 and 26-28; vol. 3, Rept. F, pp. 10-20.

[f] Geology of Hunters Island and adjacent country: Ann. Rept. Geol. Survey Canada for 1890-91, new ser., vol. 5, 1893, Rept. G, pp. 9-11.

[g] Geology of the area covered by the Seine River and Lake Shebandowan map sheets: Ann. Rept. Geol. Survey Canada for 1897, new ser., vol. 10, 1899, Rept. H, pp. 6-10.

jaspilites, and iron formation and certain schists form ridges rising at most 300 feet above the neighboring lakes, whose greatest depth is 280 feet; the other Archean rocks are "characterized by low, rounded hills, with softened outlines."

REGION NORTH OF LAKE SUPERIOR.

W. H. Collins [a] describes the region between Nipigon Bay and Heron Bay and northward to the Height of Land as "a peneplain of rounded hills of crystalline rocks 300 to 400 feet high, terminating abruptly along the south," and with steeply descending streams affording excellent water power.

Collins [b] also describes the Archean area north of the Canadian Pacific Railway and west of Lake Nipigon as possessing "a surface of low relief and moderate altitude." Water levels vary from 1,149 to 1,382 feet. Few hills reach 250 feet in height. The sky line is exceedingly even. The area also possesses the linear topography of the Algonkian in places and the mesa topography of the Keweenawan near Lake Nipigon and to the west.

REGION NORTHEAST OF LAKE SUPERIOR.

J. M. Bell [c] has characterized the region north of Lake Superior and west of the Michipicoten district to Heron Bay as hilly, with greater ranges of relief than elsewhere in the Laurentian peneplain, with valleys opened on weak rocks, ridges formed on resistant beds, and with monadnocks rising above the general peneplain level on the site of the still more resistant beds.

MICHIPICOTEN DISTRICT.

The part of the peneplain that includes the Michipicoten district has been described as follows:[d]

> The topography is of the rugged character usual on the north shore of Lake Superior, and Hematite Mountain, the highest point, rises 1,100 feet above the lake within a distance of 7 miles. In general the hills form steep ridges with a direction of about 70° east of north, corresponding to the strike of the schists, and traveling is difficult across the line of strike. * * * From the summit of Hematite Mountain, which is situated about in the middle of the region and rises 200 feet above any of its neighbors, there is presented more than the usual variety of surface, including long ridges of Huronian schist, rounded hills of eruptives, which sometimes rise like islands out of lacustrine plains, stretches of the hummocky surface so common in glaciated Archean districts, lake basins, rock rimmed or bordered with muskeg, rivers with lakelike stretches of dead water, tumultuous rapids over morainic bowlders and falls over rocky descents, and, finally, the splendid promontories of the shore of Lake Superior. * * * The intimate dependence of the topography on the geological history of the country is well brought out in the Michipicoten region, where the folding of the schists has determined the direction and steepness of the main ranges of hills; while bosses and irregular masses of eruptives give rise to less uniform hills associated with the ridges or standing isolated. The basis of the topography is to be found in the pre-Cambrian arrangement and the varying power of resistance to weathering and erosion shown by the different rocks; so that the prominent features may be of very ancient date, even Paleozoic.

REGION NORTH OF SAULT STE. MARIE.

In the upland north of Sault Ste. Marie and east of Michipicoten relief of as much as 100 to 200 feet is common. Nearer the lake and southeast of Michipicoten there are several very deep valleys, notably those of Agawa, Montreal, Batchawana, Chippewa, and Goulais rivers. Owing to the considerable relief, some very high and expensive trestles will be required where the Algoma Central and Hudson Bay Railway is to cross the first three rivers mentioned; and the building of the railway beyond Pangissin has been hindered by the necessity of high steel bridges, though the railway is graded all the way to the Michipicoten district. Such expense in railroad building in the Lake Superior region away from the lake shore is distinctly exceptional and indicates the high degree of the local relief.

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[a] Summary Rept. Geol. Survey Canada for 1905–6, pp. 80–81.

[b] Idem, p. 103.

[c] Rept. Bur. Mines Ontario, vol. 14, 1905, pt. 1, pp. 281–299.

[d] Coleman, A. P., and Willmott, A. B., The Michipicoten iron ranges: Univ. Toronto studies, Geol. ser., 1902, pp. 4–6; also Eleventh Rept. Bur. Mines Ontario, 1902, pp. 153–154.

The areas between these deep valleys are broad and relatively flat or round topped, and some of the hills "present steep slopes toward the valleys and often drop off in impassable cliffs 100 feet or more in height. None of the hills rise much over 1,000 feet above Lake Superior, but many reach 900 feet"[a] (1,500 to 1,600 feet above sea level). The surface bevels indifferently across variously durable structures of gneiss, schist, and granite in a characteristic peneplain surface, with the usual monadnocks. The deep valleys resemble those of the north shore of Lake Superior, which are crossed near their mouths by expensive bridges and trestles of the Canadian Pacific Railway; in both regions they are deep cut because of the low adjacent base-level of Lake Superior.

MARQUETTE DISTRICT.[b]

North of Marquette the granite area forms a monadnock group known as the Huron Mountains, rising about 1,200 to 1,350 feet above the lake.[c] The elevations were thus described by Foster and Whitney:

> They do not range in continuous chains, but exist in groups radiating from a common center, presenting a series of knobs rising one above another until the summit level is attained. Their outline is rounded or waving, their slope gradual. The scenery is tame and uninteresting.

C. A. Davis [d] writes with regard to the same region:

> The hills are only 150 or 200 feet above the valleys, hence the general level is relatively high and the district is a plateau, or high peneplain, rather than mountainous.

The granite of the Archean south of Marquette was early described by Brooks as having an irregular topography, with low knobs, ridges, and cliffs.[e] Rominger contrasts the area south of Marquette,[f] where the granites occupy lower levels than the Huronian, with the northern granite outcrops, which "occupy the highest elevations and constitute the most conspicuous ridges." The topography (see topographic map and structure profiles, Pl. XVII, in pocket) characteristic of the Archean formations in this district has been described in greater detail by C. R. Van Hise and W. S. Bayley [g] as follows:

> Northern complex:
> - Mona schists: Minor rugged hills, strongly glaciated.
> - Kitchi schists: Rugged hills similar to those of Mona schist.
> - Gneissoid granites: Rounded knobs, invariably smoothed by glaciation.
> - Hornblende syenite: Exactly like that of granite.
>
> Southern complex: Knobs, as in northern granite areas.

MENOMINEE DISTRICT.[h]

W. S. Bayley [i] has described the topography associated with the various Archean rock series in the Menominee district (Pl. XXVI, in pocket) as follows:

> Quinnesec schist (southern area): Rough and broken, forming deep gorges, with many ridges and elongated hills.
> Quinnesec schist (western area): Without distinctive peculiarities except small rugged knobs.
> Granites, gneisses, and schists of northern complex: Irregular rugged knolls, intensely glaciated.

CRYSTAL FALLS DISTRICT.[j]

The topography characteristic of the Archean in the Crystal Falls district (Pl. XXII, in pocket) has been described by J. M. Clements, H. L. Smyth, and W. S. Bayley [k] as follows:

> Granite: Small rounded isolated knobs, chiefly obscured by glacial drift (gaps in granite range where resistant greenstone dikes cross).

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[a] Coleman, A. P., Rept. Bur. Mines Ontario, vol. 15, pt. 1, 1906, pp. 175-177.
[b] For topography of Marquette and adjacent districts see also the chapters on these districts.
[c] Report on the geology and topography of the Lake Superior land district, 1850, pt. 1, p. 34.
[d] Ann. Rept. Geol. Survey Michigan, 1906, p. 260.
[e] Brooks, T. B., Geol. Survey Michigan, vol. 1, 1873, pp. 72-73.
[f] Rominger, Carl, Geol. Survey Michigan, vol. 4, 1881, p. 13.
[g] The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1895, pp. 152, 162, 170, 176, 191.
[h] See also chapter on Menominee district, where topography is discussed.
[i] The Menominee iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 46, 1904, pp. 132, 159, 168.
[j] See also chapter on Crystal Falls district, where topography is discussed.
[k] The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899 (western, p. 38; eastern, pp. 329, 386, 428, and 463).

Archean crystallines: Mammillated with rocky knobs separated by bowl-like depressions, the hummocks and bowls being generally elongated east and west.

Granites, gneisses, schists, and amphibolites of Felch Mountain district: Characteristic rough topography with east-west elongated hummocks and bowls. A topographic depression always exists along the contact of the Archean and Algonkian, usually holding a swamp or stream.

Gneissoid granites and various schists of Sturgeon River tongue: Scattered bare knolls.

West of the Crystal Falls, Menominee, and Marquette districts (fig. 43, p. 292; Pl. XXIV, in pocket) there is a general plain produced by erosion upon the homogeneous slates, in places deeply cut by streams and partly obscured by the glacial drift. Through both slates and drift certain knobs of resistant greenstone, etc., project as eminences.

KEWEENAW POINT.

On Keweenaw Point the highland peninsula, generally referred to in atlases and maps as the Copper Range, has rocks vertical or very highly inclined. Erosion has thus far been unable to significantly alter the plateau [a] or peneplain [b] which was developed on these inclined beds in the period of base-leveling. This is the case on the part of Keweenaw Point (fig. 59, p. 422) that extends southward from Gratiot River to Portage Lake, where the ridges of the eastern tip of the point, as described by Irving, merge into "one broad swell" or "a broad central ridge" which extends west as far as the Porcupine Mountains, beyond which it resumes its continuity to the neighborhood of Bad River, Wisconsin. Upon this long, narrow plateau relief is not wanting, small monadnocks rising above the general level, which otherwise bevels indifferently across the various weak and resistant beds. This plateau surface is also diversified between Porcupine Mountains and Bad River by "rounded ridges and knobs with cliffs facing indifferently in all directions." It is still, however, essentially a peneplain, the valleys cut in it not having notably dissected its surface into distinctive forms like monoclinal ridges or mesas. To the northeast, at the tip of Keweenaw Point, there are monoclinal ridges and longitudinal valleys, replacing the former peneplain surface, above whose level monadnocks like Mounts Houghton and Bohemia still rise, the former owing its eminence to a resistant red felsite.[c] In the plateau region, where the dips have prevented equally rapid dissection, the peneplain surface remains. It is marginally cut by deep gorges, to be sure, but these valleys are of moderate area and are not separated by monoclinal ridges or by mesas, such as occur where the dips are below 30° or nearly horizontal respectively. Minor monadnocks rise everywhere above the partly dissected peneplain.

The moderate elevation on the south shore of Lake Superior known as the Porcupine Mountains [d] forms a monadnock area rising 600 to 1,421 feet above the lake and averaging 1,800 feet above sea level. The highest point is 2,023 feet. These mountains owe their relief to the resistant quality of a body of quartz porphyries and felsites here faulted up against the adjacent weaker beds on the south and exposed by denudation. That they form a group of monadnocks was first noted by Van Hise.[b]

NORTHERN WISCONSIN.

R. D. Irving [e] in 1878 briefly described the topography of the Archean area south of the Penokee-Gogebic range as the "elevated interior" or "interior table-land," with a gently undulating surface, few ledges, low granite domes, and abundant glacial lakes and swamps.

In their report on the Penokee-Gogebic district Irving and Van Hise [f] have not specifically described the topography associated with the north edge of the peneplain within that district, but the Archean gneisses and schists there may be inferred to have characteristic knobby topography (Pl. XVI, p. 226).

[a] Brooks, T. B., Geol. Survey Michigan, vol. 1, 1873, pp. 69-70; Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 164-166, 186.

[b] Van Hise, C. R., Science, new ser., vol. 4, 1896, p. 217.

[c] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 181-182.

[d] Idem, pp. 206-225, and geologic section 3, pl. 20. Also Wright, F. E., Ann. Rept. Geol. Survey Michigan, 1903, pp. 35-44.

[e] The geology of the eastern Lake Superior district: Geology of Wisconsin, vol. 3, 1873-1879, pp. 61-62, pl. 11.

[f] The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Snrvey, vol. 19, 1892, p. 104.

CENTRAL WISCONSIN.

R. D. Irving [a] wrote as follows regarding the topography of central Wisconsin:

The region of crystalline rocks (Archean and Huronian) of north-central Wisconsin, descending gradually southward, has a gently undulating surface, which is, however, often broken in minor detail by low, abrupt ridges with outcropping tilted rock ledges.

Weidman [b] has described the topography associated with the Archean formation in north-central Wisconsin (Pls. IV, *A*, p. 90; XXXI, *A*, p. 436) as follows:

The basal group (gneiss and schists) forms a gently sloping plain, with low crystalline ledges sometimes thinly covered by sandstone, sometimes by glacial drift, but generally exposed in the river beds.

The Huronian granite and syenite form the principal undiversified peneplain here.

NORTHEASTERN WISCONSIN.

With regard to the topography in northeastern Wisconsin, T. C. Chamberlin [c] says:

The Archean surface is very irregular, and here and there knobs rise through the superincumbent formations, giving rise to isolated hills of quartzite, porphyry, and granite in the midst of the areas of lower rocks.

He infers that these knobs are protruding through the Paleozoic sediments, not intrusive in them.

LINEAR MONADNOCKS AND OTHER RIDGES.

GENERAL DESCRIPTION.

Besides the smaller monadnocks which rise above the broad uplands of the peneplain, there are numerous linear monadnocks and elongated ridges below the peneplain level, which are related to the formations that outcrop in narrow bands, notably the Algonkian formations but to some extent also the Archean. A few linear monadnocks also rise above the level of the peneplain.

Where the rocks are gently inclined erosion has been able to attack them more successfully than in the areas of steeper dips, and has developed the monoclinal ridge (Pl. IV, *B*), which has its gentler slope following the dip of the beds and its steep escarpment on the opposite side. Part of these monoclinal ridges are monadnocks, but a number are not.

In the Keweenawan rocks of the Lake Superior region these monoclinal ridges are best developed in northeastern Minnesota, on Isle Royal, and at the end of Keweenaw Point; among the Huronian rocks they are well developed in northern Minnesota and southern Ontario, near Gunflint Lake, in the Penokee Range, in the Giants Range, and in all the iron districts, and as monadnocks in the peneplain (fig. 5).

The origin of these monoclinal ridges as specialized forms due to differential erosion (fig. 6) upon weak and resistant strata has not been agreed to by all the workers in the Lake Superior region. N. H. Winchell [d] ascribed the Sawteeth Mountains of the Minnesota coast to faulting and has been followed by A. C. Lawson,[e] who ascribes the monoclinal ridges of the Animikie in southern Ontario and northern Minnesota to faulting, and by A. H. Elftmann.[f] Irving,[g] on the other hand, points out that the topography "is just such as is found in every region of flat-dipping hard rocks, and especially where softer layers are interleaved, as in this case." He also cites numerous monoclinal ridges of similar type in equivalent nonfaulted rocks on eastern Keweenaw Point, in northern Wisconsin, and elsewhere, where the sawtooth shape is well developed. U. S. Grant [h] writes:

The numerous northward-facing cliffs suggest the probability of a series of comparatively recent east and west fault lines, along the north sides of which the strata are depressed. * * * The evidence of profound faulting in these strata, aside from the evidence of topography, is small. It seems that the present surface configuration could

[a] Geology of Wisconsin, vol. 2, 1873-1877, pp. 453, 462.
[b] Bull. Geol. and Nat. Hist. Survey Wisconsin No. 16, 1907, p. 16.
[c] Geology of Wisconsin, vol. 2, 1873-1877, p. 248.
[d] Seventh Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1878, p. 12.
[e] Bull. Geol. and Nat. Hist. Survey Minnesota No. 8, 1893, p. 33; Twentieth Ann. Rept. Geol. and Nat. Hist. Survey, Minnesota, 1891, p. 192.
[f] Am. Geologist, vol. 21, 1898, p. 183.
[g] Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 142-143.
[h] Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, 1899, pp. 483, 485.

have been brought about by erosion acting on gently inclined strata of different degrees of resistance, the thin-bedded and fissile Animikie slates being more susceptible to disintegration and erosion than the diabase sills.

Grant subsequently proved absence of faulting in one of the "supposed fault scarps" to the satisfaction of a number of accompanying geologists, including N. H. Winchell and A. H. Elftmann, two of the advocates of the fault origin of these monoclinal ridges.

As major faulting has never been proved to be associated with the scarps of the monoclinal ridges, as their origin by differential erosion in nonfaulted strata has been repeatedly shown, and as they are associated only with marked cross faults—for instance, on Isle Royal and north of Thunder Bay—the fault hypothesis for the monoclinal ridges (sawteeth) is regarded as not warranted. Indeed, in the Vermilion monograph J. M. Clements,[a] who discusses this type of topography, does not even mention the possibility of faulting.

As the strike of the Algonkian rocks is generally northeast and southwest, the trend of the monoclinal ridges and of the subsequent valleys between is in the same direction, the longitudinal valleys that extend parallel to the strike of the rocks being usually broad and persistent, whereas the transverse valleys extending across the strike of the rocks are narrow and irregularly arranged.

Where these ridges and valleys are partly submerged the resulting bays are extremely long, straight, and persistent, and the peninsulas and islands are in long parallel lines, as on the coast of Isle Royal. Glaciation, acting upon this monoclinal-ridge topography, has produced one striking series of lakes in northeastern Minnesota; these, as well as similar lakes in other parts of the region, are due to glacial clogging of the subsequent axial valleys between the monoclinal ridges.

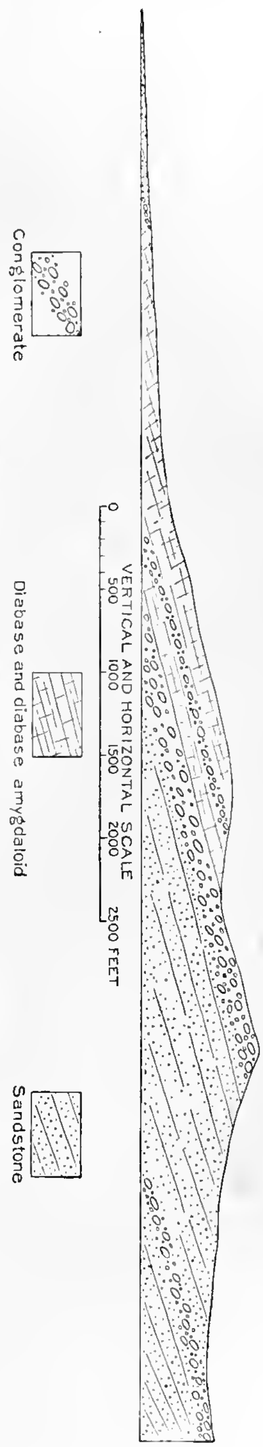

FIGURE 6.—True-scale cross section of Keweenawan monoclinal ridges near the end of Keweenaw Point.

KEWEENAWAN MONOCLINAL RIDGES.

GENERAL STATEMENT.

In northeastern Minnesota, on Isle Royal, on the end of Keweenaw Point, and in northern Michigan and northern Wisconsin, the monoclinal-ridge type of topography is so well developed that the name Sawteeth Mountains[b] has been given to these ridges on account of their resemblance to the jagged teeth of a saw when seen in profile. The same name is also applied to the Huronian monoclinal ridges near Gunflint Lake and northward in Ontario. (See fig. 5, p. 88.)

NORTHEASTERN MINNESOTA.

Ridges of this sort in Minnesota, near Grand Marais, with back slopes of 5° to 10° and steep escarpments, are described by Irving[c] as forms due to differential erosion on weak and resistant beds.

ISLE ROYAL AND MICHIPICOTEN ISLAND.

The monoclinal ridges on Isle Royal (Pl. IV, *B*) are described by Lane.[d] No other information concerning the relation of the geology to the minor topography of Michipicoten Island has been obtained by the writer.

[a] Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 400–401.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, fig. 1, p. 142; also figs. 16, 26, and 29, on pp. 297, 325, and 326.

[c] Idem, pp. 141–143.

[d] Lane, A. C., Geol. Survey Michigan, vol. 6, 1893–1897, pp. 180–183.

KEWEENAW POINT AND NORTHERN MICHIGAN AND WISCONSIN.

The parallel monoclinal ridges and intervening valleys near the end of Keweenaw Point (fig. 6) were early described by Marvine[a] and later in some detail by Irving,[b] who associated the various valleys and "parallel ridges with cliffy southern and flat northern faces" with specific gently dipping Keweenawan beds—the valleys with weak amygdaloids and easily decomposable diabases, the ridges with resistant melaphyres, coarse diabases, and bowlder conglomerates—and showed the topography associated with them in various profiles.[c] In regard to the east part of Keweenaw Point, Irving[d] emphasizes the relation of dip to topography:

Where the dip flattens the structure comes out finely in a series of bold ridges. Toward Portage Lake, however, the dip becomes as high as 50° or more and the several ridges merge into one broad swell. This holds until the Porcupine Mountains are reached, where, although the dip angle is as high as 30°, the structure is most beautifully illustrated in the outer ridge.[e] This ridge rises from the lake shore somewhat more gradually than the dip to a height of over 1,000 feet and then drops off in a bold escarpment of 400 feet into the valley of Carp Lake.

This cliff[f] extends nearly continuously across T. 51 N., R. 43 W., a distance of over 6 miles. The crown of the cliff is from 800 to 1,000 feet above Lake Superior and from 400 to 600 feet above the valley of Carp Lake. The base of the cliff is marked by a long slope of fragments fallen from the diabase and amygdaloid which forms its upper portions, but through the greater part of its length there is a perpendicular face of about 400 feet above the talus.

Farther west again, as far as Bad River,[g] the dips are high, often reaching 90°, and the harder rocks constitute merely rounded ridges and knobs with the cliffs facing indifferently in all directions. Beyond Bad River and all across Wisconsin to the St. Croix the dips flatten once more, and the "sawtooth" shape in the ridges is everywhere well marked.[h]

This is notably true throughout Douglas County, Wis.[i]

U. S. Grant[j] refers briefly to the surface features characteristic of the Keweenawan in Douglas County, Wis., where four belts of different topography are produced, varying with the part of the Keweenawan exposed, the dip, and the glacial overburden. The more resistant portions of the Keweenawan form two main ranges in northern Wisconsin because of the synclinal structure there. T. C. Chamberlin, writing as editor of the notes of the late Moses Strong, in reviewing the surface features of northwestern Wisconsin[k] says that the linear topography referred to and represented in profiles shows splendid Keweenawan monoclinal ridges.

KEWEENAWAN MESAS.

On the north shore of Lake Superior the tabular-mesa topography (fig. 5, p. 88) is developed in places where the Algonkian beds lie practically horizontal and weaker strata underlie more resistant beds, so that erosion has been able to open lowlands on the weak rocks and leave isolated highlands or ridges. Three great valleys have been opened up in the weaker beds in the upper Huronian (Animikie group) and the Keweenawan, and two great mesa ridges have been left between these valleys. The waters of Lake Superior have subsequently risen to such a level that they occupy the floors of these valleys and form Thunder, Black, and Nipigon bays (Pl. II, p. 86). Thunder Cape, the narrow end of one of the peninsulas, is a characteristic bit of mesa topography, its flat top rising 1,350 feet above the level of the lake. Pie Island is another mesa of the same kind which erosion has isolated completely, the lake waters covering the valley bottoms surrounding it, and Mount McKay,[l] south of Mount William, is a similar

[a] Marvine, A. R., Geol. Survey Michigan, vol. 1, 1873, pt. 2, p. 95.

[b] Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 164–166.

[c] Idem, fig. 2 on p. 178, and pl. 18.

[d] Idem, pp. 142–143.

[e] Described by Foster and Whitney, pt. 1, 1850, p. 35. Shown well in topographic map by Michigan Geol. Survey, Ann. Rept. for 1905, fig. 3, p. 15. Just east of the Porcupine Mountains, in the Black River region, between Bessemer and Lake Superior, the topography of the Keweenawan in a typical strip from the Penokee Range to Lake Superior is described by W. C. Gordon, who has prepared an excellent topographic map (Geol. Survey Michigan, Ann. Rept. for 1906, pp. 408–409, 420; pl. 32).

[f] Mon. U. S. Geol. Survey, vol. 5, 1883, p. 218.

[g] Idem, p. 113.

[h] See also Irving, R. D., Geology of Wisconsin, vol. 3, 1873–1879, pp. 62, 67–68.

[i] Sweet, E. T., Geology of Wisconsin, vol. 3, 1873–1879, pp. 310–329.

[j] Grant, U. S., Bull. Geol. and Nat. Hist. Survey Wisconsin No. 6, 1901, pp. 6–8.

[k] Geology of the upper St. Croix district: Geology of Wisconsin, vol. 3, 1873–1879, pp. 367–381.

[l] Mon. U. S. Geol. Survey, vol. 5, 1883, p. 374.

mesa perhaps small enough to be called a butte, rising 980 feet above Lake Superior, and isolated in the broad, unsubmerged valley of Kaministikwia River. William McInnes[a] refers to the area of flat-lying Animikie rocks near Thunder Bay as showing "table-topped hills, and escarpments with perpendicular faces and sharply angular outlines."

A. C. Lawson, who ascribed the escarpment of the monoclinal ridges near Gunflint Lake to faulting, has also indicated his belief that the east side of Thunder Bay, which "presents a very bold and remarkably straight cliff several hundred feet high composed of Keweenawan sandstone resting on Animikie slate, both flat-bedded and in apparent unconformity, * * * is probably originally and genetically a fault scarp."[b] The writer feels inclined to ascribe this escarpment to subaerial denudation, partly (1) because of the insufficient evidence of larger faulting here,[c] as pointed out in the discussion of the cliffs of the monoclinal ridges (p. 99), partly (2) because denudation in the region is producing just such escarpments where resistant horizontal strata overlie weaker beds, and partly (3) because a fault scarp in this location could not possibly have retained its present position and form since the latest possible date of formation unless it were protected by some lately removed mantle, as the larger possible fault scarps of the northwest coast of Lake Superior and the southeast side of Keweenaw Point seem to have been. (See pp. 112–116.) The chief reason for doubting the fault origin of the east boundary of Thunder Bay is that such an origin would imply the fault origin of the boundaries of all the mesas in this district which have escarpments that are very similar topographically and geologically. Because of the great complexity of block faulting that would isolate Thunder Cape and the adjacent peninsulas, as well as Pie Island and Mount McKay, etc., and the total absence of evidence of such faulting, it seems far more reasonable to ascribe these forms to the well-established cycle of forms resulting from normal subaerial denudation.

North of Lake Superior, in Ontario, near Lake Nipigon and to the east and west, there seems to be a great many more mesas and valleys of exactly this kind,[d] all in an area underlain by Keweenawan rocks or by upper Huronian (Animikie) slates and Logan sills, as along the Canadian Pacific Railway east of Port Arthur and especially beyond Nipigon. A. C. Lawson[e] writes:

> It is to the presence of these trap sheets (the Logan sills) that the bold and picturesque topography of Thunder Cape, Mount McKay, Pie Island, Nipigon Bay, and the many sheer-walled mesas and tilted blocks of the region is due.

All these mesas apparently have their present form because erosion has had more power to open up broad valleys in a region where the rocks lie practically horizontal than in adjacent regions where the rocks are more highly inclined.

Three topographic types are well represented in the Keweenawan division of the Algonkian, where they seem to form a distinctly graded series (fig. 7) rather directly associated with the

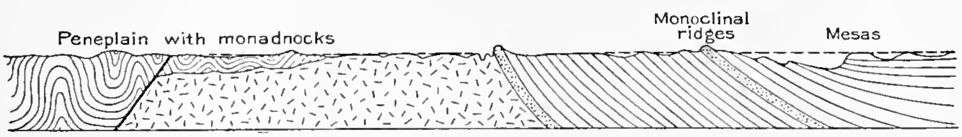

FIGURE 7.—Hypothetical cross section showing relation of secondary lowlands, mesas, monoclinal ridges, etc., to peneplain.

dip of the constituent beds.[f] In exactly the same length of time precisely the same erosional agencies have been able to produce almost no effect upon the vertical and highly inclined beds (merely cutting gorges in the peneplain), to develop longitudinal valleys between monoclinal

[a] Geology of the area covered by the Seine River and Lake Shebandowan map-sheets, comprising portions of the Rainy River and Thunder Bay districts of Ontario: Geol. Survey Canada, new ser., vol. 10, 1897, Rept. H, p. 6.

[b] Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1891, pp. 265–266.

[c] Minor faults extending in another direction with smaller possible fault escarpments are described by R. C. Allen in an unpublished thesis (1905) of the University of Wisconsin. Allen also appeals to faulting to explain the Mackenzie Valley (Pl. XIII), the depression which nearly connects Thunder and Black bays and is followed by the Canadian Pacific Railway; the writer believes it to be due to normal denudation.

[d] Collins, W. H., Summary Rept., Geol. Survey Canada, 1906, pp. 103, 105; Coleman, A. P., Rept. Bur. Mines, Ontario, vol. 16, pt. 1, 1907, pp. 107, 110.

[e] The laccolithic sills of the northwest coast of Lake Superior: Bull. Geol. and Nat. Hist. Survey Minnesota No. 8, 1893, pp. 24, 43.

[f] Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 142–143, 166.

ridges on the gently inclined beds, and to advance the region where the beds are horizontal to a maturity of form with broad valleys and small isolated uplands (mesas).

HURONIAN MONOCLINAL RIDGES AND VALLEYS.

Monoclinal ridges, however, are not confined to the Keweenawan series of the Algonkian. In a number of localities in the Huronian, diabases, quartzites, and other strata with a moderately gentle dip have developed monoclinal ridges which have the usual unsymmetrical profile with a gentle slope and a steep scarp face. (See fig. 5, p. 88.)

GUNFLINT LAKE DISTRICT.

Near Gunflint Lake and in adjacent regions of Minnesota monoclinal-ridge topography, described by U. S. Grant,[a] is developed in the upper Huronian. The slates of the Animikie group are intruded by the Keweenawan Logan sills, which are now gently tilted and exposed, forming the crests of monoclinal ridges (fig. 24) whose scarp faces show the weaker slates. These consist of "long parallel ridges running approximately east and west, with sharp mural escarpments on the north sides of the ridges and on the south gentle slopes." This topography is also described by J. M. Clements,[b] in effect as follows:

Upper Huronian (Animikie group):

Gunflint formation: Lower slope of escarpments in monoclinal ridges.

Rove slate: Weak lower slope of monoclinal ridges, in many places talus-covered.

Keweenawan Logan sills: Usually cap monoclinal ridges, at many points forming perpendicular cliffs, above gentler talus-covered slopes of Gunflint formation or Rove slate.

In this region, as in many parts of the Huronian where notably long and narrow monoclinal ridges are formed, the drainage, whatever it may have been initially, has become so thoroughly adjusted to the topography that the streams flow in longitudinal (subsequent) courses along the strike of the weaker rocks, generally with rather broad valleys. In nearly all places where the streams cross the ridges of more resistant rocks they are in much steeper-sided valleys.

PENOKEE RANGE.[c]

In the Penokee-Gogebic iron range the hills show this topographic quality most distinctly. (See structure profile, Pl. XVI, p. 226.) The Penokee Range consists of a series of hills, in the north slopes of which are iron mines. North of this range there is a broad longitudinal valley. The range is not made up of one continuous ridge but rather of a series of disconnected linear highlands (Pl. XVI) cut through by narrow gaps which cross the strike of the more resistant beds, including the iron formation, and are therefore not so wide as the subsequent valley, which follows the strike of the weaker slates. The northern boundary of the valley is a range of Keweenawan hills with well-developed monoclinal ridges, which are also cut through by narrow transverse valleys that continue northward toward Lake Superior. The narrow transverse valleys are probably consequent upon the original slope. The broad longitudinal valley is a consequent lowland, though not yet drained by any single trunk stream.

South of this principal longitudinal valley another lowland seems to be developing in places; it stands at a rather higher level than the northern one and is less continuous from end to end, because interrupted by low ridges, which extend back from many of the higher hills in the Penokee Range proper. It is a subsequent lowland in process of formation between the resistant granite and the resistant rocks of the Penokee Range. South of this incipient valley rises the northern edge of the Archean peneplain, with rather ragged hills of granite, which in many places reach directly to the foot of the Penokee Range without any intervening lowland.

R. D. Irving[d] first described the topography of the Penokee Range, "the ridge or mountain belt," as well as that of the Copper Range to the north. The former rises to about 1,500 to

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[a] Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, 1899, pp. 482–483, 492, 496.

[b] Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 38, 376, 391–392, 399–401.

[c] See also the brief statement about topography in the chapters on the Penokee-Gogebic district.

[d] Geology of Wisconsin, vol. 3, 1873–1879, pp. 62–70, 101–103.

1,800 feet, 100 to 300 feet above the lower land to the south, with a less abrupt north slope, varying from a ridge a few rods wide to a broad swell of a mile. It is a continuous ridge for nearly 50 miles from the northern half of sec. 24, T. 44 N., R. 4 W., Wisconsin, eastward beyond Sunday Lake in Michigan.[a] Beside this there are detached ridges with the same alignment to the west and to the east.

In places the ridge rises from 100 to 300 feet above the elevated swampy area south of it and from 100 to 600 feet above the lower area north. In its more western portions this range is wide and has a rather narrow serrated crest, while eastward from Tylers Fork it becomes more and more of a gentle swell until a point west of Sunday Lake is reached, where there is again a broader ridge. In much of this distance the ridge forms the most prominent feature of the topography of the country, being visible from the waters of Lake Superior in the vicinity of the Apostle Islands as a blue line against the horizon.

At Penokee Gap, where there is a notable fault, there is also a marked offset in the crest of the range[b] (Pl. XVI).

Irving and Van Hise[c] have described the detailed topography associated with the various Algonkian rocks in the Penokee-Gogebic district in effect as follows, also reviewing in a paragraph the relationship of the various formations to the crest, slopes, etc., of the ridge in various localities and showing the topography by three detailed topographic maps.[d] (These contours are used in Pl. XVI of this report.)

Cherty limestone: In one place forming a bluff 200 feet high and half a mile long.

Quartz slate member: Conspicuous outcrops forming the base or capping the Penokee Range.

Iron-bearing member: Shares with quartz slate member in forming crest of conspicuous Penokee Range, 100 to 600 feet high.

Upper slate member: Forms great east-west valley between Penokee Range and Keweenawan ridges.

Fragmental rocks south of greenstone conglomerate: Quartzite outcrops in bold exposures.

The greenstones: Form a conspicuous east-west ridge 500 feet high.

GIANTS RANGE.[e]

The Giants Range[f] (see Pl. VIII, in pocket; fig. 5, p. 88) is one of the most striking features in the topography of the Lake Superior region. It is a long, narrow range extending east-northeast and west-southwest in northern Minnesota for 80 to 100 miles, conspicuous because it rises above low, flat country on either side. It rises 400 to 500 feet above the adjacent country near the east end, the greatest height above sea level being about 1,900 feet. West of the Duluth and Iron Range Railroad the range gradually decreases in height toward the southwest, and near Grand Rapids, Minn., where it crosses Mississippi River, its height above the adjacent country is relatively small. Beyond Pokegama Lake the Giants Range loses its individuality and is completely buried beneath glacial drift, grading into the general level of the country at 1,400 feet. It is not a continuous range but is "made up of a great number of small hill ranges, having in general the trend of the main range to which they belong."[g] The west part is low and the divide at some places is on the quartzite[h] instead of the granite. There are many gentle bends in the crest and one marked bend where the range extends southward 6 miles, at Virginia and Eveleth in the "Horn."

The crest of the range is in places broad and flat, in others comparatively narrow and sharp. The southern slope is very gentle; the northern slope is somewhat less so. At frequent intervals both crests and slopes are notched by drainage channels.[i]

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of northern Wisconsin and Michigan: Mon. U. S. Geol. Survey, vol. 19, 1892, p. 188.

[b] Irving, R. D., Geology of Wisconsin, vol. 3, 1873–1879, pp. 103–104.

[c] Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 145, 188–189, 301, 361, 368, 374, 387, and 410.

[d] Idem, Pls. VII, IX, and XI.

[e] See also the brief description of the topography in the chapter on the Mesabi district.

[f] Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, Pls. LXX–LXXXI; also Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 35–36; also Mon. U. S. Geol. Survey, vol. 43, 1903, p. 21. The Giants (or Mesabi) Range is called Missabay Heights in many atlases and geographies in America and Europe. See footnote on p. 92.

[g] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, p. 36.

[h] Spurr, J. E., The iron-bearing rocks of the Mesabi range: Bull. Geol. and Nat. Hist. Survey Minnesota No. 10, 1894, p. 13.

[i] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, p. 21.

Several stream valleys cut completely across the Giants Range in deep, narrow gorges or water gaps, that of the Mississippi being relatively shallow. Of the deeper water gaps, that occupied by Wine Lake and Embarrass River is the most prominent. Another transverse valley, not occupied by a stream, is traversed by the Duluth and Iron Range Railroad; this col or wind gap is 100 feet above the adjacent country and 260 feet below the crest of the Giants Range. There are a number of similar wind gaps, each of which was doubtless formed by a stream that abandoned its course while the land surface to the north stood at the level of the gap, having been captured by an adjacent stream that continued to cut its water gap down. The water gaps which cross the range are much deeper than the wind gaps, that of Embarrass River (Wine Lake) being cut down to an elevation of 1,380 feet, or more than 400 feet below the crest of the range; soundings in the lake and diamond-drill records to the south show the valley to be many feet deeper.

C. K. Leith[a] has described several of the transverse valleys as deep, steep-sided gorges, cut or deepened by glacial waters when a glacial lake to the north overflowed southward across the Giants Range. Some of the gorges are high up in the range and are no longer occupied by streams. One such gorge 40 feet deep is shown on a topographic map (fig. 5) in Monograph 43; that crossed by the railway is well shown on the general topographic and geologic map of the Mesabi district (Pl. VIII). It seems possible that these gaps or cols were already in existence when the glacial streams found and modified them in the manner described by Leith. The lower wind gaps, especially that followed by the Duluth and Iron Range Railroad, suggest a preglacial origin; no question is raised, however, of their occupation and modification by running water when the marginal glacial lakes referred to existed.

The rock underlying the Giants Range itself is chiefly lower Huronian granite, but Keweenawan granite and Archean igneous rocks are also represented. The topographic anomaly of an exceedingly long, narrow range (figs. 4 and 5) owing its prominence to the resistant qualities of granite is so great that it seems to require a word of especial explanation. It is common for a quartzite or other sedimentary rock to form a long, narrow range of just this kind. It is usual for the protruding edge of a dike or a sill of sufficient resistance to form just such a long, narrow eminence as this. Granite, however, is not normally intruded in the form of dikes and sills, and we must therefore account for this occurrence by some selective process of folding, faulting, or erosion.

Three hypotheses accordingly present themselves. The first is that of folding. Under this hypothesis it might be conceived that the Giants Range since its intrusion has participated in the folding of a long east-northeast to west-southwest anticline. Such a deformation might result in the production of a long, narrow ridge. In the front ranges of the Rocky Mountains granites outcrop in long, narrow bands, none of which, however, is so narrow in proportion to length as the Giants Range. Moreover, there is no evidence in the Mesabi region of any such movement, though N. H. Winchell has conceived[b] that the Giants Range was uplifted in a contemporaneous isostatic adjustment with the extrusion of the gabbro, and R. D. Irving implies this sort of origin in his diagram[c] of the relationship of the Huronian on opposite sides of the Giants Range. The implied equivalence of highly folded and nearly horizontal rocks on opposite sides of the range has since been disproved by the well-established unconformity between these two series.

The second hypothesis supposes that faulting has occurred along a line parallel to the Giants Range and that the granite appears in its present position as the edge of a larger faulted granite block which is exposed only along the narrow width because other rocks overlie the granite elsewhere. This hypothesis has little more support than the first, and it seems probable from other evidence in the region that no great fault movement such as would form the Giants Range occurred since the upper Huronian, though the Duluth escarpment of Keweenawan gabbro suggests such a faulting.

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[a] Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 193–194, 199.

[b] Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1891, pp. 120–121.

[c] Mon. U. S. Geol. Survey, vol. 5, 1883, fig. 34, p. 399.

The third hypothesis supposes that the granite is the outcropping edge of a great intruded granite mass, exposed for a great distance east and west by erosion upon the granite as a retreating escarpment, and revealed for only a narrow width because it is, or has recently been, capped and protected by a resistant bed of quartzite. In other words, the Giants Range may be regarded as a monoclinal ridge exactly similar in most respects to the other monoclinal ridges of the Algonkian, but with an immensely greater length and a rather marked relief above the adjacent region because of the resistant powers of the granite, giving the Giants Range its present topographic prominence.

The Giants Range is the largest monadnock in the Lake Superior region. It is such a barrier to traffic that travel across it is limited to the valleys (Pl. VIII, in pocket). Rather curiously, the railway, in order to cross this range, selected not a water gap but a wind gap, because the glacier and stream erosion in the lower part of the adjacent water gap (the valley of Embarrass River and Wine Lake) has so deepened it and so steepened its sides that it is not a convenient pass for either a highway or a railroad.

Upon the south slopes of the Giants Range—that is, in the Mesabi iron range—the minor monoclinal-ridge topography is exceedingly well developed in one or two places, and it is suspected that even better development would be apparent in places were it not for the thick drift mantle nearly everywhere obscuring the preglacial topography. Northwest of Hibbing, for example, the Pokegama quartzite stands up as a distinct monoclinal ridge, with a lowland to the north between the quartzite escarpment and the granite and a gentler slope southward toward the iron mines. The topographic map shows this relationship in many places not visited by the writer. Rarely in other parts of the Mesabi iron range the quartzite seems to be weaker than the iron-bearing Biwabik formation, forming a lowland between the older rocks and an iron-formation ridge. In the 1,820-foot hill between Virginia and Eveleth, on the west side of the Horn (Pl. VIII), there is a quartzite lowland of this sort with an escarpment and monoclinal ridge of a resistant part of the iron formation, though the quartzite rises up to form the base of this escarpment. There are other iron-formation ridges on the east side of the Horn and elsewhere.

MARQUETTE DISTRICT.

In the Marquette district also linear topography is developed (Pl. XVII, in pocket) in the area underlain by the Algonkian rocks, though before detailed studies were made it was said to have a notably hilly surface without obvious systematic relation to the structure.[a] The relief was said by Rominger to be comparatively slight, 50 to 100 feet and rarely 200 feet,[b] though the recent topographic maps show greater extremes and an average relief of 200 to 400 feet. Upon the basis of the more detailed work the topography characteristic of the several Algonkian formations in the Marquette district has been described by Van Hise and Bayley,[c] detailed studies revealing a most faithful correspondence of the low hills and valleys to resistant and weak beds. Van Hise and Bayley[d] characterize the region as worn down from mountains but now "merely bluffy," with maximum elevations of 400 feet or less, the valleys and ridges being due to differential erosion of weak and resistant beds. The following classification of the topography and rock formations gives the substance of their descriptions:

Mesnard quartzite: Prominent ranges with minor sharp ravines and steep ridges.
Kona dolomite: Steep hills with vertical ragged cliffs.
Wewe slate: Forms valleys, except in a few places.
Ajibik quartzite: Bold ridges with precipitous bluffs and steep ravines. Some ridges 200 feet high.
Siamo slate: Prevailingly forms valleys.
Negaunee formation: Forms valleys, except locally.

[a] Brooks, T. B., Geol. Survey Michigan, vol. 1, 1873, pp. 70-72.
[b] Rominger, Carl, Geol. Survey Michigan, vol. 4, 1881, pp. 1-3.
[c] The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1895, pp. 222, 241, 257, 283-284,314, 331-332, 410, 417, 444-445, 461, 488-489, 499, 572-573; also in Fifteenth Ann. Rept. U. S. Geol. Survey, 1895.
[d] Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 644-645.

Ishpeming formation:
  Goodrich quartzite: In some places forms prominent range.
  Bijiki schist: Conspicuous ridges and headlands in Lake Michigamme.
Michigamme formation: Usually lowlands, except locally.
Clarksburg formation: Rounded knobs and narrow ridges.
Pre-Clarksburg greenstones: Prominent irregular knobs or long narrow ridges.

In the Republic trough the topography of the Archean uplands, as briefly described by H. L. Smyth,[a] shows characteristic granite knobs, rounded and glaciated; Michigamme River flows through the lower land underlain by the bedded rocks (Algonkian), and the various quartzites, mica schists, ferruginous schists, and igneous intrusives form the usual elevations and depressions, nowhere rising to the height of the granite uplands on the east and west except in Republic Mountain.

So many of the ridges are related to resistant beds and so many valleys to weak beds that the character of the rocks may be predicted with some assurance from the general form of topography. Local variations, however, make it impossible always to feel sure, for example, that the same weak slate which in one place forms a valley will also be found in the lowland in an adjacent locality. An exception of this kind is found in the Siamo slate of the middle Huronian, whose outcrop east of Teal Lake, near Negaunee, is marked by a very distinct east-west trending valley, which is followed farther east by Carp River. Directly south and west of Teal Lake, however, some more resistant members of the Siamo slate are found in the Siamo Hills and adjacent ridges, and for the next 10 or 12 miles westward the Siamo slate locally forms ridges, though more commonly found in the valleys.

Just south of Negaunee and east of Ishpeming there is a series of rather abrupt knobs which are not exactly of the class characteristic of this region. A number of diorite and diabase masses intruded in the middle Huronian iron formation have been so resistant to erosion that many of them form knobs which rise above the adjacent valleys. At near-by points, however, the iron formation itself is so resistant that it stands up as a distinct knob or ridge.

In this region the glacial deposits have not masked the preglacial topography to a great degree, because the region seems to have had rather marked relief in preglacial times, somewhat in contrast with the Crystal Falls district. Immediately adjacent to the Marquette district on the east and south are lowlands where the lack of relief in glacial time is indirectly reflected by the masking of the bed-rock topography almost entirely by glacial deposits.

MENOMINEE DISTRICT.

The topography of the Menominee district has been described by Bayley,[b] who speaks of the area as forming two plains (Pl. XXVI, in pocket), one in the bottoms of the present valleys, the other on the level of the tops of the hills. The effect of erosion on the Huronian beds of the Algonkian system has been to produce a series of east-west trending valleys and ridges which correspond very closely to the weak and resistant members of the Huronian series. There is clear evidence that the ridges and valleys in the Menominee district east of Iron Mountain, Mich., were formed in pre-Cambrian time and that they have been preserved since that time because of their burial beneath the Cambrian sandstone, which served as a protecting mantle. Erosion has recently removed most of these Cambrian overburdens and has reexposed the pre-Cambrian topography. To-day the hills rise approximately 300 to 400 feet above the valley bottoms. They are a little higher than they were before the Upper Cambrian sandstone was deposited, because a cap of sandstone still surmounts most of the hilltops. From the valleys it has been largely removed. The old cliffs and bluffs against which the Cambrian sandstone was deposited are still exposed in the valley slopes; the drainage was in preglacial time almost as well adjusted to the weak and resistant rocks as it had been before the Cambrian transgression, though Bayley has supposed the topography then to have been sharper and more rugged. Glaciation has, however, somewhat modified the stream courses, and the perfect adjustment of preglacial time is lacking, as the gorges and waterfalls suggest:

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[a] Mon. U. S. Geol. Survey, vol. 28, 1895, p. 526.
[b] Idem, vol. 46, 1904, pp. 125-129; Menominee special folio (No. 62), Geol. Atlas U. S., U. S. Geol. Survey, 1900.

Bayley[a] has described the topography associated with the various Algonkian rock formations in the Menominee district in effect as follows:

Sturgeon quartzite: Great bare regular bluffs with smooth tops and almost precipitous sides.

Randville dolomite (northern belt): Valleys and other depressions.

Randville dolomite (central belt): Usually insignificant, forming bases of hills and rarely little plateaus with small escarpments.

Randville dolomite (southern belt): Conspicuous irregular cliffs or bluffs.

Vulcan iron formation: Either inconspicuous in valleys or clinging to slopes of dolomite. Ledges rarely prominent.

Hanbury slate: Entirely confined to low ground, forming minor protrusions only where the slate is locally harder.

CRYSTAL FALLS DISTRICT.

In the Crystal Falls district, whose physiography has been described by J. M. Clements and H. L. Smyth,[b] the adjustment of ridges and valleys to resistant and weaker structures has been somewhat similarly developed (Pl. XXII, in pocket), except that here the ridges and valleys are arranged in a less simple and orderly way. The average relief is 200 feet in the western part. The Cambrian has been almost entirely removed. Furthermore, this region seems to have been, even in pre-Cambrian time, one of less relief than the Menominee region; certainly it was a region of very slight relief (called by Clements "an approximate peneplain") when the continental glacier overrode it, and as a result the glacial deposits are far more prominent and have more thoroughly obscured the preglacial topography than in any other iron district in the Lake Superior region except the Mesabi.

The topography characteristic of the several Algonkian formations in the Crystal Falls district has been described by J. M. Clements, H. L. Smyth, and W. S. Bayley,[c] in effect as follows:

Western part.

Randville dolomite: No marked effect on topography or drainage (in depressions).

Mansfield slate: Marked depressions, followed by Michigamme River.

Hemlock formation: Exceedingly irregular topography; tuffs forming valleys; lava flows or intrusives forming higher ground, and resistant tuffs forming high hills.

Bone Lake crystalline schists: Apparently forms knobs, but usually covered by glacial drift.

Upper Huronian: In many places covered by glacial drift or by Cambrian sandstone. Shales form valleys and softly rounded hills. Graywackes and cherty rocks form more striking topography.

Eastern part—Felch Mountain.

Sturgeon quartzite: Linear ridges, usually lower than those in the Archean, though locally lower than dolomite.

Randville dolomite: Low, steep-sided knolls, occasionally linear ridges.

Mansfield schist: No depressions; occasionally steep-sided valleys.

Groveland formation: Moderately resistant, forming elevations such as Felch Mountain and Groveland Hill, 100 feet high.

Upper Huronian mica schists and quartzites: Lowlands and low flat-topped ridges.

Eastern part—Michigamme Mountain and Fence River.

Sturgeon formation: Apparently here weak and forming lowlands; Randville dolomite underlying swamp.

Mansfield formation: Indistinguishable topographically in gently rolling plain of dolomite (miniature ridges).

Hemlock formation: Rough topographical details, with abrupt ridges and narrow ravines (in some parts till covered).

Groveland formation: No topographic prominence except in Michigamme Mountain; in Fence River area topography less important than that of glacial drift.

NORTH-CENTRAL WISCONSIN.

Weidman[d] has described the topography associated with the various Algonkian formations in north-central Wisconsin (see Pls. IV, *A*, p. 90; XXXI, *A*, p. 436) in effect as follows:

[a] Mon. U. S. Geol. Survey, vol. 46, 1904, pp. 177, 200, 291, 462.

[b] Idem, vol. 36, 1899, pp. 29–36, 331–335.

[c] Idem, vol. 36, 1899 (western, pp. 50–51, 54, 73, 148, 155, 187–190; eastern, pp. 331, 398, 406, 411, 415, 423, 430, 431, 438, 440, 446, 471–473).

[d] Bull. Geol. and Nat. Hist. Survey Wisconsin No. 16, 1907, pp. 42, 55, 62, 82, 88, 91, 100, 112, 118, 177, 358, 366, 371.

Lower sedimentary series (lower Huronian?).

Rib Hill quartzite: Bold knobs forming the highest land in the region in monadnocks, and prominent because surrounding weaker granite and syenite are base-leveled.

Wausau graywacke: Not prominent, forming very few low exposures.

Hamburg slate: Not forming valleys lower than adjacent more resistant formations because of lack of dissection of perfected peneplain.

Powers Bluff quartzite: Forms notable prominence 300 to 400 feet below surroundings; smaller ridges.

Quartzite at Rudolph: Low ridges and knobs.

Junction City quartzite: No notable topography.

Igneous intrusive formations (rhyolite series).

Wausau area: Absence of sharply rugged topography, though low ledges project slightly through younger formations.

Rhyolite schists of Eau Claire River: Forms striking cliffs in dells of Eau Claire River, due to joints.

Rhyolite schists of Pine River: Marked gorge, a mile long, 100 feet deep, known as dells of Pine River, with sharp tributary gorges related to joints.

Upper sedimentary series (middle Huronian?).

Marshall Hill graywacke: Steep slopes and ledges.

Arpin quartzite: Low sloping land; less resistant than Powers Bluff quartzite and more resistant than adjacent granite.

North Mound quartzite: Prominent mound rising above surrounding Cambrian lowland.

NORTHWESTERN WISCONSIN.

The Huronian quartzites of Barron and Chippewa counties, Wis.,[a] form notably prominent monoclinal ridges rising as much as 300 feet above the adjacent plain and having gentle dip slopes and steep escarpment faces with talus at the base.

THE LOWLAND PLAINS.

AREA.

The lowland region of horizontal or gently folded post-Algonkian rocks (figs. 4 and 5, pp. 87, 88, Pls. I, in pocket; II, p. 86) includes chiefly rocks of Cambrian and other early Paleozoic age so generally buried beneath glacial deposits that ledges are comparatively rare throughout the area and the preglacial topography is partly or wholly masked. A small area of drift-covered Cretaceous, also flat lying, is found in northern Minnesota.

The lowland is made up of narrow areas on the south shore of Lake Superior, a broad belted plain in Michigan, Minnesota, and Wisconsin, and another plain in Minnesota. As the map (Pl. I) indicates, there is a narrow strip at the west end of Lake Superior, on the south shore, and a narrow strip fringing the shore from L'Anse to Marquette. Besides this rather small littoral zone, a considerable area now buried by the waters of Lake Superior is, without much doubt, covered by horizontal Paleozoic rocks.

These early Paleozoic rocks cover all of the Upper Peninsula of Michigan east of Marquette and overlap the highland country of northern Wisconsin and upper Michigan, including the Archean and Algonkian areas, in a great semicircle which extends southwestward into Wisconsin to the vicinity of Grand Rapids and thence northwestward through Chippewa Falls, etc., to the region where the Paleozoic overlaps the Keweenawan of northern Wisconsin and sends a narrow tongue northeastward to join the horizontal Cambrian of the head of Lake Superior at Duluth. Very small patches are found on the north shore of Lake Superior.

CHARACTER AND STRUCTURE.

These early Paleozoic rocks consist chiefly of Upper Cambrian sandstone overlain in places by a conformable or nearly conformable series which extends upward to the Silurian in Wisconsin and to Devonian and Carboniferous in lower Michigan. North of the Archean and

[a] Geology of Wisconsin, vol. 4, 1873-1879, pp. 575-581.

Algonkian of upper Wisconsin and Michigan this Cambrian sandstone (Lake Superior sandstone) lies essentially horizontal and is probably preserved because it is downfaulted. In upper and lower Michigan, in Wisconsin, and in Minnesota, however, there is evidence that the sedimentary rocks have been thrown into a series of broad folds—a synclinal basin in Michigan and a broad anticline in south-central Wisconsin. The Cretaceous in northern Minnesota is essentially horizontal.

DENUDATION.

Earth movements have left some areas of Paleozoic rocks higher than others, and as a result of the elevation and inclination of these beds eroding agencies have removed them entirely from some areas, the boundaries of which have a direct relation to the broad folding. The upper beds of the Paleozoic are almost entirely absent in northern and central Wisconsin and northwestern Michigan (fig. 11, p. 116), from which it is inferred that, though they were once present over the whole of this area, they have since been removed by the active erosion which has taken place in this elevated region. As an evidence of the former greater distribution of the Paleozoic sediments we may refer to the isolated horizontal Cambrian beds that cap the ridges in the Menominee district east of Iron Mountain, Mich. (Pl. XXVI, in pocket), and various outliers of Cambrian age, which form mounds rising above the general peneplain level in Portage, Wood, and Clark counties, Wis.,[a] far north of the area of Cambrian rocks. Quite in contrast to these mounds of the border zone between the Paleozoic and pre-Cambrian in Wisconsin are the knobs of the older rocks which project through the thin Paleozoic edge. The knobs are inliers; the mounds are outliers. Chamberlin[b] refers briefly to such knobs that protrude through the Cambrian in northeastern Wisconsin. The Baraboo quartzite ridges and those at Necedah, Waterloo, etc. (figs. 53, 54, and 55, pp. 359, 360, 364), are features of the same sort. Because of their conspicuous positions as monadnocks on the pre-Cambrian peneplain they have been the first of the older rocks to emerge when the Paleozoic sediments which formerly covered their tops were eroded.

THE BELTED PLAIN.

The distribution of the Paleozoic sediments in a broad semicircle on the south flank of the Archean peneplain is to be explained, therefore, as a result of erosion after unequal uplift.[c] The lowest bed, the Cambrian sandstone, is distributed in a curving lowland belt around the Archean (Pl. I, in pocket), with outliers scattered far back upon the Archean surface, and the overlying Paleozoic formations are distributed in parallel curving belts, the more resistant beds standing up as highlands, the weaker beds being worn down into lowlands. A linear series of minor highlands underlain by the "Lower Magnesian" limestone stretches southwestward in Michigan and eastern Wisconsin (Pl. I), and thence northwestward in central and western Wisconsin. South and east of this is a broad valley which has been eroded upon the weaker members of the Ordovician, especially the Upper Ordovician (Cincinnatian) shales and parts of the Galena and Trenton limestones. The waters of Green Bay have filled part of this great lowland valley, which extends southward, including the broad, shallow depression containing Lake Winnebago (Pl. II, p. 86). East of this valley there is a long, low monoclinal ridge, which was produced by the effects of erosion on the resistant eastward-dipping Niagara limestone, and which has a steep scarp face on the northwest side and a gently dipping back slope toward Lake Michigan, diversified by minor monoclinal ridges due to weak and resistant members of the Niagara. It is overlain by glacial and lake deposits. It forms an upland ridge (fig. 5, p. 88) east of Lake Winnebago and extends north in the Door Peninsula, Washington and adjacent islands of Wisconsin, and the Garden Peninsula of upper Michigan; the scarp continues first northeast, then south as the Niagara escarpment of Georgian Bay, southern Ontario, and northern New York. East of this ridge is the lowland of weak rock in which Lake Michigan ies and the upland of the northern part of lower Michigan.

[a] Weidman, Samuel, Bull. Geol. and Nat. Hist. Survey Wisconsin No. 16, 1907, pp. 400, 405-407.
[b] Geology of Wisconsin, vol. 2, 1873-1877, p. 248.
[c] Idem, vol. 1, 1873-1879, pp. 248-252.

The topography in the part of western Wisconsin included in this report is described by Moses Strong,[a] that in central Wisconsin by R. D. Irving,[b] and that in eastern Wisconsin by T. C. Chamberlin.[c] The physiography of Wisconsin as a whole is briefly treated by G. L. Collie.[d]

Russell [e] has shown that in the greater part of the northern peninsula of Michigan the wearing down of the gently inclined Paleozoic rocks has resulted in belts of upland and lowland of a sufficient degree of relief to be apparent beneath the glacial deposits. The topography of this region was described previously in a more general way by Douglass Houghton [f] and by Brooks.[g]

The portion of the southern peninsula of Michigan here mapped as within the Lake Superior region has been described by Rominger [h] and by Lane.[i]

The arrangement of the gently inclined Paleozoic rocks in curving zones has led W. M. Davis to describe Wisconsin as an ancient coastal plain, referring to the peneplained Archean area of northern Wisconsin as an oldland, the area underlain by Cambrian sandstone as an inner lowland, with a first and a second cuesta (monoclinal ridge) extending around its margin along the outcrop of the "Lower Magnesian" and the Niagara limestones respectively.[j] Objection has been raised to the use of the term "ancient coastal plain" on the ground that the upland area of northern Wisconsin is not known to be the old land from which the local Paleozoic sediments were derived. Though it is hence not permissible to classify Wisconsin as an ancient coastal plain, there is good warrant for describing these parts of Wisconsin and Michigan as a belted plain (fig. 5, p. 88; fig. 11, p. 116) with upland and lowland zones systematically related to the weak and resistant rocks.

THE MINNESOTA LOWLANDS.

In the western part of the Lake Superior region, extending into the valleys of Red River of the North and Mississippi River, is a great lowland region, which seems to have been reduced to a peneplain in Mesozoic time, perhaps in the Cretaceous.[k] The Cretaceous peneplain extends into the Lake Superior region from the west and southwest and Cretaceous sediments overlap all the westward extension of the Giants Range. Just what this distribution of the Cretaceous may mean can not be said at present; but it seems probable either that sedimentation did not take place in the Lake Superior basin during the Cretaceous or else that while the Cretaceous base-leveling was going on over a great part of the United States the great mass of Paleozoic and perhaps later sediments were being removed from the basin of Lake Superior and the adjacent highlands, perhaps uncovering the several great escarpments presently to be described and producing the several lowland belts adjacent to Lake Superior and the Paleozoic areas to the south.

THE BASIN OF LAKE SUPERIOR.

GENERAL CHARACTER AND ORIGIN.

The basin (Pl. II) which contains the largest of the North American lakes probably includes parts of every system of rocks known to be in the region, from the Archean to the Recent. It is not known whether Paleozoic or Keweenawan rocks occupy the greater part of the basin.

The Lake Superior basin is exceptional in that it is nearly surrounded by highlands. Going back from Lake Superior in any direction except the southeast, one soon comes to an escarpment, as at Duluth or on the south shore, above which is a distinct upland which overlooks the lake basin. In some places this escarpment overlooks the waters of the lake directly (Pl. V); in others it is some distance back (Pl. II and figs. 4 and 5). Moreover, this escarpment (400 to 800 feet in height) at many points descends into very deep water (500 to 900 feet), so that the

[a] Geology of Wisconsin, vol. 4, 1873-1879, pp. 7-37.
[b] Idem, vol. 2, 1873-1877, pp. 453-455, 533, 548.
[c] Idem, pp. 97-106.
[d] Bull. Am. Bur. Geography, vol. 2, 1901, pp. 270-287.
[e] Ann. Rept. Geol. Survey Michigan for 1904, pp. 52-56.
[f] Geol. Survey Michigan, vol. 2, 1873, p. 241.
[g] Idem, vol. 1, 1873, pp. 68-69.
[h] Idem, vol. 3, 1876, pp. 1-20.
[i] Water-Supply Paper U. S. Geol. Survey No. 30, 1899, pp. 57-58, 90-91.
[j] Davis, W. M., Physical geography, 1898, pp. 136-137, fig. 85.
[k] Leith, C. K., Econ. Geology, vol. 2, 1907, p. 149.

whole height of the surrounding rim is not everywhere apparent. Some of the other Great Lakes have such a boundary on one side, but none is so nearly walled in as Lake Superior.

As the submerged contours (Pl. II) show, this basin has a depth of almost 1,000 feet, the deepest sounding being 163 fathoms, or 978 feet, near latitude 87° W., longitude 47° 45′ N., or nearly 400 feet below sea level, without considering the possible filling of recent lake silts or glacial deposits. There is a notable depression between the pre-Cambrian of northern Wisconsin and the pre-Cambrian of Minnesota and Canada. This depression consists of a long, narrow trough trending northeast and southwest and limited on the north by the great escarpment which extends from Duluth northeastward to the mouth of Nipigon Bay, a distance of 250 miles. This trough is 25 to 70 miles wide. Its southern boundary is Keweenaw Point and the Michigan and Wisconsin shore; at Oronto Bay, east of Ashland, there is an angular offset in passing the Apostle Islands, diminishing the width of the lake by half. Thence the wall of the depression goes on parallel to and near the Wisconsin shore, the fault line converging westward toward the Duluth escarpment fault line, probably meeting it west of the head of the lakes in Minnesota.

From the mouth of Nipigon Bay the border of the Lake Superior depression extends southeastward to Sault Ste. Marie as a high wall or escarpment of unknown origin. Here it is not a straight line but has great embayments and salients. On the south shore a fault escarpment extends southward on the east side of Keweenaw Point. The highland border thence trends irregularly southeastward to the vicinity of Marquette, beyond which it extends south and a little west of south into Wisconsin. The area between Marquette and Sault Ste. Marie on the south shore is lowland.

The North American Great Lakes are situated in pairs on either side of an escarpment which faces the boundary between the resistant pre-Cambrian and the relatively weak Paleozoic rocks. In this respect they resemble the great lakes of the pre-Cambrian area of northwestern Europe. An escarpment thus situated and formed is called by Suess a glint line. Lake Superior, however, should not be included among the glint lakes, where it is classified by Suess,[a] together with Lake Ontario, Georgian Bay, Lake Winnipeg, etc. The southeastern part of Lake Superior might be considered a glint lake because it has one early Paleozoic and one Archean shore, as was pointed out by Agassiz,[b] if it were not known on other evidence to be chiefly a structural basin.

In the origin of its basin, also, Lake Superior is exceptional. The other great lakes, four to the east in the United States and four to the north in Canada, lie in lowland areas where differential erosion acting upon alternate weak and resistant beds would produce basins if aided by glacial erosion, glacial clogging, etc., though some of the basins are possibly also in part structural. Lake Michigan, for example, lies between the broad, anticlinal, southward-pitching fold of central Wisconsin and the basin-like syncline of central Michigan, its location suggesting a partly structural basin, as does also the known warping in the basins of the other great lakes, though the structural feature is certainly of minor importance. The correspondence of the Lake Michigan lowland with a belt of weak strata (Silurian and Devonian), perhaps somewhat deepened by glacial erosion,[c] is probably of principal importance.

The reason for the present depression of the Lake Superior basin is somewhat doubtful, the earliest explanations being regarded as inadequate to account for certain features of it. The fact that it is a syncline (see structure section, Pl. I, in pocket), first pointed out by Foster and Whitney[d] and amplified by Irving,[e] has never been called in doubt, for there is ample proof of it. But for so old a structural basin to remain unfilled[f] and for it to retain abrupt boundaries which bear all the characteristics of youth are departures from the normal condition which require special explanation.

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[a] Suess, Eduard, The face of the earth (Das Antlitz der Erde), translated by H. B. C. and W. J. Sollas, vol. 2, Oxford, 1906, p. 65.
[b] Lake Superior, etc., 1850, p. 420.
[c] Chamberlin, T. C., Geology of Wisconsin, vol. 1, 1873–1879, pp. 253–259.
[d] Report on the Lake Superior land district, pt. 1, 1850, p. 109.
[e] Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 410–418.
[f] Barrell (Jour. Geology, vol. 14, 1906, p. 335) has computed that it would take Mississippi River only 66,000 years to completely fill Lake Superior if it flowed into that water body with its present volume and load.

The hypothesis that the present Lake Superior basin exists because of a geosyncline, as first stated, needs to be modified, therefore, by consideration of the possibility of graben or rift faulting. The amplification of this revised hypothesis and its verification in detail remain for future work. The possibility, however, seems worth outlining here.

It is thought reasonable to suppose that after the late Algonkian deformation, whose structural warping produced or redeepened the major syncline, the basin was filled to a considerable extent by lavas and by sediments overlying the Keweenawan flows. Between the close of this period of deposition and the beginning of the Upper Cambrian a great period of denudation produced the pre-Cambrian peneplain, whose surface of low relief beveled across the weak and resistant members of the Archean and Algonkian, the synclinal basin perhaps being filled with the material worn away in making the peneplain or perhaps being replaced by part of the peneplain surface. At some subsequent date, probably also pre-Cambrian, faulting took place, producing the great escarpment which extends northeastward from Duluth and smaller nearly parallel escarpments on the south shore of the lake. These two fault lines bound what is perhaps a great graben or rift, which forms the rectangular body of northern and western Lake Superior (fig. 8). The evidence of the fault origin of these escarpments may be gathered from a detailed consideration of their characteristics.

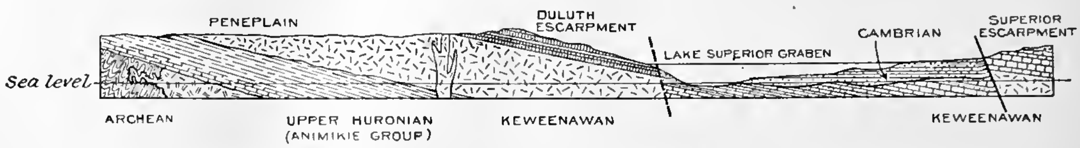


FIGURE 8.—Graben or rift valley of western Lake Superior, showing escarpment on either side and peneplain above.

DESCRIPTION OF ESCARPMENTS.

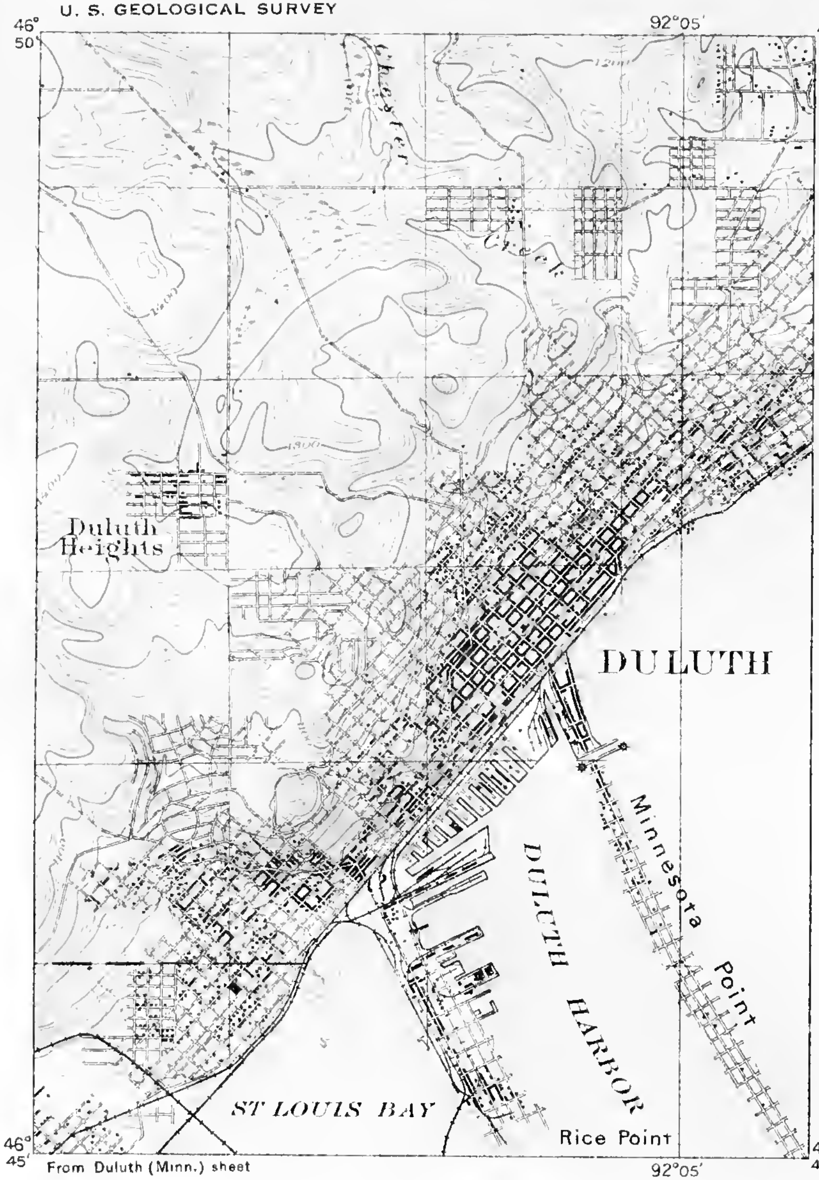
DULUTH ESCARPMENT.

Rising steeply above the waters of Lake Superior for about 600 to 800 feet at Duluth and with diminishing height toward the northeast is the Duluth escarpment (Pl. II, p. 86). It has a slope at Duluth of 450 to 1,000 feet to the mile, and the steeply ascending face is 1½ to 2 miles wide (Pl. V, *A*). Above rises the fairly level-topped gabbro plateau, which extends northward as part of the peneplain. The escarpment, which bounds this plateau on the southeast, is remarkably simple in its outline, with none of the irregularity which characterizes slopes long eroded by streams. This simplicity of outline is shared by the gently curved escarpment of Keweenaw Point and by that of northern Wisconsin, both of which are known to follow fault lines. Lawson has suggested that the Duluth escarpment also follows a fault line.[a] We have then to account for its fresh and uneroded form, for it is quite inconceivable that a fault scarp could have been produced, as this may have been, in pre-Paleozoic or very early Paleozoic time and not have been more largely altered by weathering and stream erosion.

The streams of the Duluth escarpment descend very steeply to Lake Superior; few of them head more than 4 or 5 miles from Lake Superior (Pl. II), the greatest distance being 12 to 14 miles, in contrast with lengths of 30 to 75 miles on the north and northeast shores of Lake Superior. Many of them have as steep an average grade as 150 to 250 feet to the mile (Pl. V, *A*), the general average being 80 to 160 feet to the mile. No one of these rather tumultuous streams has cut a significantly deep valley in the face of the escarpment and most of them have only cut short gorges with small rapids and waterfalls.

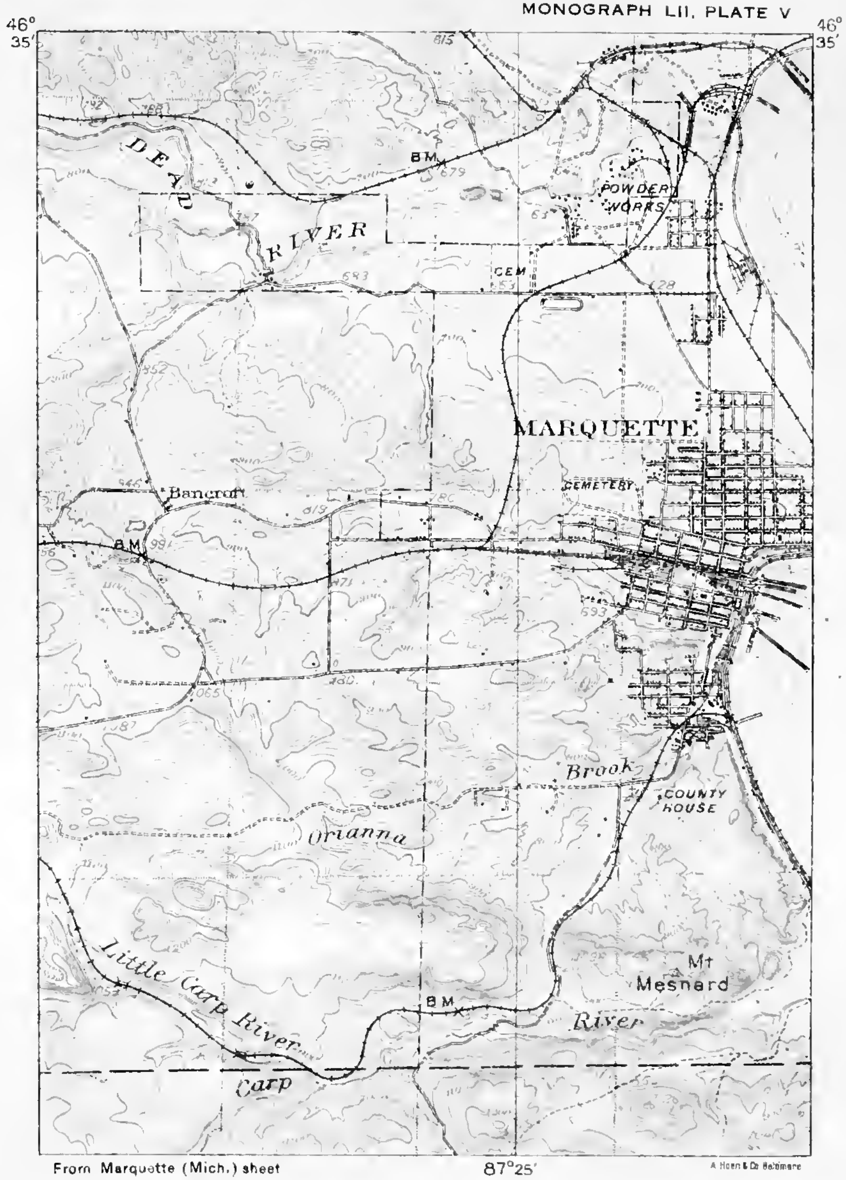
Quite in contrast with these steep-graded, rapidly falling streams of the escarpment are the leisurely flowing streams of the plateau surface above. The Cloquet, the upper St. Louis, and various other rivers have an average slope of about 8 or 10 feet to the mile. It is well established that a rapidly flowing stream with a steep grade is able to deepen its valley rapidly and to extend its headwater area so that it encroaches upon the area drained by an adjacent

[a] Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1891, p. 192.



A
THE DULUTH ESCARPMENT AND EVEN UPLAND OF PENEPLAIN ON DULUTH GABBRO IN MINNESOTA. THE SPITS AT DULUTH

Scale 1:62500
0 1 2 Miles
Contour interval 20 feet



B
LAKE SHORE ESCARPMENT OF ARCHEAN SCHISTS AND HURONIAN QUARTZITE NEAR MARQUETTE, MICHIGAN

Scale 1:62500
0 1 2 Miles
Contour interval 20 feet

leisurely flowing stream (fig. 9), capturing and diverting the latter or some portion of its headwaters. Stream captures or piracies, as they are called, of this kind are common. We should expect, then, that in the course of stream development for a great length of time several of the swiftly flowing streams of the escarpment would have extended their headwaters back to the region drained by the leisurely flowing streams of the plateau surface and captured part or all of these drainage systems. The fact that many of the large streams have not done so is evidence of their youth.

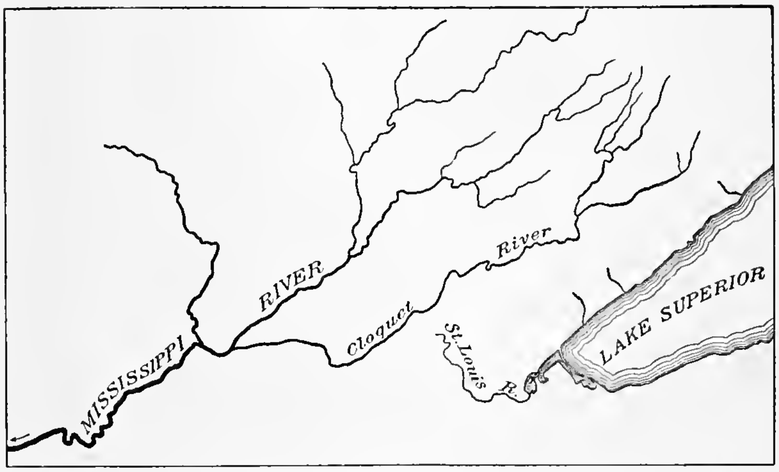


FIGURE 9.—The drainage of the St. Louis and Mississippi headwaters before the stream captures along the Duluth escarpment.

The largest stream in the region, however, seems to have already done just what would be expected (fig. 10), and it is natural that the largest stream should be able to do this first. St. Louis River, cutting back at a point near the end of the escarpment where it is rather low, has been able to extend its headwater region northwestward until it has captured the southwestward-flowing Cloquet and the southwestward-flowing stream that forms the present headwaters of the St. Louis itself. These captured streams had been a part of the leisurely drainage system of the plateau surface, and, it seems certain, were within the Mississippi basin (Pls. I and II). Indeed, a large valley extending southwestward from the town of Floodwood, where the St. Louis now turns abruptly to the southeast, indicates that this is probably the latest elbow of capture at which the piratical St. Louis has been able to divert to the Lake Superior–St. Lawrence drainage system a large headwater tributary of Mississippi River, as it had previously diverted the Cloquet, another Mississippi headwater, or possibly one of the St. Croix.

FIGURE 10.—The drainage of the St. Louis and Mississippi headwaters at present, after stream captures and diversions.

A study of similar fault scarps acted upon by stream erosion in other parts of the world indicates that this fault scarp has not been acted upon by erosional agencies for a great length of time. If it had been so eroded for a long period, we should find it deeply cut by valleys with outlying knobs on the lower slopes, like the erosion escarpment at Marquette (Pl. V, *B*), and with stream captures at the upper shoulder, where the escarpment meets the plateau top.

Comparison of this escarpment with the equally abrupt escarpments on the north shore of Lake Superior from Thunder Bay to Sault Ste. Marie emphasizes the freshness of the Duluth escarpment; there is a striking contrast in stream and valley distribution. The north-shore escarpment has much longer streams flowing directly to the lake from the north, with deep valleys everywhere cut to lake level. It is a much-breached wall; the Duluth escarpment is an unbroken barrier. The drainage of the former proclaims greater length of time for stream dissection in the same language by which the drainage of the latter announces youth.

It seems possible that erosion by the Lake Superior lobe of the Labrador ice sheet might have so smoothed the face of this escarpment and steepened and intensified it that topography of the kind suggested would be destroyed or that longer streams draining to Lake Superior would be diverted by the ice barrier and acquire new courses. Such modification may have taken place to a slight degree, but even if the maximum of glacial erosion is assumed the lack of stream diversions is quite unexplained, as is also the resemblance to the acknowledged fault scarp on the east side of Keweenaw Point.

Along the line by which this escarpment can be discriminated as a form initially produced by faulting rather than by glacial erosion a scrutiny of the submerged continuation of the same escarpment reveals several significant facts. Fortunately the detailed soundings made by the Corps of Engineers of the United States Army in charting the Great Lakes give us detailed information (Pl. II) concerning the escarpment below present lake level. First, it continues to descend at as steep or steeper angles than on the land, a depth of 400 to 600 feet being found within 2 to 3 miles from any part of the shore. The escarpment, therefore, is not merely 400 to 600 feet but 1,000 to 1,200 feet in height. Second, it extends directly across the mouths of the several large bays (Thunder, Black, and Nipigon) at the north end of the lake, where the escarpment feature in the unsubmerged land surface is interrupted by these broad valleys, partly drowned beneath the present lake level. These are therefore hanging valleys, entering the lake basin or the linear depression to which they are tributary at levels 400 to 600 feet [a] above its bottom. (See Pl. II.) This submerged hanging valley condition might be explained either by glacial erosion or by faulting.

The facts in favor of glacial erosion are (*a*) known ice flow along this coast and parallel to it; (*b*) probably accentuated erosive ability in this portion of the Lake Superior basin, where more rapid movement would result from the constriction of the ice between Isle Royal and the mainland; (*c*) the known ability of glaciers of no greater thickness and less width to erode so deeply that main valleys receive discordant tributaries (hanging valleys) as much as 500 to 1,000 feet above, as in Alaska, the Swiss Alps, Scotland, Norway, New Zealand, etc.

Points in favor of faulting are the following: (*a*) The straightness of the escarpment; (*b*) the continuation below lake level of a topographic feature whose drainage and other land phenomena are inexplicable by glacial erosion alone; (*c*) the uniform level at which the submerged hanging valleys stand (Thunder Bay 22 to 23 fathoms, Black Bay 22 fathoms, Nipigon Strait 20 to 21 fathoms). Such uniformity is unusual in glacially eroded hanging valleys, where the size of the glaciers in tributary valleys, their width, thickness, and eroding power, produce hanging valleys at diverse levels. Glaciers of the unequal sizes denoted by these bays would surely have done so. (*d*) The varying age, character, and resistance of the rocks beveled across by this supposed fault (Cambrian sandstones, Keweenawan lavas and sediments, upper Huronian intrusives and slates, and older rocks).

The escarpment therefore seems to have features inexplicable by glacial erosion alone, but none that do not fit the hypothesis of glacial erosion modifying a faulted form. The exceptional depth of water just opposite the mouth of Thunder Bay (156 fathoms), making this point 936 feet deep, or more than 300 feet below sea level, and the second deepest place in the lake, can be readily explained by glacial scooping at just this point, for such irregularity in the bottoms of glacially eroded channels like the Norwegian and Alaskan fiords are not uncommon.

The writer accordingly feels that there is a reasonable possibility that the northwest shore of Lake Superior from a point west of Duluth to St. Ignace at the north, with its direct but broadly-curving course, represents the position of a fault line. This fault scarp, with 1,000 feet or more of throw, may either be very recent, though several considerations lead to the belief

[a] Bottom of Thunder Bay, 22 fathoms or 132 feet; depth of trough opposite mouth, 113 fathoms or 678 feet.

that this is not so, or else it may have been faulted long ago and then buried and protected so that erosion has only recently begun to attack it. Accordingly it may owe the preservation of its southwesterly portion (Minnesota shore) to protection by Cambrian or later sediments and the dissection of its northeasterly part (Ontario shore) to the earlier removal of such a protecting Cambrian mantle. Glaciation is believed to have modified this escarpment in its minor features only, as in changing a more precipitous slope to the present flaring wall and in locally deepening the depression at its base.

KEWEENAW ESCARPMENT.

The escarpment of the east side of the Keweenaw Point [a] very closely resembles the Duluth escarpment in form and condition of erosion though not so high nor so steep (Pl. II). A northeast-southwest trending escarpment borders the east side of "an elongated promontory,[b] not greatly dissected by erosion nor deeply undulate nor serrate in its crest line," whose flat top has been formed by the base-leveling [c] of a series of steeply dipping Keweenawan beds and whose western and northwestern sides slope more gradually to the level of Lake Superior; the east side slopes steeply to the open lake near the tip and is elsewhere separated from the lake by the low-lying flat portion underlain by the Cambrian sandstone (Pl. XXVIII, p. 380).

This escarpment differs, however, from the Duluth gabbro escarpment in one important respect. It is cut entirely through by stream valleys in at least two places. It is believed that the great transverse valley of Portage Lake (Pl. XXX, *B*, p. 434) and the valley of Ontonagon River were formed before the present Lake Superior existed, by streams which were superposed on this long, narrow peninsula through a mantle of Cambrian (Lake Superior) sandstone, whose remnants are still preserved high upon the fault scarp near the highest part of Keweenaw Point.[d] Irving and Chamberlin,[e] after careful consideration of the many earlier hypotheses, reach the conclusion that the Keweenaw Point scarp is a pre-Potsdam fault modified by wave work, buried, and slightly refaulted in post-Potsdam or post-Cambrian time. (See fig. 75, p. 574.)

ESCARPMENT OF NORTHERN WISCONSIN (SUPERIOR ESCARPMENT).

The escarpment which forms the boundary of the northern highlands of Wisconsin [f] and overlooks the basin of Lake Superior from a point west of Duluth eastward to the Apostle Islands is a lower and more gently sloping scarp (Pl. II). It has the characteristics of the other two escarpments in being without topographic outliers and in having short, steeply sloping stream courses which have not extended headward much beyond the shoulder of the escarpment.

Chamberlin [g] concludes that this escarpment of Bayfield and Douglas counties, Wis., is a pre-Potsdam fault scarp, and Grant [h] has supported this conclusion but makes its age post-Potsdam. Like the Duluth and Keweenaw escarpments, it seems to have been protected so that its dissection has been somewhat postponed Its youth is therefore not so anomalous as W. M. Davis has suggested.[i]

ISLE ROYAL ESCARPMENT.

On the north side of Isle Royal there is a submerged escarpment of 400 to 500 feet, suggesting a parallel fault here (Pl. II), which Irving and Chamberlin [j] conceived of as possibly a continuation of the fault of Bayfield and Douglas counties on the south shore. There is no continua-

[a] Irving, R. D., and Chamberlin, T. C., Observations on the junction between the Eastern sandstone and the Keweenaw series on Keweenaw Point: Bull. U. S. Geol. Survey No. 23, 1885, pp. 12, 98–119.

[b] Idem, p. 103.

[c] Van Hise, C. R., Science, new ser., vol. 4, 1896, pp. 217–220.

[d] Bull. U. S. Geol. Survey No. 23, 1885, pp. 109–110.

[e] Idem, p. 119.

[f] Chamberlin, T. C., Geology of Wisconsin, vol. 1, 1883, pp. 105–106. Grant, U. S., Bull. Geol. and Nat. Hist. Survey Wisconsin No. 6, 1901, p. 6.

[g] Geology of Wisconsin, vol. 1, 1883, p. 105.

[h] Bull. Geol. and Nat. Hist. Survey Wisconsin No. 6, 1901, pp. 17–20.

[i] Science, new ser., vol. 15, 1902, p. 234.

[j] Bull. U. S. Geol. Survey No. 23, 1885, p. 111.

tion of this steep slope northeast or southwest of Isle Royal, which stands on a high base with steep descents on all sides of it, especially the northwest and southeast. If the channel northwest of Isle Royal is ascribed to block faulting, the island itself must be regarded as a land mass that stands as a horst above the deep surrounding basin because of failure to be faulted down.

Isle Royal and Keweenaw Point accordingly have certain features in common aside from familiar fact that the Keweenawan rocks in Isle Royal dip southeast and those at Keweenaw Point dip northwest. The slopes facing each other seem to be dip slopes, but of the sides facing away from each other that of Keweenaw Point is known to be a fault line, and that of Isle Royal may possibly be a smaller one. This structural feature, then, would be a great synclinal trough between Isle Royal and Keweenaw Point, with downfaulting on each side.

Massing of the contours in other parts of the lake (Pl. II) suggests submerged escarpments east of this trough, but there is not enough information for detailed discussion.

AGE OF ESCARPMENTS.

For all these subparallel escarpments grouped about the west end of Lake Superior the hypothesis is advanced that they have been formed by faulting. Their later history may have accorded with one of two hypotheses. One supposes that they are old escarpments (pre-Cambrian) slightly modified by stream erosion and in places possibly developed into sea cliffs and then buried beneath Paleozoic sediments. During the ensuing long period of denudation the escarpments themselves were protected from erosion by the overlying sediments. They were gradually uncovered and are now just in the beginning of a cycle of erosion, which was postponed until their rather recent disinterment. The alternative hypothesis that these are much more recent fault scarps (post-Cretaceous or pre-Pleistocene) is supported by the evidence of slight post-Cambrian movement along two of these scarps (along which there was surely much greater pre-Cambrian faulting) and by the evidence of post-Cretaceous and of post-Pleistocene faulting in other parts of the area. The question of the date of this faulting is a large one, involving the determination of the age of the great peneplain of the area and the age of the present Lake Superior basin.

BEARING OF ESCARPMENTS ON AGE OF PENEPLAIN.

There are three fields for attacking the problem of the age of the peneplain in the Lake Superior region. The first is in northern Wisconsin, where the truncated surface of the pre-Cambrian now dips down under the Paleozoic. The conditions here are shown in figure 11.

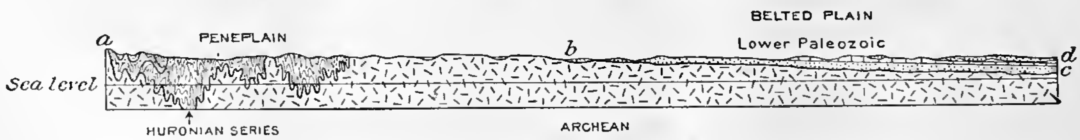


FIGURE 11.—Structure profile in northern Wisconsin, showing the south edge of the peneplain on the pre-Cambrian rocks and the northern part of the belted plain of the Paleozoic.

Weidman has demonstrated that *b–c* is a buried pre-Potsdam peneplain and inferred that *a–b* is its exhumed equivalent. Van Hise previously referred to *b–d* as a Cretaceous peneplain and to *a–b* as its equivalent. So far as the writer can see, evidence for deciding conclusively between these two hypotheses is not present, though the Paleozoic outliers on the peneplain suggest that it is pre-Potsdam rather than Cretaceous.

The second field of attack is in the region to the west, in Minnesota (Pl. XIV, p. 212). Here the Cretaceous overlaps the peneplain. Numerous diamond-drill holes through the glacial drift on the Cuyuna range show the Cretaceous as a thin mantle on the peneplain of pre-Cambrian rocks. Elsewhere the drift covers it deeply, but on the border of the Giants Range monadnock, in the Mesabi iron range, Cretaceous outliers are found in valleys and on ridge slopes (Pl. VIII, in pocket). These are marine Upper Cretaceous, so the peneplain might perfectly well be either pre-Cambrian or early Cretaceous in age. If the Cretaceous can be found in valleys in the peneplain as well as in valleys on the slopes of its monadnocks, the probability of pre-Cambrian age will be strengthened.

The third and most promising field for investigation is in the fault scarps themselves. The escarpments were clearly made after the great peneplain was developed, for the nearly base-leveled upland areas now extend neatly up to the edges of these steep slopes (fig. 8, p. 112) and could not have done so when the peneplain was formed. The two latest periods of great base-leveling in the area are thought to be pre-Cambrian (pre-Potsdam) and Cretaceous. The known periods of faulting are pre-Cambrian, post-Cambrian, post-Cretaceous, and post-Pleistocene. The Lake Superior basin was surely here in pre-Pleistocene time, so the post-Pleistocene may be eliminated as a period of major faulting. The choice seems to lie between (*a*) regarding the peneplain as due to Cretaceous base-leveling and the escarpments as due to post-Cretaceous faulting, to which there are certain objections, and (*b*) regarding the peneplain as an exhumed slightly dissected pre-Cambrian surface and the escarpments as due to pre-Cambrian faulting. The assumption of protection by Paleozoic sediments is necessary in order to explain the relatively fresh fault-scarp forms, and from this assumption naturally follows the hypothesis of the clearing out of the basin and exhumation of the escarpments during the Cretaceous base-leveling and the glacial period, all the later faulting being considered of slight amount. There are objections to this hypothesis also, but in the mind of the writer they are of less weight.

CHAPTER V. THE VERMILION IRON DISTRICT OF MINNESOTA.[a]

LOCATION, AREA, AND GENERAL GEOLOGIC SUCCESSION.

The Vermilion iron-bearing district lies in northeastern Minnesota, in St. Louis, Lake, and Cook counties (Pl. VI). The district extends about N. 70° E. from near the west end of Vermilion Lake, in west longitude 92° 30′, to the vicinity of Gunflint Lake on the international boundary, longitude 90° 45′, and lies between 47° 45′ and 48° 15′ north latitude. The district is for the most part 5 to 10 miles broad but locally as much as 12 or 15 miles, and at the eastern end it is divided into two narrow belts by the granite of Saganaga Lake. The length of the district is about 100 miles.

The productive iron-bearing rocks are bounded on the north by the granite of Basswood Lake, on the east by the granite of Saganaga Lake and the Animikie group, and on the south in turn from east to west by the Keweenawan Duluth gabbro, lower Huronian granite, and Archean granite. On the west the iron-bearing and other formations disappear under the Pleistocene. Part of the eastern half of the Vermilion range extends north of the international boundary into Hunters Island. The rocks of the eastern extension of the north arm of the Vermilion range are known locally as the Hunters Island iron-bearing series.

The stratigraphic succession in the Vermilion district is as follows, in descending order:

Quaternary system:	
Pleistocene series	Drift.
Unconformity.	
Algonkian system:	
Keweenawan series	Duluth gabbro and Logan sills.
Unconformity.	
Huronian series:	
Upper Huronian (Animikie group)[b]	Rove slate. Gunflint formation (iron bearing).
Unconformity.	
Lower-middle Huronian	Intrusive rocks: Granites, granite porphyries, dolerites, and lamprophyres. Knife Lake slate. Agawa formation (iron bearing). Ogishke conglomerate.
Unconformity.	
Archean system:	
Laurentian series	Granite of Basswood Lake and other intrusive rocks.
Keewatin series	Soudan formation (iron bearing). Ely greenstone, an ellipsoidally parted basic igneous and largely volcanic rock.

This chapter is primarily concerned with the Archean and the lower-middle Huronian, which really constitute the rocks of the Vermilion district. The higher rocks will be mentioned only so far as it is necessary to do so in order to give a satisfactory treatment of the lower rocks. The Animikie group, which occurs at the east end of the district, and the Keweenawan series, which borders a large part of the southern portion of the district, will be treated in Chapters VIII and XV.

[a] For a further detailed description of the geology of this district, see Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, and references there given.

[b] Confined to east end of district.

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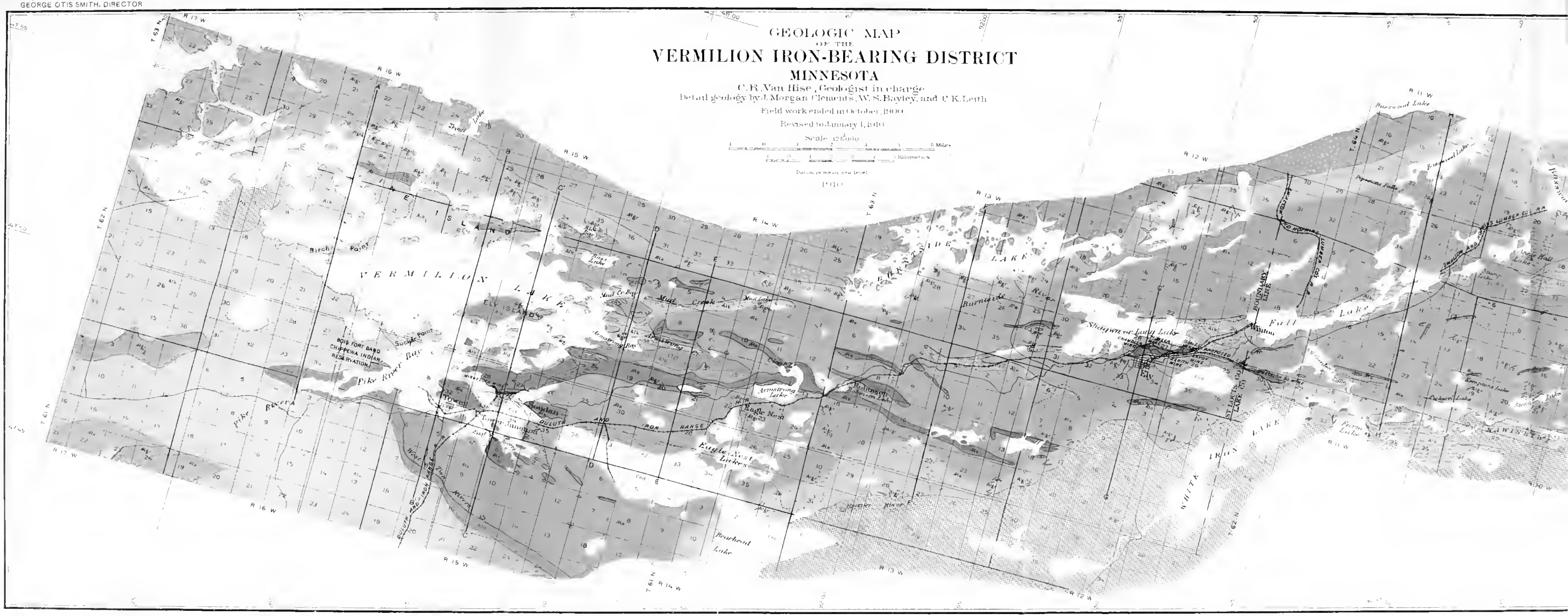
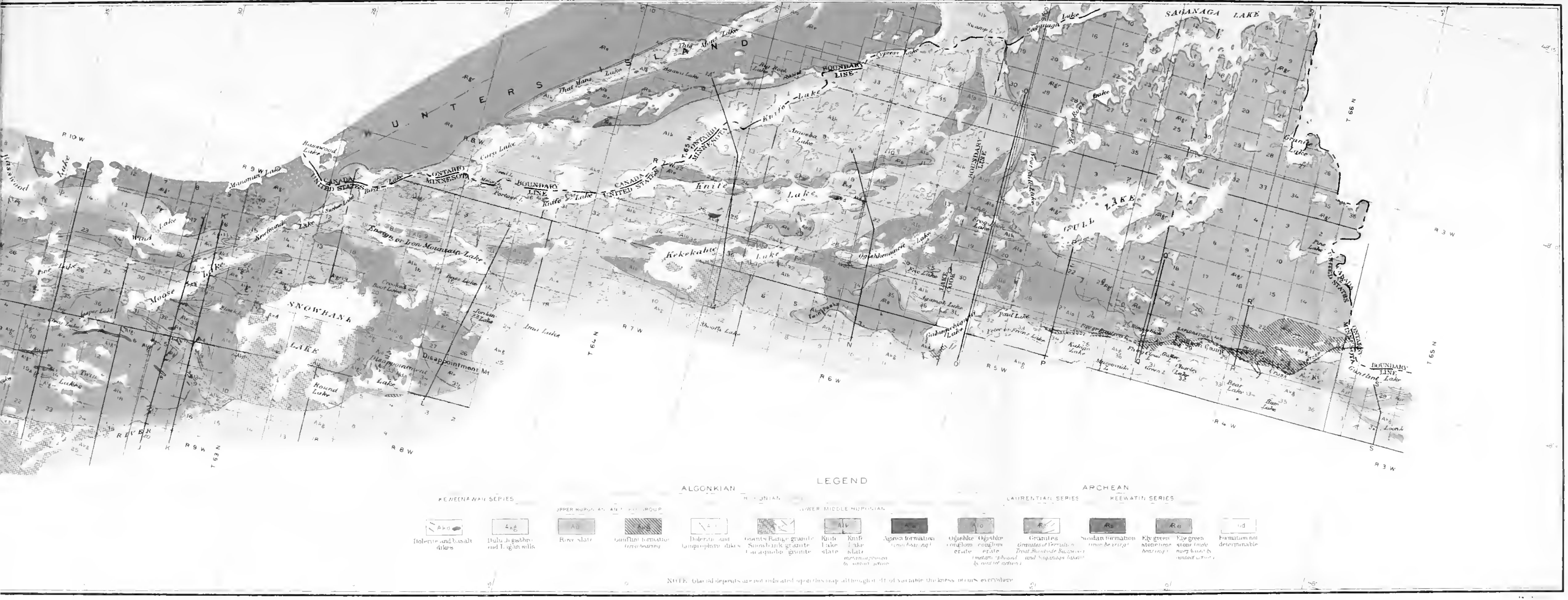



SAGANAGA LAKE
WUNTERS LAND
BOUNDARY LINE
CANADA
UNITED STATES
ONTARIO
MINNESOTA
Knife Lake
GULL LAKE
SNOWBANK LAKE
Moose Lake
Kekekabic Lake
Disappointment Mt
Ogishkemuncie Lake
Ensign or Lon Mountain Lake
Round Lake
Bear Lake
Gunflint Lake
R 10 W
R 9 W
R 8 W
R 7 W
R 6 W
R 5 W
R 4 W
R 3 W
T 63 N
T 64 N
T 65 N
T 66 N
LEGEND
ALGONKIAN
ARCHEAN
KEWEENAWAN SERIES
LAURENTIAN SERIES
KEEWATIN SERIES
LOWER MIDDLE HURONIAN
Dolerite and basalt dikes
Duluth gabbro and Logan sills
Rove slate
Gunflint formation (iron bearing)
Dolerite and lamprophyre dikes
Giants Range granite Snowbank granite Cacaquabic granite
Knife Lake slate
Knife Lake slate
Agawa formation (iron bearing)
Ogishke conglomerate
Ogishke conglomerate
Granites
Granites of Vermilion, Trout, Burntside, Basswood and Saganaga lakes
Soudan formation (iron bearing)
Ely greenstone (iron bearing)
Ely greenstone
Formation not determinable
NOTE. Glacial deposits are not indicated upon this map although drift of variable thickness occurs everywhere

TOPOGRAPHY.

The topography of the district may be defined briefly as characterized by linear bluffy ridges, in the depressions between which are numerous linear lakes, the whole constituting a relatively even peneplain with a few monadnocks. The general physiography is discussed in Chapter IV.

The position of the ridges and valleys is determined by the character of the rocks. The more resistant rocks form the ridges, the less resistant the valleys. On the whole the most resistant rock of the region is the Ely greenstone, and this constitutes a greater proportion of the bluffs of the district than any other formation.

Next in importance to the greenstone as a bluff-making formation is the iron-bearing Soudan formation. This independently constitutes a number of high bluffs, and conjointly with the greenstone helps to make many others.

The depressions, especially those containing lakes, are mainly engraved in the Knife Lake slate. This is true of most of the important lakes of the district, such as Vermilion Lake, Long Lake, Fall Lake, Moose Lake, Ogishke Lake. However, some of the lakes, especially those that are roundish, are in other formations, notably the granite, which in this district seems to be not much more resistant than the slate. Important lakes of this class are White Iron Lake, Basswood Lake, Snowbank Lake, and Saganaga Lake.

The Ogishke conglomerate is intermediate in resisting power between the slates and greenstones. In places, therefore, it occupies the valley, as at Vermilion Lake, and in places makes considerable bluffs, as in the eastern part of the district; but more commonly the conglomerate is found on the slopes, because it lies structurally between the harder greenstones and the softer slates.

ARCHEAN SYSTEM.

The Archean is represented by both the Keewatin series and the Laurentian series. The Keewatin comprises the Ely greenstone and the Soudan formation. The Laurentian includes granites, porphyry, and associated acidic rocks.

KEEWATIN SERIES.

ELY GREENSTONE.

DISTRIBUTION.

The Ely greenstone is the most conspicuous and extensive formation of the district. From Vermilion Lake to the central part of the district it occupies the larger part of the area between the granites to the north and south. In the eastern half of the district it is less extensive.

The formation is conspicuous not only because of its areal extent, but because of its topographic importance. In general its rocks are resistant, and many of the high knobs of the district are composed of them—for example, those about Tower and Ely. They form Disappointment Mountain, near Disappointment Lake, one of the most prominent features of the district. They compose the great promontory of Knife Lake, in sec. 21, T. 65 N., R. 7 W., so conspicuous a feature along the international boundary. In fact, most of the high knobs to be seen from almost any commanding point of view between the northern and southern granites are composed of the Ely greenstone. Such knobs are conspicuous even where the areas of the greenstone are subordinate—for example, the high bare headland above Moose Lake.

A few of the important bluffs are due to the resistant quality of the Ely and Soudan formations together—for instance, Soudan and Lee hills, near Tower, and a number of the prominent bluffs of Hunters Island, along the north side of Otter Track Lake, and elsewhere.

APPEARANCE AND STRUCTURE.

The Ely greenstone has as its dominant color various tones of green. It comprises greenstones, tuffs, and slates, but the latter two varieties of rock are very subordinate. The dominant rocks of the formation are called greenstone rather than a petrographic name because many of them have been so modified by metamorphism that in the field it is often impossible to determine their character or to discriminate between the different phases. This alteration is no more than one would expect from their great age. For the most part the changes are dominantly metasomatic rather than dynamic, so that the massive rocks still retain their original structures and textures, though their mineral composition is now largely or wholly changed.

Clements's petrographic study of these greenstones shows that they correspond to intermediate andesites and basic basalts. The massive exposures of this greenstone very commonly show one or more of the three structures—the amygdaloidal, spherulitic, and ellipsoidal. Not only are these macroscopic structures common, but textures such as ophitic, poikilitic, and porphyritic often may be seen. The rocks vary greatly in their fineness of grain from aphanitic to coarse grained.

Of the structures mentioned as characteristic of the rocks the most common is the amygdaloidal, this structure usually being found in the finer-grained varieties. It is especially noticeable on the weathered surface.

The greenstones not uncommonly show true spherulitic structures, but these are not by any means so common as the amygdaloidal structure. This structure, though very rare in basic rocks, is exhibited in this ancient formation in as great perfection as in modern acidic rocks.

The third structure, the ellipsoidal, is the most distinctive one of the formation. Almost any large mass of the Ely greenstone encountered between Tower and Gunflint Lake will exhibit this structure. The rock, observed at a distance, seems to be mainly composed of a mass of ellipsoids of rock, varying from a few inches to several feet in diameter (Pl. VII). Ordinarily, however, the ellipsoids range from 6 inches to 3 feet in diameter, and perhaps most commonly they are between 1 and 2 feet in diameter. These ellipsoids are set in a matrix of material not greatly different from the ellipsoids themselves but usually of slightly different color and texture. In many places they have undergone peripheral alteration, so that they exhibit a zonal arrangement.

If the ellipsoids are examined somewhat more closely, many of them are found to be amygdaloidal; moreover, in many of the spheroids the amygdules are more abundant near the border than in the interior, and not uncommonly all the ellipsoids of an exposure are more amygdaloidal on the same side. The origin of these ellipsoidal rocks is discussed by Clements in the monograph on the Vermilion district and by the authors on pages 510–512 of this monograph.

Within short distances the greenstones vary from fine to coarse textures and from varieties which exhibit the structures mentioned to others in which they are absent. In many places these phases alternate at short intervals.

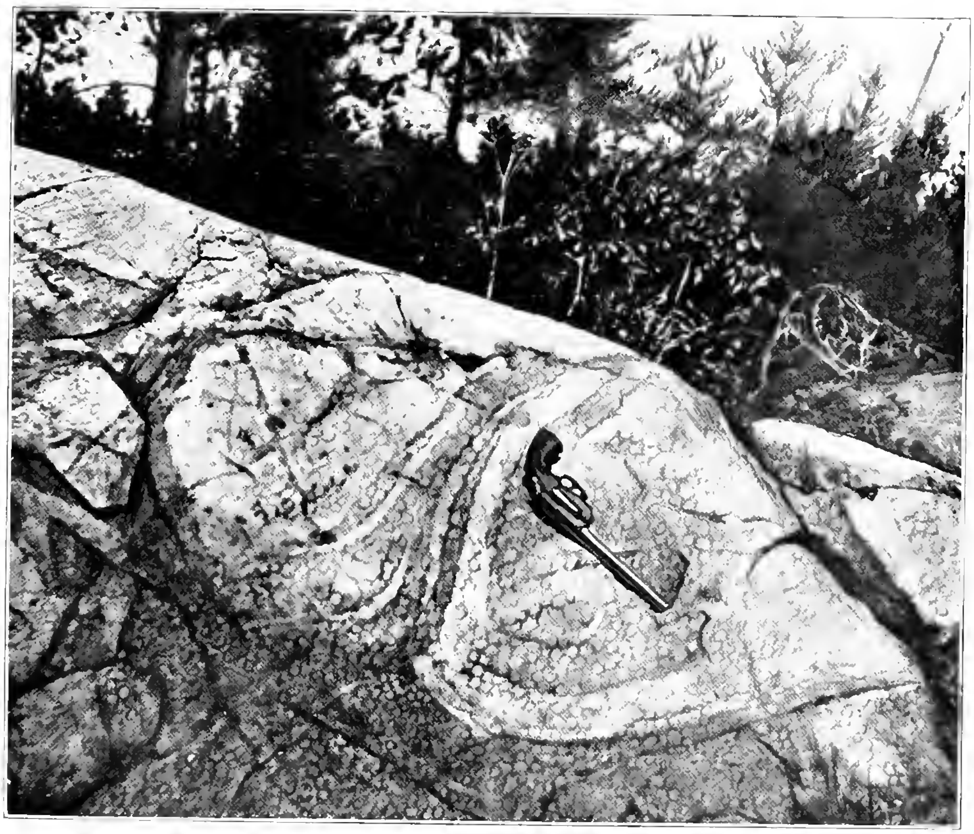
Every gradation may be found from the undeformed ellipsoids to a schist. In the transition the ellipsoids become flatter and flatter, until finally the representative of each is a lenticular area perhaps many times as long as it is broad. Since the exterior of the ellipsoids, as has already been explained, usually has a different color from the core and a somewhat different texture, an extremely flattened ellipsoid has three bands. The occurrence of this phenomenon in the many ellipsoids transforms the greenstone to a fissile banded schist which has a very marked sedimentary appearance. Indeed, in dealing with the extremely altered phases it is difficult to believe that the rock is not a sediment rather than a metamorphosed lava.

In many places, without reference to the ellipsoidal structure, the greenstones are schistose. However, this schistosity is not nearly so common as in the Marquette and Menominee districts. In consequence of the relative lack of schistosity, the original characters of the Archean greenstone are better exhibited in this district than in any other on the American side of the boundary. It is not unreasonable to suppose that it may be possible by further detailed mapping to work out the succession of flows for the Ely greenstone.

MINERAL CONSTITUENTS.

A microscopical study of the greenstones shows that the original minerals are largely altered. The following original constituents are disclosed: Hornblende, augite, plagioclase, quartz, titaniferous magnetite, and apatite. The original hornblende is the common brown variety. The augite varies from yellow to yellowish green and possesses its normal characters.

A. ELLIPSOIDAL PARTING IN ELY GREENSTONE.
After Clements. See page 120.



B. ELLIPSOIDALLY PARTED ELY GREENSTONE, SHOWING SPHERULITIC DEVELOPMENT.
After Clements. See page 120.

The feldspar is generally so much decomposed that one can not determine its exact characters. It is presumed to be a labradorite. There is very little quartz, but some was found in micropegmatitic intergrowth with the feldspar and is presumed to be a primary constituent. It may fill irregular interstices between the other minerals as primary quartz representing the last product of the crystallization of the rock.

The secondary constituents are calcite, common green hornblende, actinolite, biotite, chlorite, sericite, epidote, zoisite, sphene, rutile, feldspar, quartz, pyrite, and hematite. The feldspar has usually altered to a mass of sericite, kaolin (?), feldspar, and quartz. In some places it is completely saussuritized. There were observed occasional irregular but in general rounded serpentinous areas, which strongly suggest aggregates of olivine individuals in which the olivine possesses no definite crystallographic outline. Locally the rock is largely replaced by calcite. The abundance of secondary calcite is one of the conspicuous features of the formation.

CLASTIC ROCKS.

At a very few localities associated with the greenstones are small masses of tuffaceous-looking rocks which are believed to have been interbedded volcanic clastics. Locally these tuffaceous rocks grade into fine-grained volcanic ash, and in some places this passes into a well-banded slaty rock, the material of which was doubtless arranged by water. It is probable that by far the greater amount, if not all, of the material for the slate has been derived from other parts of the Archean Ely greenstone. Parts of the iron-bearing Soudan formation have similar relations to the Ely greenstone. (See pp. 126–128.)

ACIDIC FLOWS.

Interbedded and conformable with the ellipsoidal basalts are frequently to be observed intermediate and acidic flows with surface textures, in many places closely associated with thin layers of the Soudan formation. These acidic flows have been connected with a dike of quartz porphyry similar to the porphyry cutting the Ely ellipsoidal flows, as in secs. 13 and 14, T. 62 N., R. 13 W. (See fig. 13, p. 123.) These flows seem to be later, more acidic phases of extrusion than the Ely basalts and undoubtedly have a close relation to the acidic intrusive rocks discussed under later headings.

INTRUSIVE ROCKS.

The Ely greenstone is intruded by the great batholithic area of Archean granite of Basswood Lake on the north and by Archean, Huronian, and Keweenawan granites on the south. There is a considerable zone, varying from less than half a mile to 1½ or even 2 miles in extent, adjacent to these intrusive masses, in which profound metamorphism has taken place in consequence of the intrusions. The amount of metamorphism is least at a distance from the granite and gradually becomes more intense as the distance lessens.

The first of the changes that are noted in passing from the greenstone toward the granite area is that the greenstone becomes more schistose and crystalline; also there is a large development of hornblende. Thus the rock becomes a hornblende schist. With approach to the granite the hornblende schist becomes better and better developed until it is a coarsely crystalline typical hornblende schist. The schist may be injected parallel to the schistosity, so that there is produced a banded gneiss, a part of the layers of which consist mainly of the modified greenstone in the form of hornblende schists and the other part of the granite. Both parts are igneous rocks, the more basic parts being dominantly profoundly metamorphosed lava, the more acid parts mainly an intrusive rock. Within the breadth of a hand specimen there may be a dozen or more alternations of this schist and granite. In many places where the granite can not be distinguished as clear-cut parallel layers in the schist granitic minerals are found along the laminæ, so that the rock has abundant feldspar. There are all transitions from the little-altered greenstone to the hornblende schist, and from this kind of rock to rocks in which feldspathic minerals are developed along the laminæ, and from this variety to rocks in which the granite is clearly injected in parallel layers, thus producing a gneiss.

No better instance is known to us of the production of schists and gneisses the different parts of which are of different origins and ages. The background of the schist or gneiss is an ancient basic or intermediate lava; another portion is a deep-seated acidic intrusive rock. By combination of dynamic and contact action the profoundly metamorphosed rock has been produced.

A microscopic study shows that the schists and gneisses contain the following constituents in varying proportions: Common green hornblende, actinolite, biotite, muscovite, chlorite, epidote, calcite, sphene, quartz, feldspar, pyrite, and magnetite. The mica is present in very small quantity and is invariably associated with amphibole.

The more metamorphosed rocks not only contain minute granitic injections but also are cut by many large and small granite dikes, which may run parallel to the schistose structures or traverse them at any angle.

Also within the intrusive rocks are fragments of the Ely greenstone, ranging from small to great. These are usually profoundly metamorphosed and some of them are partly absorbed.

The character of the contact metamorphism may be particularly well seen on the islands and mainland along the northern part of Vermilion Lake and in the area between Ely and White Iron Lake. The relations illustrated between the granite and the greenstone are identical with those which have been described by Lawson with reference to the Keewatin and Laurentian of the Rainy Lake and Lake of the Woods district.

The Ely greenstone where intruded by the gabbro, at the south side of the east end of the district, has been metamorphosed into a spotted hornblendic rock with less schistosity than the rock along the granite contacts.

EXTENSION OF ELY GREENSTONE BEYOND DISTRICT.

It has already been noted that the Ely greenstone extends to the northeast into Hunters Island. This formation has a very wide extent in that district and the Rainy Lake and Lake of the Woods region; in fact, it is the most characteristic rock of the Keewatin of the Lake Superior geologic province. It is therefore clear that this volcanic formation is regional rather than local.

SOUDAN FORMATION.

DISTRIBUTION.

The chief exposures of the iron-bearing Soudan formation occur between Tower on the west and a few miles east of Ely on the east, a distance of less than 30 miles. Numerous smaller exposures of the formation are found within the area of the Ely greenstone for 12 or 15 miles farther east, and large exposures are also known to exist in the eastern part of the district, in the vicinity of Emerald Lake. A few of the more important localities in which the formation may be well studied are Tower, Lee, and Soudan hills and Jasper Peak. The Soudan formation is confined to the area of the Ely greenstone and its border. Even the belts mapped as Soudan formation consist of bands of the iron-bearing formation interbedded or at least interlaminated with small quantities of clastic rocks and associated with large quantities of the Ely greenstone and later intrusive rocks. From the large belts more than half a mile wide, dominantly composed of the Soudan formation, to very narrow stringers or patches in the Ely greenstone there are all variations. Though here and there the large areas are well exposed, on the whole the formation is relatively soft as compared with the Ely greenstone, and therefore it usually forms valleys. This is true even of the belt at Ely, which has been so great a producer of iron ore.

Westward and southwestward from Lake Vermilion, beyond the limits of the Vermilion map (Pl. VI), Keewatin, Laurentian, and Huronian formations have been traced for a considerable distance. An iron-bearing formation, correlated with the Soudan, forms a considerable belt extending from Tps. 60 and 61 N., R. 22 W., southwestward to T. 58 N., R. 27 W. It is sparsely exposed and is known principally by its disturbance of the magnetic field. A small amount of exploration has been done on this belt. For the most part this iron formation seems to be lean and unpromising.

DEFORMATION.

The folding of the Soudan formation is of the most complicated character. The major folds extend parallel to the trend of the range. The pressure has been so great as to give at many places monoclinal dips entirely across the formation. For instance, at the section near Tower the dips are almost uniformly to the north, the angles running as low as 50°. However, at many places on Tower, Lee, and Soudan hills the dips are nearly vertical, and at one place on Lee Hill, on the south side, they are steep to the south.

The cross folding of the district has been only less severe than the major folding. The pitches of the folds are ordinarily steep, from 50° to 60°, and at many places are vertical or even overturned.

Both the longitudinal and the cross folds are composite—that is, folds of the second order are superposed upon the major folds in each direction, and upon these folds are folds of the third order, and so on down to minute plications. The pressure has been so great as to produce all varieties of minor folds, including isoclinal and fan-shaped. Moreover, these varieties of folds may be almost equally well seen in a ground plan or in a vertical cross section. They are beautifully shown at various places about Tower and Ely, but perhaps the most extraordinary complex folding to be seen is that at the west end of the large island in the east part of Emerald Lake. A common type of fold is a drag fold (illustrated in fig. 12), by which the formation becomes locally buckled along an axis lying in any direction in the plane of bedding. This type of folding, while leaving great local complexity, does not destroy the general attitude or trend of the bed. It is frequently possible, where these folds are present, to work out the general trend of the formation and its top and bottom—as, for instance, in secs. 13 and 14, T. 62 N., R. 13 W., Minnesota (see fig. 13)—and for other areas it will be possible by close detailed surveys to work out the stratigraphy of the Keewatin series.

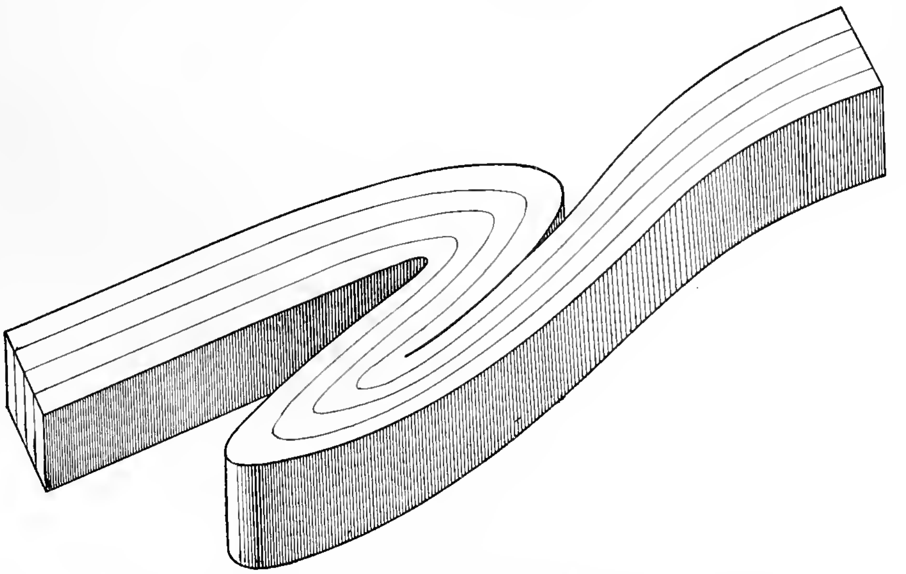


FIGURE 12.—Diagram to illustrate folding of "drag" type, common in the Vermilion and other ranges. Note the facts that folding tends to multiply the thickness by 3 and that folding of adjacent beds may not be marked.

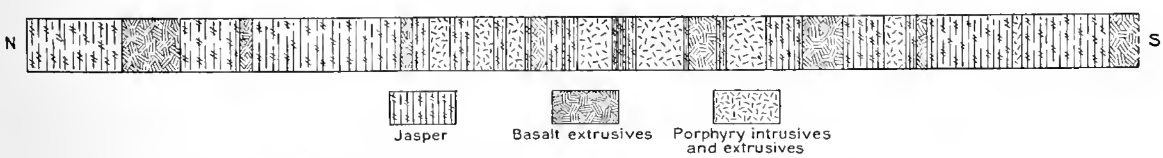


FIGURE 13.—Section across jasper belt in secs. 13 and 14, T. 62 N., R. 13 W., Vermilion iron range, Minnesota, Scale, 1 inch=about 85 feet.

The folding, notwithstanding the extraordinarily brittle character of the rock, was accomplished without major fracture. Frequently a solid belt of jasper may be seen bent back upon itself within its own radius with no sign of fracture. The deformation, therefore, was in the zone of rock flowage, and no better instance is known to us of this kind of earth movement. Though the folding is so complex as to give isoclinal or fan-shaped folds, ordinarily the turns are round rather than acute, as they commonly are in the Menominee district.

Folding without brecciation is the rule, but in some places the Soudan formation has been brecciated in an extraordinary manner. It is broken through and through by cracks and crevices, along which minor faulting has taken place. In some places the grinding of the fractured fragments over one another has been so marked as to give them a well-rounded character, and such a rock resembles a conglomerate, though it is really autoclastic. This local brecciation of the Soudan formation has been favorable to the deposition of the ores, and it may be suggested that the general absence of the brecciation is the partial explanation, at least, of the very irregular distribution and scarcity of the ore bodies.

The Vermilion district affords excellent illustrations of complex folds, or folding in two directions at right angles, and the formation which best exhibits this folding is the Soudan. This is because the banding of the formation is very marked, so that the position of bedding is readily determined, and also because for the most part the rock does not take on schistosity. Schistose structure is absent partly because the minerals of the rocks are not adapted to a parallel arrangement. Furthermore, the Soudan rocks are frequently found in contact with the Ely greenstone, and the contacts give the pitches of the cross folds.

The remarkable complex folding partly explains the distribution of the Soudan formation with reference to the Ely greenstone. As upon the major folds are superposed secondary and tertiary folds, numerous patches of the jasper are naturally found in the greenstone. Moreover, because of the cross folding these patches may be very narrow at one place, widen out within a very short distance so as to make a thick formation, and again become narrow. When the extraordinary complexity of this folding is understood it is only necessary to premise an erosion extending to different depths in the Soudan formation before the lower Huronian was deposited in order to see how in the greenstone there may be patches of jasper ranging from a few feet in width and length to the dimensions of great continuous formation about Tower and Ely. But folding is not the only cause of the present relations, as is shown on page 126.

LITHOLOGY.

The iron-bearing Soudan formation comprises two classes of rocks. To all the varieties of the first the miners apply the name "jasper," although only a portion of it falls strictly under this designation. This is the dominant variety of the rock. Locally interstratified with the "jasper" or under it is an argillaceous variety, which is mainly slaty but in some places is conglomeratic.

The "jaspery" phase of the Soudan formation consists of interlaminated bands of finely crystalline quartz, iron oxides, and various mixtures of the two. With these preponderating minerals are various subordinate constituents, among which amphibole is the most abundant, including actinolite, cummingtonite, and grünerite. Pyrite is also present in many places. The alternate bands of material of different color, combined with the complicated fracturing and brecciation of the formation, make it a striking rock which always attracts the attention of the traveler, even if he is not accustomed to closely noticing rocks. The bands of material of different color vary from a fraction of an inch to several inches across. The quartzose bands have various colors—nearly pure white, gray, red of various hues, including brilliant red, and black. The difference in the color is chiefly caused by the contained iron. Hematite, if in sufficiently fine particles, gives the brilliant red colors; magnetite and hematite in larger particles give the grays and blacks.

Between the bands dominantly quartzose are usually bands mainly composed of iron oxide This iron oxide may be either hematite or magnetite or various intermixtures of the two. Occasionally also some limonite is present.

The chief varieties of the "jasper" are (1) the cherty variety, (2) the black-banded variety, (3) the red-banded variety, and (4) the white-banded variety. With these are subordinate masses of (5) the carbonated variety and (6) the ore bodies.

1. The cherty variety is characterized by the presence of a predominating amount of gray chert, the iron oxide being subordinate. The rock is there a slightly ferruginous well-banded chert.

2. The black-banded form of the Soudan formation has dark-gray or black chert bands interlaminated with black iron-oxide bands. The iron oxide is commonly in large part magnetite. Usually associated with this magnetite are some of the amphibole minerals already mentioned.

3. In the red-banded kind the quartzose layers are stained with innumerable minute flakes of hematite, which give the rock a red color, in many places a brilliant red. The iron oxide between the red bands is ordinarily hematite, usually specular hematite. With this hematite may be some magnetite. This red-banded variety is a well-known jasper of the Lake Superior region, to which Wadsworth has applied the name jaspilite.

4. In the white-banded kind the quartzose bands contain comparatively little iron oxide. The iron-oxide bands between the layers of chert are generally hematite, but this hematite differs in many places from that of the jaspilite bands in that it is of the red or brown variety. With it also, in many places, there is a certain amount of limonite.

5. The banded carbonate variety, while subordinate in quantity, is important in reference to the genesis of the formation. It is a gray-banded rock, the light-colored layers of which consist largely of siderite. Between this sideritic rock and the ordinary forms there are all stages of gradation.

6. The positions of the iron-ore bodies will be fully discussed later. In the iron ores the silica is very subordinate, the place of the quartzose bands being taken by iron oxide. The iron ore is dominantly hematite.

At the contact of the Soudan formation and Ely greenstone the cherty variety of rock is very common indeed. In many places the rock at this horizon is much brecciated and commonly has a conglomeratic appearance, which, however, is believed to be due to movement rather than to deposition as a conglomerate. Ordinarily this cherty variety of the formation is not more than a few feet thick. Resting upon the cherty zone in many places is the black-banded kind. Ordinarily at the top of the formation is the red-banded rock, jasper, or the white-banded kind.

The succession given above prevails in many places where the formation is now thick. Where the formation is thin the red and white banded rocks extend from the top to the bottom, and as at many places the formation is rather thin it may be said that the entire Soudan formation for much of that district consists of these kinds of rocks, the cherty variety and the black-banded variety not appearing.

The sideritic rock is notably local in its occurrence. It is generally found close to the overlying upper Huronian rocks.

The slaty phase of the Soudan formation differs from the ordinary phases in having between the silica and iron-oxide bands so large an amount of argillaceous material as to make laminæ of slate. In some places a slaty cleavage has developed in the clayey layers but does not pass through the iron-oxide bands, and this may be so even where the bands of slate are not more than one-fourth inch across. Locally the slate may be in a belt several feet thick without interstratified jaspery material. In some places this slate is graphitic. At a few places at the bottom of the Soudan formation the slate passes down into a fine-grained conglomerate or into a tuff. A microscopic examination of the argillaceous varieties of the slates shows these sediments to be made up of chlorite, actinolite, epidote, sericite, sphene, quartz, carbonaceous material (graphite), and some iron oxides, in various proportions. The graphitic slates consist essentially of graphite and quartz in exceedingly fine grains and in some specimens in very small quantity.

The conglomeratic phases of the formation, when studied under the microscope, are found to be substantially identical with the tuffs of the Ely greenstone. They now consist largely of actinolite, chlorite, epidote, and quartz.

ORIGIN.

From the foregoing facts it is clear that the Soudan is a sedimentary formation, mainly of nonclastic character. This would perhaps be evident from the well-bedded character of the formation and especially from the iron carbonate. Also, as already indicated by the description of the different rock varieties, certain phases of the formation have argillaceous bands between the iron-oxide bands, which are not uncommonly graphitic. Finally, it contains local conglomerates.

There is reason for believing that many varieties of rock in the Soudan formation are derived from siliceous iron-bearing carbonate, precisely as similar rocks are derived from this material in other districts of the Lake Superior region. The analogy between the Soudan formation and the Negaunee formation of the Marquette district is especially close. Substantially every variety of rock which is found in one district may be found in the other. A variety may be somewhat more prevalent, however, in one district than in the other; for instance, the amphibole minerals are less abundant in the Soudan formation than in the Negaunee formation. In the absence of local specific evidence of the original character of the iron-bearing rocks in the Vermilion district it is probably not safe to put too much stress on the similarities with other districts where the original character of the rock is certainly known. One must admit the distinct possibility that the iron-bearing sediments may have been originally deposited substantially as banded chert and iron oxide of the jasper type.

RELATIONS OF ELY GREENSTONE AND SOUDAN FORMATION.

The main mass of the Soudan formation seems to be above the Ely greenstone. In certain places it is known to be in pitching troughs formed by folding, the greenstone forming the walls and bottom, as, for instance, at Ely and Soudan.

Some of the jasper belts of the Vermilion district are clearly interbedded with successive basalt extrusives. Such beds, but a few feet thick, may be traced for hundreds of yards with uniform widths, even contacts, and lack of folding. When the adjacent igneous rocks are examined closely it is found that the sedimentary bands lie parallel to the tops and bottoms of separate flows, as marked by amygdaloidal and other surface textures, without intervening fragmental sediments. This is well illustrated in secs. 13 and 14, T. 62 N., R. 13 W., Minnesota. (See fig. 13, p. 123.)

Many of the jasper bands are associated even more closely with intrusive and extrusive porphyries than with the greenstones. (See p. 128.) These porphyries are found to be closely related to the extrusive basalts but on the whole to follow them and to be associated with their later phases of extrusion. This association of the iron with the later acidic phase of extrusion is also seen in the Woman River district of Ontario. Its significance is discussed on page 513.

The most common contact between the Ely greenstone and the Soudan formation is perfectly sharp—indeed, knifelike in its sharpness. The rocks are as sharply separated from each other as if the Soudan formation were intersected by the greenstone by intrusion, and doubtless this is, at least in a few places, the true significance of the relations. Contacts of the kind mentioned may be seen at many places in both the west and the east end of the district. They are especially clear and numerous in Hunters Island and at Jasper Lake, Birch Lake, and Emerald Lake. At each of these lakes, almost at every large outcrop of Soudan material, somewhere along the base of the formation the contact may be found.

The kind of contact next most common to that just described is that in which a brecciated rock occurs between the iron-bearing Soudan formation and the Ely greenstone. This breccia ordinarily is not more than a few feet wide. In some places it involves only the greenstone, elsewhere the Soudan formation only, in still other places both. Thus a conglomerate-like rock may show fragments and matrix mainly of greenstone or almost wholly of Soudan formation, or the two intermingled. In the last case the greenstone is more likely to be the matrix and the Soudan rock to constitute the fragments. A breccia of the greenstone class is well seen on an island near the west end of Otter Track Lake. The brecciated Soudan formation is well exhibited in belts of Soudan rock north of Robinson Lake, in sec. 7, T. 62 N., R. 13 W. A breccia composed of greenstone and Soudan material is seen at various places on Lee Hill. Here is a green schist matrix containing numerous fragments of red jasper, each exhibiting its banding, which lies in diverse directions. Some of these fragments are well rounded; others are subangular; many others have angular rhomboidal forms, such as are produced by shearing stresses. However, these fragments are not more angular than those in a basal conglomerate at many localities.

The question may be asked whether the breccias were conglomerates before they were breccias. At present their dominant structure is doubtless that of a dynamic breccia, but it is also possible that some of them at least were originally conglomerates and were subsequently brecciated. This question, early asked, is still unanswered. Probably certain of the rocks referred to are wholly breccias, being produced by readjustment along the contact of the two formations during orogenic movements. A sharp contact of the first class might, by close folding and adjustment between the formations, produce a contact of the second class by brecciation and rounding of the fragments, thus forming a pseudoconglomerate.

At contacts of a third kind is a rock which seems to be a metamorphosed mechanical sediment. As a rule, this rock varies from a few inches to several feet in thickness. It consists of alternating layers of green schist or slate and light-colored, strongly siliceous, graywacke-like material. These alternations of schist and graywacke naturally give a remarkably sedimentary appearance; in fact, it seems as if the banding could have been produced in no other way. The two localities which best exhibit these materials are a neck of land between two small lakes about a mile north of Moose Lake and one place on Lee Hill. At the first locality alternating bands of slate and graywacke rest against perfectly typical ellipsoidal greenstone, and interstratified with these slates and graywackes are narrow bands of jasper. These alternations are overlain by a broader belt of jasper. The probable interpretation of the phenomena seen here is that a few feet of mechanical sediments were deposited upon the Ely greenstone before the deposition of the nonclastic material of the Soudan formation. Moreover, it seems that there were alternations between the condition of mechanical deposition and the peculiar condition of chemical or organic deposition of the Soudan formation.

The relations at Lee Hill are substantially the same, except that at this place the folding is so close that a cross cleavage cuts through the finer-grained sediments, and on account of this close folding and the secondary cleavage the phenomenon is more difficult to certainly interpret. However, the slate and graywacke appear to plunge under the jasper of the Soudan formation, and the explanation is with little doubt the same as for the contact north of Moose Lake.

A contact of a fourth kind is marked by a thin belt of greenstone conglomerate. The best localities at which this is seen are north of Robinson Lake and at the pits of the Lee mine. At the first locality, at the west end of the belt of Soudan formation, the ellipsoidal greenstone is overlain by a layer a few feet thick of greenstone conglomerate, which passes up into graywacke. The pebbles of this greenstone conglomerate are flattened, and it could not be said positively that the rock is not a tuff rather than a conglomerate.

Finally, the Soudan and Ely formations may be separated by a thin layer of graphitic black slate, well shown on the southwest side of Soudan Hill.

From the fact that the greater masses of the Ely greenstone were deposited before the larger masses of the Soudan formation it is believed that the great volcanic period of the Ely greenstone had practically ceased before Soudan time. However, the extremely intricate relations and apparent interstratification of the minor masses of the Soudan formation with the Ely greenstone and the fact that both the Ely and Soudan formations locally contain interstratified fragmental material lead to the belief that volcanic activity had not entirely died out in all parts of the district at the time of the deposition of the earliest Soudan rocks. In consequence there are interlaminations of rocks essentially belonging to the Ely with rocks essentially belonging to the Soudan.

What were the physical conditions which permitted the deposition of the nonmechanical Soudan formation upon the Ely greenstone with so insignificant an amount of intervening mechanical sediment and erosion surfaces? If the Ely greenstone was subaerial, it is difficult to understand how this material could have got below the water without the deposition of a greater thickness of mechanical sediments than exists in the Vermilion district. We know that such lavas are very rough in their surface expression and vary greatly in thickness, and therefore in altitude. It is impossible to believe that the sea could advance over such an area without the production somewhere of mechanical sediments of considerable thickness. The answer to this question seems to be that the eruptions of the Ely greenstone were submarine. The ellipsoidal textures are regarded as evidence of submarine flows, for reasons given on pages 510–512. The lack of erosion surfaces in the flows and the absence of fragmental material at the base of the formation itself are evidence of such an origin. If these lavas issuing from the interior of the earth were spread out below the surface of the water, after the period of volcanism had ceased and conditions became quiescent nonmechanical sediments of the iron-bearing formation might at once be deposited, provided the conditions were proper. The conditions of sedimentation are further discussed in the chapter on the origin of the iron ores.

LAURENTIAN SERIES.

PORPHYRY.

Intrusive into the Ely greenstone and Soudan formation are various Archean felsites and porphyries in dikes and bosses. These are exceptionally well seen in the Vermilion Lake area, especially at Stuntz Bay. As already noted, these intrusives may be in part connected with acidic flows interbedded with some of the later flows of basalt in the Ely greenstone. (See p. 126.)

Petrographically the porphyry comprises rhyolite porphyry, feldspathic porphyry, microgranite, granite, microgranite porphyry, and granite porphyry. In places these rocks have been metamorphosed into sericite schists and chlorite schists. There is no doubt that these rocks are older than the lower Huronian, because they yield fragments to the Ogishke conglomerate, but at various places their relations to the conglomerate are extremely intricate. (See p. 131.) The folding has formed breccias and pseudoconglomerates from the felsites and porphyries, which when very much mashed have been sometimes confused with the true Ogishke conglomerate.

GRANITE OF BASSWOOD LAKE.

The granite of Basswood Lake extends as a great continuous formation north of the Ely greenstone and the Huronian rocks from the western to the eastern end of the district, where it is locally known as the "Saganaga Lake granite." Lakes are rather numerous in this great granitic area, but they are not so numerous nor so regularly ordered as those in the Ely and Soudan formations. On the whole the granite area is one of highlands and divides between the waters running north and south.

Petrographically the granite varies from hornblende and mica granite to syenite. Structurally it varies from massive granite through schistose granite to gneiss. Texturally it includes granites and granite porphyries. The mineral constituents are green hornblende, biotite, orthoclase, quartz, and plagioclase, with accessory sphene, zircon, and iron oxide. In many places these minerals have been very much altered, so that their places are taken largely by secondary minerals, of which chlorite is the most prominent and epidote, sericite, and secondary feldspar come next. There is a variation in the mineral character, hornblende being virtually absent in some specimens and abundant in others. No specimens were found in which quartz was not present, but the amount is small in some of them.

The granite is intrusive into the Ely and Soudan formations. The field relations are most complex but are practically the same in all parts of the district—that is, the phenomena to be seen in passing from the other Archean formations to the granite are substantially the same whether the traverse be made at Vermilion Lake, at Burntside Lake, at Basswood Lake, or at any other point.

In approach to the granite from the Ely greenstone side little stringers of quartz first appear in the greenstone, then sparse veins of feldspar, then clean-cut dikes of granite, usually of small size. With closer approach these increase in number and size until they constitute a plexus of granite dikes in the greenstone. Still farther north the greenstone and granite may be found in such confused and intricate relations as to make it difficult to say which is the more abundant. Here great knobs of granite as well as dikes occur in the greenstone masses. In the granite knobs are included fragments of the greenstone, large and small, in many places in great numbers. Farther north the granite becomes dominant and finally altogether excludes continuous masses of greenstone. If any greenstone is found it will be only in the form of included masses. In brief, the relations are like those, so clearly described by Lawson, between the batholiths of granite and the contiguous greenstones of Rainy Lake and Lake of the Woods.

The granite has been spoken of as if its intrusion were a single episode. This is not supposed to be true. On the contrary, the relations of the different granites to one another and to the greenstones are very intricate, hence it is thought that various intrusions were separated by long intervals of time, that many of the intrusions were of themselves complex and long continued, and that, in fact, this igneous period was a complex and long-continued one.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER-MIDDLE HURONIAN.

GENERAL STATEMENT.

The inferior series of Huronian rocks occupies the general position of the lower and middle Huronian of the south shore. It will be called lower-middle Huronian, with the understanding that it may include either or both lower Huronian and middle Huronian.

The lower-middle Huronian consists of four divisions—(1) a lower division, predominantly conglomeratic, which is most typically developed near Ogishke Muncie Lake and is known as the Ogishke conglomerate; (2) a division represented only in the eastern portion of the district, consisting of iron-bearing rocks and known as the Agawa formation; (3) a division which is predominantly a slate formation and which is called the Knife Lake slate because it is well developed and splendidly exposed on and near Knife Lake; and (4) intrusive rocks.

OGISHKE CONGLOMERATE.

DISTRIBUTION.

The Ogishke conglomerate extends from the western end of the district to the east end, though it varies greatly in thickness. In places it is a great formation; in other places it is nearly absent or is so thin that it can not be represented on the maps without a gross exaggeration.

The localities at which the conglomerate can be best studied, beginning at the west, are (1) southeastern Vermilion Lake and especially Stuntz Bay and vicinity; (2) Moose, Snowbank, and Disappointment lakes and vicinity; (3) Ogishke Lake and the extensions of the belt there to the southeast, northeast, and west.

DEFORMATION.

The Ogishke conglomerate is infolded in an extremely intricate manner with the underlying formations. This infolding is almost if not quite as complex as the infolding of the Soudan formation and the Ely greenstone already described. Owing to isoclinal folding and cross folding with steep pitches, a rock surface cutting diagonally across the plane of contact shows the most extraordinarily irregular distribution of the Ogishke and the underlying formations. Because of this it was supposed by a number of the early geologists that the Ely greenstone and the porphyry of Stuntz Bay were intrusive into the Ogishke conglomerate.

LITHOLOGY.

In general all the belts of conglomerates are coarser below and become finer toward higher horizons. This statement is, however, only true as an average. There are places where the conglomerate is somewhat fine at the bottom, is coarser above for a certain thickness, and thence becomes finer upward.

The character of the Ogishke conglomerate depends largely on the nature of the underlying formations. These formations, as already noted, are the Ely greenstone, the Laurentian granite of Basswood Lake, the Soudan formation, and the Laurentian porphyry of Stuntz Bay. Where the conglomerate rests on one of these formations the material composing it is mainly derived from that formation. There are four special varieties of the Ogishke conglomerate—(1) greenstone conglomerate, (2) granite conglomerate, (3) porphyry conglomerate, (4) chert and jasper conglomerate. The common kind of Ogishke conglomerate (5) represents combinations of the special phases.

Greenstone conglomerate.—The Ogishke is a greenstone conglomerate at those localities where the conglomerate rests upon the Ely greenstone and other lower formations are not adjacent. One of the localities which exhibit this greenstone conglomerate in its typical character is the south side of Ogishke Lake and, peripheral to the Ely greenstone massifs, to the east on Frog Rock Lake. The rock is also found in equally good development on Hunters Island, at the southwest of Lake Saganaga.

At these localities the greenstone conglomerate consists for the most part of very well rounded fragments of the Ely greenstone set in a matrix derived from the same source. These fragments are ordinarily of a size to make pebble conglomerates, but at some places many of them are so large as to constitute bowlder conglomerates. Between the bowlders and pebbles are smaller fragments of the same material, and between these is a finer matrix derived from the same source. In most places upon the weathered surface the conglomerate character of this rock is evident, but on a freshly broken surface the matrix and pebbles are so similar that the rock seems to be a continuous mass of greenstone. The conglomerate character is especially difficult to discover in the unbroken forests, where the rocks are covered with moss and other vegetation. The débris, being derived from the Ely greenstone, consists of all the varieties of rocks shown by that formation. There are, accordingly, fragments of dense, massive greenstone, of amygdaloidal greenstone, of various kinds of ellipsoidal greenstone, etc. These rocks grade locally into rocks that may be tuffs. In certain places the conglomerate is discriminated from the tuff only by finding that the rock occupies a definite stratigraphic zone at the base of the lower Huronian sediments. Locally discrimination is still impossible.

Granite conglomerate.—The granite conglomerate occurs along the west border of Lake Saganaga. At the west side of the south arm of Cache Bay is a great bowlder conglomerate the fragments of which are directly derived from the granite. The matrix also came almost wholly from this source. The exact contact of the conglomerate and granite may be seen. The bowlders and pebbles of the granite conglomerate are well rounded, and in every respect this conglomerate bears the same relations to the granite that the greenstone conglomerate does to the Ely greenstone.

The granite conglomerate is associated with a peculiar variety of rock, which may be called recomposed granite. It appears that when the Ogishke formation was laid down the granite only locally yielded coarse débris. For the most part it yielded the separate individual minerals of the coarse granite—that is, feldspar, quartz, etc. As a result a clastic formation was laid down upon the granite, the particles of which were the individual minerals of the granite. Furthermore, these particles were but little waterworn. The result is that when they were recemented a rock was produced which closely resembles the granite. This resemblance is, indeed, so close that the rock was first mistaken by a number of geologists for the granite.

This rock is exposed along the west side of Cache Bay, at Swamp Lake, at the west side of West Seagull Lake, and at intervening points. For much of this distance this peculiar formation has a breadth of nearly half a mile.

Porphyry conglomerate.—The porphyry conglomerate is confined mainly to the area about Stuntz Bay, the débris being derived from the Laurentian porphyry. In the past it has been known as the "Stuntz" conglomerate. In places there is a coarse bowlder conglomerate, in other places a fine conglomerate, and in still other places a graywacke composed of the individual minerals of the porphyry, so that the rock closely resembles the original porphyry. Furthermore, so similar are the bowlders and the matrix that the conglomerate itself has been confused with the brecciated porphyry.

Chert and jasper conglomerate.—The chert and jasper conglomerate is found where the underlying formation is the Soudan. This conglomerate is, however, not anywhere known to be solely composed of the Soudan material. In this respect this variety of rock differs from the varieties already described. Locally, however, the conglomerate is predominantly composed of material derived from the iron-bearing formation. This variety of rock may be seen on Lee Hill, just north of Tower, on the Burnt Forties southeast of Vermilion Lake, and at other localities.

Common Ogishke rock.—The varieties of the Ogishke conglomerate heretofore described, each consisting largely of material from a single source, are, on the whole, rather exceptional, though the greenstone conglomerate and the porphyry conglomerate occupy considerable areas. It is natural to suppose that the Ogishke would have material derived from more than one of the previously existing formations, and ordinarily it has. Thus the normal Ogishke conglomerate consists of intermixtures in various proportions of the materials derived from the Ely and Soudan formations, the granite of Basswood Lake, and the Laurentian porphyry, or two or more of them. Hence there is every gradation between the average form of the Ogishke conglomerate and the special forms which have been described. Within the Ogishke conglomerate, in addition to the common fragments already enumerated, there are occasional unquestionable slate fragments. These are seen at various places, but are especially abundant south of Moose Lake. It is believed that the source of the fragments of this kind is the slate and graywacke of the Ely and Soudan formations.

METAMORPHISM.

The Ogishke conglomerate varies greatly in its metamorphism. In general the processes of the change have been mainly those of metasomatism and cementation, but locally the conglomerate is recrystallized and schistose. These phases are especially likely to be adjacent to the massive granite, greenstone, or other rock against which they rest. Where the process has gone to an extreme it is difficult to place the exact dividing line between the original and recomposed formations. The difficulty is particularly likely to occur in reference to the greenstone conglomerate and the Ely greenstone.

The extreme phase of the metamorphism of the Ogishke conglomerate results from the intrusion of igneous rocks, and especially the Huronian Snowbank granite and the Keweenawan Duluth gabbro. Adjacent to these intrusives the conglomerate is a conglomerate schist or gneiss, the matrix of which is usually mica schist where the Huronian is of an acidic kind or amphibole schist where it is of a basic kind.

The conglomerate schist adjacent to the gabbro may be found from points east of Fay Lake to Lake Gabimichigami. The conglomerate schist near Snowbank Lake and Disappointment Lake has suffered the metamorphosing effect of the Snowbank granite and the Duluth gabbro. The changes in the conglomerate are analogous to those which have taken place in the Knife Lake slate, which is in a similar position with reference to the granite. (See pp. 133–135.)

RELATIONS TO ADJACENT FORMATIONS.

The Ogishke conglomerate, as the foregoing description plainly shows, is unconformable with the underlying formations. It may safely be inferred that this unconformity is one of great magnitude. The evidence is of two kinds—the character of the detritus and the structural relations.

The detritus includes every variety of each of the formations of the Archean, including the many phases of the Ely and Soudan formations and the granite of Basswood Lake. In order to produce these many varieties, the Archean went through a long and complex history of folding, intrusions, metamorphism, and erosion.

As to the structural relations, the Ogishke conglomerate is here in contact with one of the underlying formations, there with another. It is therefore clear that after the Archean complex was produced it underwent deep erosion before the deposition of the Ogishke conglomerate, for some of the formations constituting the Archean were produced at great depth.

Upward the Ogishke conglomerate grades into finer and finer material and passes conformably into the Agawa formation or the Knife Lake slate.

THICKNESS.

The thickness of the Ogishke conglomerate varies greatly. It is nowhere possible to make accurate measurements, owing to the general absence of bedding and to the close folding, but it is certain that the formation has a considerable thickness, certainly several hundred feet, and perhaps in some places more than 1,000, possibly 2,000. From this maximum thickness the formation varies to a thickness of only a few feet or less, and is absent in places.

AGAWA FORMATION.

In the eastern part of the district, above the Ogishke conglomerate, or, where that formation is absent, beneath the Knife Lake slate, is an iron-bearing formation called the Agawa. On the American side of the international boundary this formation is so thin that it can not be regarded as continuous. On the Canadian side of the boundary, especially at That Mans, Agawa, This Mans, and Other Mans lakes, the formation ranges up to 50 feet in thickness and has all the characteristic rocks of the other iron-bearing formations of the Lake Superior region, including ferruginous carbonate, ferruginous slate, ferruginous chert, jasper, and iron oxides. Interlaminated with the ferruginous varieties are belts of slate. Thus the iron-bearing formation is both small and impure. There is every reason to suppose that the origin of this iron-bearing formation is similar to that of the other Lake Superior iron-bearing formations.

The Agawa formation, so far as at present known, has no economic importance, but it may have a geologic significance, considering that it is in the lower-middle Huronian. The only iron formation at this horizon in other parts of the Lake Superior region is the Negaunee, and so correlation would be suggested with that formation. The bearing of this suggestion on the position of the group to which the Agawa belongs is pointed out elsewhere (pp. 603–604).

KNIFE LAKE SLATE.

GENERAL STATEMENT.

The Knife Lake slate was so named because it occurs in its typical character at Knife Lake. Nearly all the long arms of that lake lie within the slates, and by far the greater number of the many islands and headlands are composed of them.

The slates are found in two great areas, one in the western part of the district and the other in the central and eastern parts. The western area extends from the east end of Vermilion Lake westward to parts where the rocks are covered by the Pleistocene. It occupies much of the shore and many of the islands of Vermilion Lake. The eastern area begins west of Long Lake and extends eastward, becoming gradually broader, and in the eastern part of the district is the most extensive formation there found.

LITHOLOGY.

The Knife Lake slate comprises the following main varieties:

1. Argillaceous slates.
2. Cherty slates.
3. Graywacke slates and graywackes.
4. Conglomerates.
5. Tuffaceous slates.
6. Micaceous (and, less commonly, amphibolitic) schists and gneisses.
7. Gray granular rocks.

There are also all gradations between these varieties. The materials of different coarseness are in many places finely interlaminated, so that it is easy to ascertain strikes and dips.

The argillaceous slates vary in color from gray to black. They are usually very dense, break with a smooth, conchoidal fracture, and have a perfect cleavage, which in a general way commonly follows the trend of the district but whose direction varies much locally, depending on the surrounding rocks, the folding, and other factors.

The cherty slates differ from the argillaceous slates in that they contain an unusual amount of finely crystalline quartz. In many places this quartz is the dominant constituent. Between the beds of very siliceous slate in many places there are also pure bands of chert. These cherty bands in most places appear to be secondary segregations. In many places the amount of the finely crystalline quartz in the separate cherty bands and in the main mass of the slate is so great as to suggest that the deposits of fine mud had mingled with it silica of organic or chemical origin. Conchoidal fractures are especially characteristic of the cherty slates.

The argillaceous slates and cherty slates pass into varieties which may be called graywacke slate and graywacke. These differ but little from the finer-grained slates except that cleavage is less likely to be developed in them. Cleavage is usually present in the graywacke slates but not in the graywackes.

Not uncommonly the graywackes pass into conglomerates. The fragments found in the conglomerate comprise all the varieties of material found in the Ogishke conglomerate. These, it may be recalled, are the many phases of material derived from the Archean. Indeed, there is no essential difference between these conglomerate bands and the Ogishke conglomerate, except that the conglomerate bands of the Knife Lake slate are ordinarily fine grained and are subordinate in quantity to the slates.

During Knife Lake time there was volcanic action, and close to the volcanoes, as at Lake Kekekabic, ash and larger fragments produced by explosive volcanic action are mingled with the other materials of the Knife Lake slate. These volcanic materials constitute the tuffaceous slates. Between the tuffs and the conglomerates and slates there are all gradation varieties. Indeed, microscopic examinations show that the ashy products of the volcanoes were widely distributed and are important constituents of the varieties of the formation already described—the argillaceous and cherty slates and graywackes.

The mica slates, mica schists, and mica gneisses are confined to areas adjacent to subsequent intrusive rocks. The most important areas are south of Tower, along Kawishiwi River, adjacent to Snowbank, Disappointment, and Kekekabic lakes, and adjacent to the Keweenawan gabbro.

At Snowbank Lake and near it the granite has been intruded into the slates in a most complex fashion, and here next to the granite the Knife Lake slate is represented by mica schists. Between the mica schists and the ordinary slates there are gradations through mica slates. Here the granite is found in numerous great dikes intersecting the Knife Lake slate. Moreover, in many places the granite injections have followed the banding of the slate so as to give close parallel injections. In some places there are within a single hand specimen several bands of granite. Also bands are found intermediate in character between the well-recognized granite and the slate. There is no doubt that these bands are due to granitization. Where the injection is of the most complex kind the rock is a mica gneiss, the darker-colored bands of which are largely the extremely metamorphosed granite. However, some material in the black bands has doubtless been derived from the granite and some material in the light bands has been derived from the slate.

The schists and gneisses are especially well exposed on the north side of Snowbank Lake. South of Tower, adjacent to the granite, and especially at localities near the Duluth and Iron Range Railroad, the alterations are essentially the same as at Snowbank Lake, except that the amphibole schists are more prominent. Also the alteration phenomena at Kekekabic Lake are in the same direction as at Snowbank Lake, but the processes have not gone so far.

At Kawishiwi River southwest of Snowbank, and at Disappointment and Gabimichigami lakes, the great gabbro mass of the Keweenawan has profoundly affected the character of the Knife Lake slate and has produced a peculiar gray granular rock which the Minnesota geologists have called "muscovado." These rocks differ from the slates and schists about Snowbank Lake in being almost massive. They are particularly well seen at Disappointment Lake. Between the schists north of Snowbank Lake and the granular rocks of Disappointment Lake there are gradations. These granular metamorphic rocks adjacent to the gabbro are regarded by Grant as the result of contact metamorphism of the Knife Lake slate. They recrystallized under deep-seated static conditions at high temperature and probably influenced by abundant moisture. The difference between them and the schists and gneisses of Snowbank Lake shows how important a part orogenic movement probably had in the production of the structures of the latter rocks. The schists and gneisses of the Knife Lake slate are the joint product of dynamic and contact action. The granular rocks which are adjacent to both the Snowbank granite and to the gabbro have doubtless undergone two periods of metamorphism, the earlier one at the time of the introduction of the Huronian Snowbank granite and a later one by the Keweenawan gabbro. At the earlier time doubtless schists and gneisses were produced under dynamic conditions which at the earlier time were transformed to granular rocks under static conditions.

MICROSCOPIC CHARACTER.

Clements's microscopic study shows that the rocks of the Knife Lake slate, including argillaceous and cherty slates, graywacke slates, graywackes, conglomerates, and tuffs, have as recognizable primary constituents feldspar, quartz, brown mica, white to green and violent-brown pyroxene, and greenish-brown hornblende. The clastic mineral grains very commonly have been extensively altered, and from these have been produced the following secondary minerals, which, in some places where the rocks are completely recrystallized, are the sole constituents: Chlorite, epidote, sericite, actinolite, massive dark-brown and green hornblende, quartz, calcite, and pyrite. The minerals between the grains in the coarser sediments are sericite, chlorite, epidote, quartz, and feldspar. These are believed to have been produced from the recrystallization of the fine detrital material originally lying between the larger grains.

The minerals constituting the mica slates, mica schists, and mica gneisses, recrystallized under the influence of the granite intrusion, are usually biotite and locally some muscovite, hornblende, actinolite, quartz, feldspar, epidote, and garnet.

The granular rocks metamorphosed by the gabbro are mica, hornblende, and pyroxene feldspar rocks containing little quartz. The mica (chiefly biotite, but with some muscovite) and hornblende together predominate over the feldspar, and the mica is usually more abundant than the hornblende. With these chief constituents there occur considerable amounts of hypersthene, light-green pyroxene, olivine (?), and magnetite, and with these subordinate amounts of titanite, epidote, garnet, and chlorite. Exceptionally in these gabbro contact rocks the hypersthene is the predominant constituent, when it is usually associated with considerable mica and magnetite. In general we may say that the production of minerals rich in magnesium and iron is characteristic of the gabbro contact.

DEFORMATION.

The Knife Lake slate has undergone the same orogenic movements as the Ogishke conglomerate. The slates have therefore been folded in a composite and complex fashion. For the most part it is difficult to make out in detail the structure of the slates, but enough has been done to show that the folding is exceedingly complex. Superimposed upon folds of the first order are those of the second order; on these there are those of the third order, and so on indefinitely. The relations of the Knife Lake slate to the Ogishke conglomerate and to the Ely greenstone disclose in a general way the character of the major folds.

Usually the slates are in synclines between anticlines composed of the Ely and Ogishke formations or one of them. As the formation is relatively nonresistant, many of the lakes are in the centers of these synclines. Such synclines are occupied by the following linear lakes or groups of lakes: Vermilion Lake; Long and Fall lakes; Pine, Moose, New Found, Sucker, Birch, and Carp lakes; That Mans Lake, Agawa Lake, This Mans Lake, and No Mans Lake; Knife Lake and its two principal arms; Kekekabic and Ogishke lakes. Not uncommonly the synclines of slate are broken up into two or more minor folds by subordinate anticlines, which may be marked by the appearance at the surface of the Ogishke conglomerate.

RELATION TO ADJACENT FORMATIONS.

The Knife Lake slate in the eastern part of the district reposes on the Ogishke conglomerate or the Agawa formation. For the western part of the district it lies on the Ogishke conglomerate. In both places the transition to the Knife Lake slate is conformable. The Knife Lake slate is not in observed contact with the Animikie group within the Vermilion district, but there is almost certainly an unconformity between them. The lower-middle Huronian rocks are characteristically steeply inclined and schistose, contrasting with the less folded and less schistose Animikie rocks. Also, rocks similar to the lower-middle Huronian of the Vermilion district are on satisfactory evidence found in the Mesabi district to be unconformably below the Animikie or upper Huronian.

THICKNESS.

On account of the complicated folding of the Knife Lake slate it is impossible to determine its thickness with any degree of exactness. But the extent of the areas which the formation continuously covers in the eastern and western parts of the district—a district which has been profoundly folded—leaves no doubt that the formation is one of great thickness, probably thousands of feet.

INTRUSIVE ROCKS.

Later than the deposition of the Knife Lake slate, in several parts of the district many igneous rocks were intruded. These vary from comparatively small masses to those covering very considerable areas. In chemical character they include basic, acidic, and intermediate rocks. In texture they include porphyritic, ophitic, and granolitic rocks. In age the intrusives range from rocks which are slightly later than the Knife Lake slate, and which therefore suffered orogenic movements and metamorphism with that formation, to intrusive rocks of much later age, which have been but comparatively little modified.

The more extensive of these intrusive masses are the Giants Range granite, the Snowbank granite, and the Cacaquabic granite. In addition to these there are many smaller areas of acidic and basic intrusive rocks.

The Giants Range granite extends for 20 miles or more along the Vermilion range in contact with various formations. It includes a series of granites ranging in color from light gray to very dark gray, to flesh color, pink, and red. The rock varies from very dense fine-grained granites through medium to coarse-grained ones. Though this rock is as a rule granitic in texture, there are also variations to granite porphyries and exceptionally to some that can be spoken of as rhyolite porphyries. The constituents of these granitic rocks as disclosed by the microscope are orthoclase (microcline), plagioclase, quartz, hornblende, mica, zircon, apatite, sphene, and a little iron oxide.

This granite is intrusive into the Archean and the lower-middle Huronian. The contacts will not be further mentioned, as descriptions of them and their resultant metamorphism have been given in connection with the formations which have been intruded.

The Snowbank granite is confined to Snowbank Lake and vicinity. It varies from the fine-grained to the coarse-grained form, the medium-grained facies being most abundant. Porphyritic facies of the granite also occur. Mineralogically the Snowbank granite varies from a normal mica and hornblende granite to an augite granite and, by loss of quartz, to a syenite. The Snowbank granite is intrusive into both the Ogishke conglomerate and the Knife Lake slate. The character of the contacts and the resultant metamorphism have been described in connection with those formations.

The Cacaquabic granite has been carefully mapped and described by U. S. Grant,[a] and from his report the following summary is taken.

The granite occupies an oval area south of Kekekabic Lake; also many of the islands of that lake and a few small isolated areas in the vicinity of the lake. Petrographically the rock is an augite granite, rich in soda. Its main mass has a granolitic texture; small masses are porphyritic. Grant inclines to the view that the latter is somewhat later than the former. He also regards the granite as intrusive in the Ogishke conglomerate and the Knife Lake slate, because where it is in contact with the conglomerate the granite is uniformly finer grained than elsewhere, and because the slate at one place on the north shore of Kekekabic Lake is cut by "a small irregular dike of granite, which sends many stringers into the argillite and also includes fragments of it."[b] Grant mentions no metamorphic effects of the granite on the Ogishke conglomerate and Knife Lake slate.

In addition to these granites, acidic dikes have been found cutting through the formations of the district. They are supposed to have relations with the large eruptive masses, but for the most part this connection has not been definitely traced, though it is very strongly indicated by the greater abundance of the acidic intrusive rocks adjacent to the large granite masses already described than at points remote from them.

At many places in the district are basic intrusive rocks which have a more or less well-developed schistose structure and are otherwise metamorphosed. These intrusives evidently reached their present position before the strong orogenic movements following upper Huronian time had ceased. A considerable body of these rocks occurs near Epsilon Lake and is called porphyrite by Grant.[c] Metamorphosed basic intrusive rocks of upper Huronian age are known, but they are very subordinate and unimportant in this district.

UPPER HURONIAN (ANIMIKIE GROUP) AND KEWEENAWAN SERIES.

The upper Huronian (Animikie group) occurs in a small area in the eastern part of the district just west of Gunflint Lake and in a few patches between the lower-middle Huronian and the Keweenawan as far west as Gabimichigami Lake. The relations of the Archean and lower-middle Huronian to the upper Huronian in this region are interesting, but they are discussed more appropriately in Chapter XX (pp. 599 et seq.). It is here merely to be remarked that in the Vermilion district these relations are not clear, and that for a time it was supposed that the Animikie group represented rocks equivalent to the lower-middle Huronian but less metamorphosed. Later studies of the relations of these rocks, especially in the Mesabi and Loon Lake districts, show clearly that between the lower-middle Huronian and the Animikie groups there is a very marked unconformity. (See Chapter VIII, pp. 198–210.)

[a] Rept. Geol. Survey Minnesota, vol. 4, 1899, pp. 442–448.

[b] Idem, p. 444.

[c] The geology of Kekequabic Lake in northeastern Minnesota, with special reference to an augite-soda granite: Twenty-first Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, p. 55.

As has been noted, the Keweenawan Duluth gabbro bounds the eastern half of the Vermilion district on the south. In the lower-middle Huronian and Archean rocks are numerous comparatively fresh dolerite dikes and bosses. There are also more sparingly late acidic dikes in the Archean and the Huronian. It is supposed that these fresh rocks, showing comparatively little orogenic movement, are of Keweenawan age, although they have not been connected areally with the greater masses of Keweenawan rocks. The metamorphosing effects of the Keweenawan gabbro upon the Archean and Huronian have already been considered. The Keweenawan rocks themselves are discussed in Chapter XV (pp. 366–426).

THE IRON ORES OF THE VERMILION DISTRICT, MINNESOTA.

By the authors and W. J. Mead.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The iron ores of the Vermilion district occur in the Soudan formation, belonging to the Keewatin series of the Archean system. This formation rests upon the Ely greenstone, is in places interbedded with it, is interbedded with and intruded by acidic porphyries, and as a whole has been closely folded, with the result that the iron-bearing formation stands with contorted and steeply inclined bedding, with steep walls and bottoms of green schist and mashed porphyry. These constitute deep, narrow, pitching troughs in which the ores are found. The jaspers constitute for the most part the hanging wall of the ore.

The total area of the ores is but a minute fraction of that of the iron-bearing formation of the district. It is significant that notwithstanding the enormous sums of money spent in the exploration of the district no ore deposit of magnitude has been developed outside of the two principal series of deposits at Tower and Ely, which were the first discoveries in the district.

One additional deposit in sec. 30, T. 63 N., R. 11 W., about 4 miles east of Ely, has been considerably explored, leading up to the first shipment of ore in 1910.

On Soudan Hill near Tower the structural relations of the iron-bearing formation to the green schists and mashed porphyries are so complex that it is extremely difficult to follow the ore bodies. The steeply pitching troughs branch, change their pitch, and are duplicated by parallel troughs to such an extent that in spite of the enormous amount of underground exploration to which the hill has been subjected it is not certain yet that all the ore deposits have been found. The Soudan ores may have (*a*) "paint rock" or "soapstone" as foot wall, below which is jasper, and similar paint rock or jasper as the hanging wall; or (*b*) they may have jasper both as a foot and a hanging wall, and hence may lie within it and grade in all directions into the Soudan formation. Deposits of this kind are small. The Soudan ores are mainly of the first form. They have now been found to a depth of 2,000 feet.

At Ely there is a single trough of the iron-bearing formation in the greenstone, beginning as a comparatively wide body at the west and narrowing and deepening toward the east. The northeast side of the trough seems to be formed in part by lower Huronian slates or graywackes. The greenstones associated with the ores are altered to paint rock along the contacts. This trough is a comparatively simple one, but there is also a minor parallel anticline separating the Zenith ore deposits into two portions and separating the trough longitudinally into two great synclines, one between the Zenith and Pioneer mines and the other between the Zenith and Savoy mines. (See fig. 14.) Here also parts of the formation are found separated from the main mass by greenstone masses in such a manner as to make it difficult to explain them on the basis of occurrence in troughs alone. It would seem that the main mass of the ormation here has been infolded in such a manner as to give a steep monoclinal trough dipping northward, but that in addition to this main mass, which originally rested upon the greenstone, minor masses of the iron-bearing formation may be interbedded with the greenstone, so that after the folding they would be separated from the main mass by layers of greenstone.

The deposits of Soudan Hill come to the surface near the crest at an elevation of 1,660 feet, about 150 feet above a cross valley to the east between Soudan Hill and Jasper Peak. The Ely ore deposits are below comparatively low-lying ground, the upper part of the deposits being at

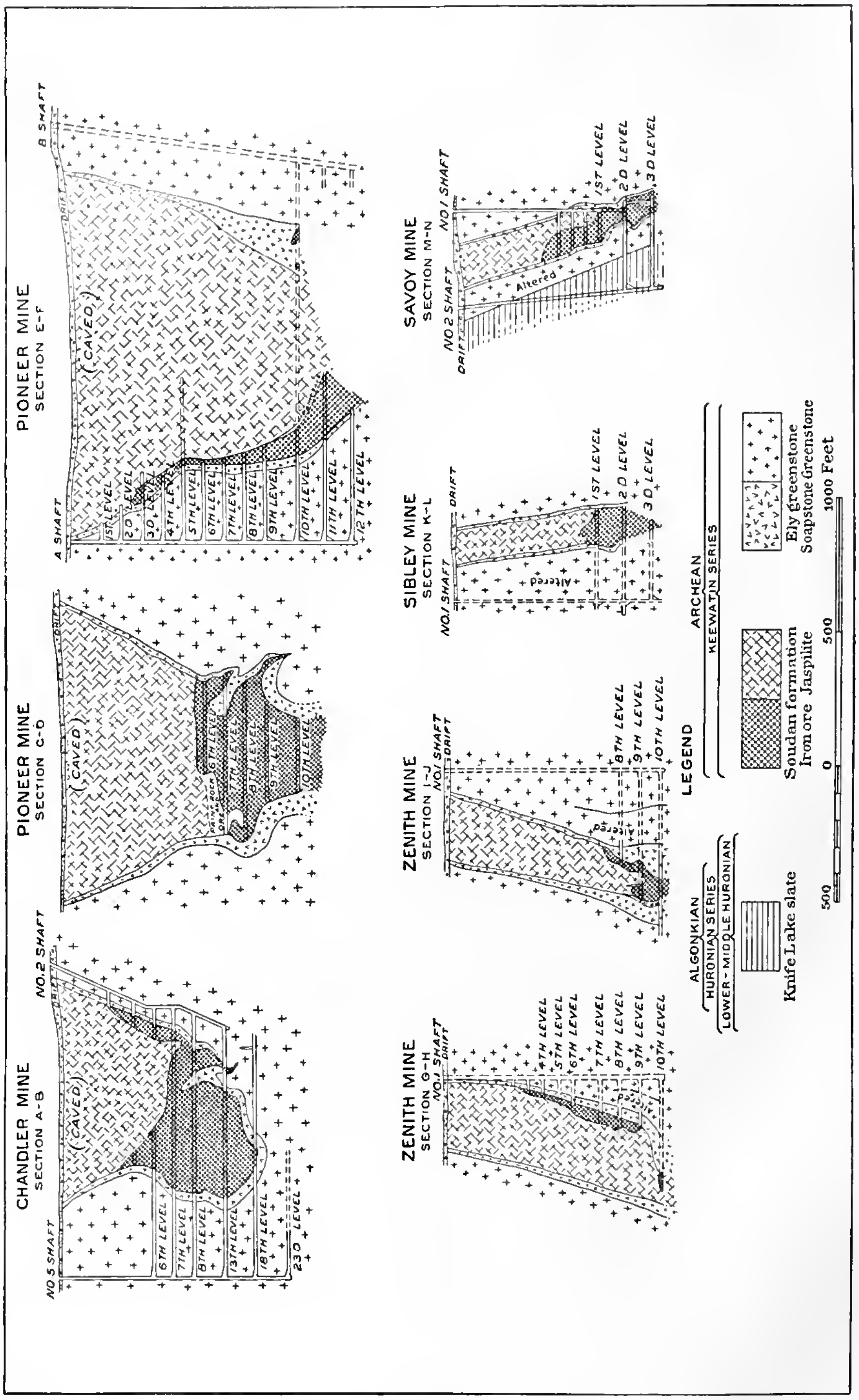


Figure 14.—Transverse sections of Chandler, Pioneer, Zenith, Sibley, and Savoy mines, Vermilion district, Minnesota, by C. E. Abbott.

about the 1,400-foot contour, and are surrounded on the north, west, and south by an amphitheater of high ground composed of the Ely greenstone, the higher points of which rise to an elevation of 1,500 feet. Farther east is a cross valley which is somewhat less than 1,400 feet high. To what extent the cross valley is filled is unknown, but the drift covering is moderately thick. The pitch of the ore deposits is parallel to the range, as it is in the Menominee, Marquette, and Penokee-Gogebic districts and toward this valley. The ores in general are located below crests and slopes.

The newly developed Section 30 mine, in sec. 30, T. 63 N., R. 11 W., is located on a bend of the iron-bearing Soudan formation, trending a little east of south. The jasper is bounded on both sides by greenstone, that to the south probably being basal and that to the north being overlying. The bend in the jasper seems to represent the result of shearing between these two greenstones. Outcrops of rich, highly contorted jasper led to the sinking of the shaft. Below the surface the jasper becomes in general softer and small leads of ore in the jasper widen out into shoots of commercial value. Mining operations have shown the ore to come to the surface where covered by the drift. The ore body is yet too little developed to permit an accurate description of the structure. The ore thus far developed seems to be in two main masses—one in the southeast with an easterly or southeasterly linear trend, pitching west at the west end, apparently east at the east end, and with minor rolls between; and another ore body north of the west end of this one, having a similar trend and seeming to pitch to the west. There is little doubt that these ore bodies are developed along the axial lines of the pitching drag folds in the jasper. Their greatest dimension is in the direction of the pitch.

CHEMICAL COMPOSITION.

The average composition of all ore mined in the Vermilion district in 1909, obtained by combining average cargo analyses in proportion to their respective tonnages, is shown below. The range for each constituent is from the cargo analyses and represents the variation in composition of the marketed ore and not of the ore in the mine.

Composition of ore shipped from the Vermilion district in 1909 (1,108,790 tons).

	Average.	Range.
Moisture (loss on drying at 212° F.)	5.06	0.75 to 5.66
Analysis of dried ore:		
Iron	63.79	60.91 to 65.34
Phosphorus	.052	.037 to .168
Silica	4.90	3.06 to 8.07
Manganese	.11	.09 to .15
Alumina	2.93	1.40 to 3.27
Lime	.23	.20 to .47
Magnesia	.05	.04 to .15
Loss on ignition	.85	.40 to 2.18

Partial average analyses of ores and jaspers.

	Average analyses of ore from Soudan Hill in 1906.	Average analyses of ore from Soudan Hill in 1909.	Average analyses of ore from mines at Ely in 1906.	Average analyses of ore from mines at Ely in 1909.	Average of 10 partial analyses of jasper from Soudan Hill.	Average of several partial analyses of jasper from mines at Ely.	Average of 20 analyses of iron formation bands from secs. 13 and 14, T. 62 N., R. 13 W.
Moisture (loss on drying at 212° F.)	1.37	0.79	5.26	5.37			
Analysis of dried material:							
Iron	66.07	64.85	65.00	63.70	38.27	28.97	16.20
Phosphorus	.088	.167	.046	.049		.022	.042
Silica	3.43	4.76	3.39	4.91			70.95
Manganese	.10	.09	.11	.10			
Alumina	1.27	1.57	1.90	3.03			
Lime	.13	.36	.34	.22			
Magnesia	.02	.08	.06	.05			
Loss on ignition[a]	.55	.47	1.24	.90			

[a] Loss on ignition includes both water of hydration and CO_2, as well as minor amounts of organic matter. The ores from the mines near Ely contain an appreciable amount of iron carbonate and the loss on ignition in these ores is probably largely CO_3.

MINERAL COMPOSITION OF THE ORES AND CHERTS.

The principal iron minerals of the ores are hematite and minor amounts of magnetite and siderite. The siderite is noticeably abundant in the ore from the Savoy and Sibley mines. In addition to the iron minerals are quartz, chlorite, calcite, kaolin, pyrite, and small amounts of minerals bearing phosphorus, magnesium, and manganese, not sufficiently abundant to be identified. A variety of copper minerals, including native copper, malachite, azurite, cuprite, and several sulphides of copper, are found locally in small amounts in both the Ely mines and the mines at Soudan Hill. These copper minerals are not sufficiently abundant, however, to affect the average composition of the ores.

Approximate mineral composition of ores and jaspers, calculated from the partial analyses given above.

	Ore from mines at Ely.		Ore from mines at Soudan Hill.		Ely jasper.	Soudan jasper.
	1906.	1909.	1906.	1909.		
Hematite with some magnetite	92.85	91.00	94.50	92.75	41.40	54.50
Quartz	1.15	1.34	1.93	2.92	58.60	45.50
Hydrous aluminum silicate	4.85	7.18	3.22	3.97		
Miscellaneous (chlorite, apatite, pyrite, etc.)	1.15	.48	.35	.36		
	100.00	100.00	100.00	100.00	100.00	100.00

All the ores of the Ely district are dark red and blue hematites, with a small amount of magnetite and siderite. They are practically anhydrous, the water of hydration averaging less than 1 per cent.

The jasper is a dense, brittle rock made up of layers of nearly pure anhydrous hematite separated by layers of comparatively barren chert. The jaspers contain more or less magnetite; in places nearly all of the iron is in that form.

PHYSICAL CHARACTERISTICS OF VERMILION ORES.

TEXTURE.

In texture the Vermilion ores show a complex gradation from dense massive hematite through brecciated or broken ore to fine blue granular ore.

The Soudan ore is massive hematite, all of the ore requiring crushing.

The Ely ores exhibit a complete range from dense hematites with practically no pore space to fine granular hematites with large porosity.

The textures of the ores of the Vermilion district are shown in the following table of screening tests. These screening tests were made by the Oliver Iron Mining Company on three of the typical grades of Vermilion ore representing a total of 1,034,221 tons. For each of the grades samples were taken biweekly and quartered down monthly in proportion to the tonnage mined, and at the end of the season the entire sample was quartered down to 100 pounds and screened. A comparison of the textures of the ores of the several Lake Superior districts is shown in figure 72 (p. 481).

Textures of Vermilion ores as shown by screening tests.

	Ely ore.	Soudan ore.
	Per cent.	*Per cent.*
Held on ½-inch sieve	16.93	62.40
¼-inch sieve	41.76	28.10
No. 20 sieve	16.23	4.40
No. 40 sieve	6.96	1.10
No. 60 sieve	3.81	.60
No. 80 sieve	.59	.40
No. 100 sieve	9.32	.40
Passed through No. 100 sieve	4.38	2.30

These screening tests show plainly the difference in texture between the ores from the mines at Soudan Hill and the ores from the vicinity of Ely. The former are dense massive ores with practically no fine material except what results from the blasting and crushing due to mining. The latter ores are of much finer texture, being easily broken down with a pick.

The average ore of the Ely district is well described by the local term "broken ore," as it is a rubble of more or less unconsolidated fragments of hard hematite, which range in size from small grains to large masses. This rubble or brecciated material is cemented locally by infiltrated hematite and iron carbonate, in some places the infiltrated minerals almost completely filling the voids. The bedding of the jasper is plainly preserved in the ore where slumping has not destroyed it. In the Zenith mine a fresh surface of the ore showed perfectly the folded structure of the jasper. No sharp line of contact exists between the ore and jasper, the gradation being complete. The slumping of the ore has in most places produced a drag which destroys the bedding texture in this transitional zone, producing a mixture of broken ore and jasper.

DENSITY.

The mineral density of the ores varies with the iron content and ranges from 5.10 for the pure hematites to 4.40 in the lower-grade ores. The average for the district (1906 production) is approximately 4.88. As the ores consist essentially of hematite and quartz, the approximate mineral density may be readily calculated from chemical analyses.

POROSITY.

Owing to the texture, porosity determinations on the Ely ores are rather difficult to obtain. Ten determinations made on typical specimens of the cemented brecciated ore showed an average pore space of approximately 20 per cent of the volume of the ore. If the average moisture content of the ore as given above is assumed to be the moisture of saturation of the ore, calculation shows that it represents a porosity of 21.5 per cent. This moisture content, however, is probably less than the moisture of saturation of the ores; hence the porosity of the average ore may be assumed to be greater than the moisture determination indicates. Engineers estimate 9 to 10 cubic feet of the ore in place to the ton. If the average mineral specific gravity for the ore is 4.93, as calculated above, this figure indicates an average porosity of from 20 to 28 per cent. Though these estimates of porosity are all approximations, their rather close accordance indicates their probable correctness.

The Soudan ores are much more compact than the Ely ores and have an average porosity of less than 10 per cent.

CUBIC CONTENTS.

Calculations based on the mineral density, porosity, and moisture of the ores give an average of 8.75 cubic feet per long ton for Soudan ore and approximately 9.5 cubic feet per ton for Ely ore.

SECONDARY CONCENTRATION OF VERMILION ORES.

PRECEDENT CONDITIONS.

In the Vermilion district the steeply pitching foot walls of Keewatin greenstone and associated porphyry afford impervious basements and troughs for the concentration of waters from the surface. This is especially well shown in the western end of the eastward-pitching Ely trough. (See p. 137.)

Originally the iron-bearing Soudan formation consisted largely of cherty iron carbonate interlayered with more or less of sideritic slates and perhaps banded chert and iron oxide.

MINERALOGICAL AND CHEMICAL CHANGES.

The alteration of the cherty iron carbonate to ore has been accomplished in the general manner described (p. 529) as typical for the region—(1) oxidation and hydration of the iron minerals in place; (2) leaching of silica; and (3) introduction of secondary iron oxide and minor amounts of iron carbonate from other parts of the formation. These changes may start simultaneously, but the first step is usually far advanced or complete before the second and third are conspicuous. The early products of alteration, therefore, are ferruginous cherts—that is, rocks in which the iron is oxidized and hydrated and the silica is not removed. The later removal of silica is necessary to produce the ore, except in layers originally rich enough in iron to make ores without the removal of silica.

It is shown in discussing the secondary concentration of the Mesabi and Gogebic ores that the degree of hydration of the iron-oxide layers in the cherts and jaspers is not changed by the alteration to ore. This appears to be true also of the Vermilion ores, as both the jaspers and the ores are practically anhydrous.

SEQUENCE OF SECONDARY ALTERATIONS AND DEVELOPMENT OF TEXTURES.

Before lower Huronian time the iron-bearing formation at the surface at Soudan had been altered to iron ores, cherts, and jaspers, for all these substances were yielded to the conglomerate at the base of the lower Huronian. The concentration of the ore may be supposed to have stopped while the formation was covered by the lower Huronian sediments. Close folding following the lower Huronian deposition rendered the ores hard, anhydrous, and crystalline, developed green schists out of the basaltic wall rocks and talcose and sericitic schists from the porphyry wall rocks, and in general developed a steep, vertical structure in both ore and wall rock, making it difficult to decipher the structural relations. Erosion later exposed the iron-bearing formation, but owing to its refractory character it was not further concentrated.

At Ely also the concentration began before the deposition of the lower Huronian and was interrupted when the iron-bearing formation was covered by lower Huronian sediments. Later, when the formation was again exposed to weathering, the concentration continued, and then accomplished the greater part of its work, the process differing in this respect from that undergone by the ores at Soudan, which were comparatively little affected by the later concentration. The fact that the iron-bearing formation at Ely was less closely folded and rendered less schistose than the iron-bearing formation at Soudan, thereby retaining more openings through which concentrating solutions might work, may explain why concentration was so effective after the folding. That at least a part of the concentration followed the folding is shown by the retention in the ore of the folded bedded structures of the jasper and by the development of pore space as a result of the leaching of silica from the folded jasper, discussed below.

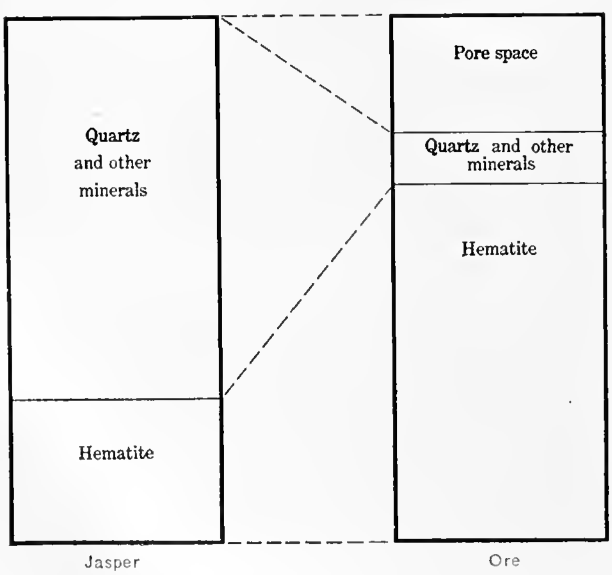


Figure 15.—Diagram illustrating volume changes involved in the alteration of jasper to ore at Ely, Minn. From average analyses and porosity determinations.

VOLUME CHANGE IN ELY ORE.

Comparison of the volume compositions of the ore and jasper shows the removal of a large amount of silica from the jasper. In order to sufficiently reduce the silica content it is necessary that silica equivalent to 63.7 per cent of the volume of the jasper be removed. The average porosity of the ore is approximately 22 per cent of its volume; hence the remaining space left by the removal of silica, or 41.7 per cent of the volume of the jasper, has been filled by infiltration of iron and by mechanical slumping of the ore. The relative importance of these two factors can not be definitely determined, but it is known that both have been effective. The broken and brecciated condition of the ore and the drag at the jasper contacts give abundant evidence of slump, and secondary hematite and siderite cementing the ores indicate that a considerable amount of iron has been introduced in solution. Figure 15 illustrates the volume changes above discussed.

DISTRIBUTION OF PHOSPHORUS.

Phosphorus and iron contents of the Vermilion ores and associated rocks are as follows:

Phosphorus and iron contents of Vermilion ores and associated rocks.

	Iron.	Phosphorus.	Relation of phosphorus to iron.
	Per cent.	*Per cent.*	*Per cent.*
Average ore at Ely	65.00	0.0459	0.0707
Average jasper at Ely	28.97	.0218	.0759
Average ore at Soudan	65.21	.108	.1655
Average jasper at Soudan	38.27	....	....
Paint rock from Pioneer mine	16.32	.127	.778

As calculated from the figures of the Lake Superior Iron Ore Association, 89.3 per cent of the total production of the Vermilion range in 1906 was of Bessemer grade. The lowest phosphorus grade was Pilot lump (iron 67.22 per cent, phosphorus 0.0297 per cent), and the highest phosphorus grade was Vermilion lump (iron 66.07 per cent, phosphorus 0.0878 per cent). The phosphorus contents of individual samples show a much greater range than the grade analyses, the ore containing as high as 0.500 per cent of phosphorus locally.

The paint rock is an altered phase of the greenstone and porphyry, consisting principally of kaolin more or less stained with iron oxide. It is similar both in appearance and composition to the altered dike rocks of the Gogebic range. These altered igneous rocks are higher in phosphorus than the ores (the above analysis being a typical one), owing probably to the high phosphorus in the greenstone.

"Chemical maps" have been made by the chemists and engineers of the Oliver Iron Mining Company of the mines on the Vermilion range operated by that company, the phosphorus and iron contents of the ore being entered in the proper place directly on the mine maps. Study of these maps fails to show any relation between the distribution of phosphorus and the wall rocks. The only general conclusion that may be drawn is that in general the phosphorus content is lowest in the largest ore bodies and has a tendency to be high in the small shoots of ore away from the main ore body. The maps show no relation between high-phosphorus ore and paint rock; in fact, in several places ore running as low as 0.030 per cent of phosphorus occurs in the immediate vicinity of high-phosphorus paint rock.

Owing to the very small amount of phosphorus even in what are termed "high-phosphorus" ores, very little is known as to its mineral occurrence. So far as is known, no phosphorus minerals have been identified in the ores or jaspers; hence any conclusions regarding the chemical combinations in which phosphorus exists are necessarily based entirely on chemical evidence. Phosphorus is present in the ores in at least two different forms, known to the iron-ore chemists as "soluble" and "insoluble" phosphorus, part of it being easily dissolved in hydrochloric acid and the remainder requiring ignition before it can be dissolved. Chemical analysis of the insoluble residue shows it to be an aluminum phosphate. This occurrence of both soluble and insoluble phosphorus is common to ores of the other Lake Superior districts, particularly those of the Marquette range.

CHAPTER VI. THE PRE-ANIMIKIE IRON DISTRICTS OF ONTARIO.

LAKE OF THE WOODS AND RAINY LAKE DISTRICT.

INTRODUCTORY STATEMENT.

The Lake of the Woods and Rainy Lake district includes these large lakes and the surrounding lands. The district may be considered as being bounded on the south by parallel 48° 30′, on the north by parallel 50°, on the east by meridian 92° 30′, and on the west by meridian 95° 30′. The area which has been most closely studied is an angular one running northwest and southeast. The Canadian Survey has published detailed reports by A. C. Lawson on the Lake of the Woods [a] and Rainy Lake [b] district and one by W. H. C. Smith [c] on Hunters Island.

The geology of this region may be said to duplicate in most essential respects, save the distribution of the formations, the geology of the Vermilion district of Minnesota. The rocks therefore include lower-middle Huronian, Laurentian, and Keewatin.

ARCHEAN SYSTEM.

KEEWATIN SERIES.

The series of Keewatin rocks in the district of the Lake of the Woods is that to which the term was first applied. Lawson's study of it, supplemented by later work of others, shows that the Keewatin series is dominantly igneous but includes subordinate amounts of sediments, precisely as in the Vermilion district. The igneous rocks comprise ancient lava flows, volcanic clastics, and contemporaneous and subsequent intrusives. They are dominantly of basic and intermediate varieties, exactly as in the Vermilion district, and among these the characteristic ellipsoidal greenstones are conspicuous. Locally felsites and quartz porphyries occur. In many areas subsequent dynamic action has gone very far, so that the rocks uncommonly have a slaty or schistose structure. These belts of slaty and schistose rocks Lawson has separated into two divisions,[d] one of which he describes as hydromicaceous schists and nacreous schists, with some associated chloritic schists and micaceous schists and included areas of altered quartz porphyry, and the other of which he calls clay slate, mica schist, and quartzite with some fine-grained gneiss. Subsequent examinations of the areas by other geologists have led to the conclusion that large areas of these rocks are but altered facies of the ordinary varieties of the Keewatin igneous rocks. Thus the slates are to a large extent mashed varieties of the ellipsoidal greenstones and tuffs. At various places the transition between the ellipsoidal greenstones and slaty varieties of rocks produced from them by metamorphism is well shown. However, there are present with the slaty and schistose rocks of igneous origin subordinate amounts of sedimentary graywacke and slate, including small belts of ordinary black slate which are in some parts carbonaceous. There has not yet been discovered in the Lake of the Woods district any iron-bearing formation corresponding with the iron-bearing Soudan formation of the Vermilion district, and this is the chief difference between the two series. The only rocks which could possibly be regarded as a correlative of the iron-bearing Soudan formation

[a] Geology of the Lake of the Woods region, with special reference to the Keewatin (Huronian?) belt of the Archean rocks: Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1885, vol. 1 (new ser.), 1886, Rept. CC, pp. 5-151, with map.

[b] Geology of the Rainy Lake region: Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1887–1888, vol. 3 (new ser.), pt. 1, 1888, Rept. F, pp. 1-182, with two maps.

[c] Geology of Hunters Island and adjacent country: Ann. Rept. Geol. Survey Canada for 1890-1891, vol. 5 (new ser.), pt. 1, 1892, Rept. G, pp. 1-76. See also The Archean rocks west of Lake Superior: Bull. Geol. Soc. America, vol. 4, 1893, pp. 333-348.

[d] Geology of the Lake of the Woods region, p. 56.

are very subordinate beds of limestone which occur at various places. The nature of this limestone is represented by that at Scotty Islands, where there are narrow bands from a fraction of an inch to 2 feet wide in a schistose and banded greenstone. The layers are usually lens-shaped, and along their strike they may become narrow and pinch out. Commonly the division between the limestone and the greenstone is rather sharp.

For the Lake of the Woods district Lawson [a] gives various sections of the Keewatin, ranging from 6,500 feet to 23,756 feet in thickness. As this is a volcanic series and practically all the structures are secondary, it may be doubted whether these figures have any real significance.

In conclusion it may be well to give the statement of the International Geological Committee,[b] consisting of Messrs. Frank D. Adams, Robert Bell, A. C. Lane, C. K. Leith, W. G. Miller, and Charles R. Van Hise, concerning the Keewatin of the Lake of the Woods:

> In the Lake of the Woods area one main section was made from Falcon Island to Rat Portage, with various traverses to the east and west of the line of section. The section was not altogether continuous, but a number of representatives of each formation mapped by Lawson were visited. We found Lawson's descriptions to be substantially correct. We were unable to find any belts of undoubted sedimentary slate of considerable magnitude. At one or two localities subordinate belts of slate which appeared to be ordinary sediment and one belt of black slate which is certainly sediment are found. In short, the materials which we could recognize as water-deposited sediments are small in volume. Many of the slaty phases of rocks seemed to be no more than the metamorphosed ellipsoidal greenstones and tuffs, but some of them may be altered felsite. However, we do not assert that larger areas may not be sedimentary in the sense of being deposited under water. Aside from the belts mapped as slate, there are great areas of what Lawson calls agglomerate. These belts, mapped as agglomerates, seem to us to be largely tuff deposits, but also include extensive areas of ellipsoidal greenstones. At a number of places, associated and interstratified with the slaty phases are narrow bands of ferruginous and siliceous dolomite. For the most part the bands are less than a foot in thickness, and no band was seen as wide as 3 feet, but the aggregate thickness of a number of bands at one locality would amount to several feet.

LAURENTIAN SERIES.

The Laurentian series is represented mainly by granite, syenite, granite gneiss, and syenite gneiss. These rocks occur in masses varying from small areas to those many miles in diameter. They are intrusive in the Keewatin series and comprise batholiths, bosses, dikes, and stringers. The nature of the contacts between the Laurentian and Keewatin in the Lake of the Woods area is identical with that of the contacts in the Vermilion district. Along the borders of the batholiths the Keewatin is metamorphosed into hornblende schist or gneiss, exactly as it is in the Vermilion district. Indeed, between the more metamorphosed varieties of these rocks and their less metamorphosed forms there are all gradations. Included in the great batholiths of granite are various masses of Keewatin which have generally been profoundly metamorphosed and in many places partly absorbed.

The chemical and mineralogical compositions of the batholiths have thus, to some extent at least, been affected by the included material. Similarly the chemical and mineralogical characters of the Keewatin have been affected by the material derived from the granite. Indeed, there are few better examples of endomorphic and exomorphic effects than those furnished by this district. All these relations may be conveniently studied in the vicinity of Rat Portage. Intrusive into both the Keewatin and Laurentian are later masses of granite and also various basic rocks, including diabase, gabbro, and peridotite.

Lawson's maps of the Keewatin and Laurentian in the Lake of the Woods and Rainy Lake district show certain interesting features which have here been better worked out than anywhere else in the Lake Superior region. The great batholiths have a tendency to a schistose structure, which is parallel to their borders and is more marked at their exteriors than at their interiors. The Keewatin schists around the borders are in bands, the schistosity of which is roughly parallel to the batholith boundary. Very commonly a band of Keewatin widens or narrows within a short distance or separates into two or more bands. This subdivision may go on until a band is lost in stringers in a granite mass. With many large areas of schists there appear subordinate granite batholiths, bosses, and dikes.

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[a] Geology of the Lake of the Woods region, pp. 104-112.

[b] Report of the special committee on the Lake Superior region, with introductory note: Jour. Geology, vol. 13, 1905, pp. 95-96.

The area covered by the Laurentian granites is much greater than that covered by the Keewatin. It is certain that after the Keewatin volcanic rocks were once spread over the entire region, as they doubtless were, they must have been raised in great domes, pushed aside, and jammed in between the batholithic intrusions. It is probable that the greater areas of Keewatin which once overlaid these batholiths have been removed by erosion and that the existing masses of Keewatin are but mere remnants of a great volcanic formation which once covered the entire district. It has been suggested also that parts of the Keewatin may have foundered and sunk in the granite batholiths at the time of intrusion.[a]

The foregoing facts in reference to the relations of the Laurentian and Keewatin have led Lawson[b] to his subcrustal fusion theory, his idea being that the Laurentian represents the fused and recrystallized masses of the Keewatin. There is no doubt that along the border of the batholithic masses a certain amount of Keewatin material has been absorbed, and no doubt that the Keewatin along the borders of the granites has derived material from them; thus there appears in some places to be an approach to chemical gradation between the two.

The known facts, then, are these: The Keewatin volcanic period antedated the Laurentian. The Keewatin rocks were intruded by the various Laurentian granites and syenites, extending through an enormous period of time. There were important exomorphic and endomorphic effects. There is difference of opinion as to the amount of the Keewatin which has been absorbed by the Laurentian. Our own view tends toward conservatism in this matter.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

The Huronian rocks in this district belong to the lower-middle Huronian. They are chiefly confined to the southern part of the Rainy Lake area. From west to east their northern boundary roughly follows Rainy River, the central body of Rainy Lake, and Seine River with its various enlargements. From this line the Huronian extends across the international boundary into Minnesota for distances not yet determined, except at a few points. This is the main mass of rocks to which Lawson gave the name "Coutchiching." In the area under discussion the rocks consist dominantly of mica schists, but there are argillaceous slates, mica slates, graywackes, and conglomerates at the bottom. All the evidences of unconformable relations between these rocks and the Laurentian and Keewatin series are found in many places along the contact. Where the underlying rocks are Keewatin detritus is mainly derived from that series; where they are granite, as at Bad Vermilion Lake, the detritus is mainly derived from granite. In intervening areas both granite and greenstone are found. Also with these materials is found detritus of other kinds, such as felsites, quartz porphyries, and gneiss. The materials include practically all the varieties of the Keewatin rocks. In places the conglomerate passes up into a feldspathic quartzite and this into a micaceous graywacke or slate. Wherever the bedding can be recognized the dip is steep to the south.

The main areas of the lower-middle Huronian micaceous schists have been intruded by large masses of granite which may be especially well seen at the end of the southeast arm of Rainy Lake and in Namakon Lake along the international boundary. From masses of very considerable size the intrusive granite varies to masses of much smaller size, and cutting through the mica schists are very numerous granite dikes, a large number of which are roughly parallel to the foliation. Largely in consequence of the intrusions of the granite the main mass of the lower-middle Huronian has been transformed to a well-crystallized mica schist. As a result of these intrusions, from the end of the southeastern arm of Rainy Lake northwestward to the base of the series the rocks are less and less metamorphosed. Possibly this gradation was one of the factors in Lawson's conclusion that the Keewatin series was higher and rested unconformably upon his "Coutchiching," which exactly reversed the true relation. As the relation

[a] Daly, R. A., The mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 26, 1908, p. 30.
[b] Geology of the Rainy Lake region, p. 131.

of the great mica schist series to the Keewatin is one about which there is difference of opinion, the statement of the International Geological Committee,[a] consisting of Messrs. Frank D. Adams, Robert Bell, A. C. Lane, C. K. Leith, W. G. Miller, and Charles R. Van Hise, who visited this district and examined the contact, is here quoted:

In the Rainy Lake district the party observed the relations of the several formations along one line of section at the east end of Shoal Lake and at a number of other localities. The party is satisfied that along the line of section most closely studied the relations are clear and distinct. The Coutchiching schists form the highest formation. These are a series of micaceous schists graduating downward into green hornblendic and chloritic schists, here mapped by Lawson as Keewatin, which pass into a conglomerate known as the Shoal Lake conglomerate. This conglomerate lies upon an area of green schists and granites known as the Bad Vermilion granites. It holds numerous large well-rolled fragments of the underlying rocks, and forms the base of a sedimentary series. It is certain that in this line of section the Coutchiching is stratigraphically higher than the chloritic schists and conglomerates mapped as Keewatin. On the south side of Rat Root Bay there is also a great conglomerate belt, the dominant fragments of which consist of green schist and greenstone, but which also contain much granite. The party did not visit the main belts colored by Lawson as Keewatin on the Rainy Lake map, constituting a large part of the northern and central parts of Rainy Lake. These, however, had been visited by Van Hise in a previous year, and he regards these areas as largely similar to the green-schist areas intruded by granite at Bad Vermilion Lake, where the schists and granites are the source of the pebbles and bowlders of the conglomerate.

As to the existence of areas of sediments equivalent in age to the lower-middle Huronian in other parts of the Rainy Lake and Lake of the Woods district, no definite statements can yet be made. It is probable, however, that close structural studies of these areas will disclose such sediments. Indeed, a traverse of the Rainy Lake section by the senior author led him to think that in the belt of rocks mapped as Keewatin, running from the southeastern end of Crow Lake to Manitou Lake, there are representatives of this upper series, but the area was not sufficiently studied for its areal distribution to be given. On the other hand, it is certain that some areas which have been mapped as "Coutchiching" on the Rainy Lake sheet of the Geological Survey of Canada, and especially on adjacent sheets, are but the chloritic and hornblendic schists of the Keewatin metamorphosed by the intrusive granite. It is plain that the term "Coutchiching," if it is to have any structural significance, must be restricted to the sedimentary series of Rainy Lake, its extensions and equivalents. It must not be used as a term to cover the more schistose varieties of rocks of the region without reference to their stratigraphic position.

As to the thickness of the so-called "Coutchiching," Lawson [b] gives estimates varying from 23,760 feet to 28,754 feet. These measurements, however, are clearly based on cleavage structures rather than on bedding, and close examination shows that the two do not conform; hence there is grave doubt whether the thickness of the series is more than a fraction of these estimates.

It has already been indicated that in the lower-middle Huronian schists ("Coutchiching" of Lawson) there are intrusive masses of granite which have produced metamorphic effects. In addition to these granitic masses cutting all the formations of the district are later diabases, dikes, and bosses which are supposed to be of Keweenawan age.

STEEP ROCK LAKE DISTRICT.

GENERAL GEOLOGY.

The Steep Rock Lake district has been described and mapped by H. L. Smyth [c] and W. N. Merriam.[d] The authors have visited the district for general correlation purposes but have not studied it in detail. The following account is based principally on Merriam's work.

[a] Jour. Geology, vol. 13, 1905, p. 95.
[b] Geology of the Rainy Lake region, pp. 101-102.
[c] Structural geology of Steep Rock Lake, Ontario: Am. Jour. Sci., 3d ser., vol. 42, 1891, pp. 317-331.
[d] Private report.

The geology of the Steep Rock Lake district is similar in essential respects to that of the Vermilion and Rainy Lake districts. The succession, in descending order, is as follows:

Algonkian system:
- Intrusive rocks.
- Huronian series:
  - Lower Huronian... Interbedded sediments and eruptive rocks: Dark-gray slate, agglomerate, greenstones and green schists, conglomerates, and limestone, forming part of Steep Rock "series" of Smyth, estimated by Smyth to be 5,000 feet thick.

Unconformity.

Archean system:
- Laurentian series...... Granites and gneisses intrusive into Keewatin.
- Keewatin series........ Ellipsoidal greenstones and green schists containing iron formation.

The lake resembles an irregular letter M, of which the western arm runs north and south and the eastern arm northwest and southeast.

The Keewatin greenstones have a wide distribution on the south side of the lake, especially near Straw Hat Lake. They are in isolated areas surrounded and overlapped by the lower Huronian sediments. The principal showing of iron-bearing formation is southwest of Straw Hat Lake. It is in contact with ellipsoidal greenstone on the west side, but the relation on the east is not known. Lean iron ore also outcrops on the west side of the lake and in various other parts of the district. Glacial fragments of iron ore have been found on the south side of the lake opposite Mosher's Point.

The Laurentian granites and gneisses are exposed principally on the north and east sides of the lake. Along the contact of the Laurentian and Keewatin in the southeastern part of the district there is a great series of hornblende schists intricately associated with both Keewatin and Laurentian rocks. These are regarded as contact phases of the Keewatin where it is intruded by the Laurentian, similar in all respects to those of the Vermilion district. Smyth regards them as overlying the lower Huronian sediments and as passing upward into the schists of Atikokan River, which he designates as the "Atikokan series."

The lower Huronian fringes the Laurentian on the southwest. Its principal exposure is on the south and west shores of the lake, but small patches of it rest against the granite on the points projecting from the east and north sides of the lake. It dips at 60° to 80° away from the Laurentian. The basal conglomerate carries fragments of various phases of Laurentian and Keewatin rocks. Where the conglomerate rests against the granite it is made up so largely of granitic débris and has been so metamorphosed that it is frequently difficult to determine the exact contact of the granite and the sediments. According to Smyth, the succession above the conglomerate is: Lower limestone, ferruginous horizon, interbedded crystalline traps, calcareous green schists, upper conglomerate, greenstones and greenstone schists, agglomerate, and dark-gray clay slate. Some of the greenstones and green schists included by Smyth in the lower Huronian are regarded by Merriam and by the authors as, at least in part, Keewatin unconformable beneath the Huronian.

According to Smyth, the Steep Rock group is folded into an eastern synclinal, a middle anticlinal, and a western synclinal, the latter being faulted. The axes of these folds have a high pitch to the south, varying from 60° to nearly 90°. Throughout the whole area is a regional cleavage which has a nearly uniform direction transverse to all the members of the Steep Rock group and also to the contact between this group and the basement complex. This has largely obliterated the original lamination of the sediments and is now the dominant structure. It is therefore the effect of the last force which has left its marks upon the rocks of the lake. Before this last force acted upon the rocks the Steep Rock group had been folded into a southwestward-dipping monoclinal, which, under the action of the cleavage-producing force in a northeast and southwest direction, caused the present fluted outcrop of the formations of the Steep Rock group. That the basement complex itself yielded to this latter force is shown by the irregular outcrops of the dikes cutting it.

At least three varieties of intrusives cut the Laurentian and Keewatin and have supplied pebbles to the conglomerate at the base of the lower Huronian. Other intrusives cut the

Keewatin, Laurentian, and lower Huronian rocks but have been subjected to folding. Finally, a single massive dike appears to be subsequent to the latest period of folding.

IRON ORES.

Lean, banded iron-bearing rocks appear in the Keewatin of the Steep Rock Lake district. The principal showing is southwest of Straw Hat Lake. The rocks are in contact with ellipsoidal greenstone on the west side, but the relation on the east is not known. Lean iron ore also outcrops on the west side of the lake and in various other parts of the district. Glacial fragments of iron ore have been found on the south side of the lake opposite Mosher's Point. Explorations southwest of Straw Hat Lake are reported to have recently disclosed an ore deposit.

ATIKOKAN DISTRICT.

The existence of iron ore along Atikokan River and Sabawe Lake to the east of Steep Rock Lake requires mention of the geology of this area. The area has not been geologically mapped in detail.

As a result of visits to the district Mr. Merriam and the authors believe the geology to be similar in all essential features to that of the Steep Rock Lake and Vermilion districts—that is, there are represented in this district Keewatin, Laurentian, and lower Huronian rocks. The ores are in the Keewatin series.

The Atikokan iron ores are 3 miles north of the Canadian Northern Railway, on the north side of Atikokan River, just east of its expansion into Sabawe Lake. Here is a ridge of magnetite, green schist, massive greenstone, and iron carbonate running approximately parallel to the river. The greenstone is essentially a diorite with a large proportion of hornblende. The magnetite is coarsely crystalline and dense and carries abundant amphibole and iron pyrites and small amounts of the nickel minerals. The relations of the magnetite and greenstones are complex, as in the Vermilion district, but as a whole the greenstone seems to be intrusive into the magnetite. To the west of the main magnetite exposure iron carbonate appears in similar relations to the greenstone. So intricate are the relations of the ore to the greenstone that it is difficult to determine the true shape of the magnetite deposit from the surface outcrop. The bands are narrow, at most not more than 44 feet, and extend along the bluff for more than 400 yards. They are now being opened for mining. The ores will be roasted and used in furnaces at Port Arthur.

To the west, down the river, the iron-bearing formation is exposed with similar association to greenstone and green schist at a number of places.

KAMINISTIKWIA AND MATAWIN DISTRICT.

The Kaministikwia and Matawin district is characterized by lean, slightly magnetic cherts and jaspers in vertical bands and lenses, very irregular, closely associated with green schist and ellipsoidal basalt typical of the Keewatin series. Granite and quartz porphyry intrude the Keewatin at many places. The association of the jasper and greenstone and porphyries presents all the problems of the Vermilion district. The principal exposures are along Kaministikwia River between Kaministikwia and Mokoman. Just north of the railway, a mile north of Mokoman, is a jasper and greenstone breccia and conglomerate. The rock here exposed has essentially the features of a breccia, but parts of it contain fragmental quartz and are truly conglomerate, suggesting that it is perhaps the basal conglomerate of the lower Huronian.

Still farther south, near Kakabeka Falls, the flat-lying iron formation and slates of the Animikie group (upper Huronian) are exposed along the river and at Kakabeka Falls.

Farther west in the same township (Conmee) are more extensive outcrops of banded jasper in chert containing impure siderite. It is strongly magnetic.

Farther south in Conmee Township, on the south half of lot 7 in the sixth concession, the iron range is found again with a trend of about northwest and southeast and a nearly vertical dip on a long ridge about 150 feet wide. The silica is mainly jasper, often of beautiful color, banded with magnetite, the bands often folded in complex ways, and here also there is more or less of a peculiar breccia of grained silica or jasper in a fine gray matrix.

In the southeast end of lot 7 in the fifth concession there is finely banded jasper and some impure carbonate intermixed, but on lot 4 in the third concession the rock is unusually black from the presence of magnetite, and some specimens are heavy enough to make fairly good ore. Bands having a width of 1 or 2 feet appear to be nearly solid magnetite and seem rich enough to work, though a small amount of pyrite present would lower the grade of the ore. The banding varies in direction from southeast to south; and here again a conglomerate or breccia is commonly found mixed with the ore, the whole having a length of 10 chains and a width of 135 feet.

Altogether this series of iron deposits has been traced for about 8 miles, running parallel, it is said, to a similar range located by Pumpelly and Smyth 2 miles to the southwest; and probably both are continuations of the Matawin ranges, though curving in a somewhat different direction.[a]

The Matawin iron belt extends from Kaministikwia station westerly beyond Greenwater Lake. Banded magnetic and hematitic cherts and jaspers outcrop at many places on Matawin and Shebandowan rivers. West of this belt banded iron ores were seen outcropping at Copper Lake, south of Shebandowan Lake, and on the eastern shore of Greenwater Lake. Ores which probably form an extension of the same belt occur south of Moss Township, on the farther side of the gneiss area of Greenwater Lake.

MICHIPICOTEN DISTRICT.

The following account of the Michipicoten district is taken largely from the writings of A. P. Coleman and A. B. Willmott[b] and of J. M. Bell.[c] The present writers have made no detailed survey of the district, but have visited the area and agree with the essential conclusions reached by the men named.

GEOGRAPHY AND TOPOGRAPHY.

The Michipicoten district, on the northeast shore of Lake Superior, is about 25 miles in length from southwest to northeast, with a greatest width of about 7 miles, and runs from the mouth of Dore River, a few miles beyond Parks Lake on the northeast. It lies northwest of Michipicoten River near its entry into the bay of the same name on the northeast side of Lake Superior and shows the rugged topography so characteristic of that shore.

The country rises rapidly from the lake in steep hills, often ridgelike, with the general direction of the strike of the schists about 70° east of north, and culminates in the ridge of iron-range rock just east of the Helen mine, called Hematite Hill or Mountain, which reaches a height of 1,100 feet above the lake or 1,700 feet above the sea. This is the highest point for many miles around and makes a conspicuous landmark, though other hills reach a level of 800 or 900 feet.

As Hematite Mountain is only 7 miles from Lake Superior, the rise is rapid, and the location of the railway to the Helen mine, which is at a level of 650 feet, just at the foot of the mountain, required some skill in the choice of a route, old lake beaches and sand plains being utilized where possible.[b]

SUCCESSION.

The succession of formations here given is that of Coleman and Willmott, but the names of the series are changed in accordance with the recommendation of the special committee on the Lake Superior region and the series are grouped into the Algonkian and Archean systems.[d]

Algonkian system:
- Huronian series:
  - Lower-middle Huronian ("Upper Huronian" of Coleman and Willmott).
    - Basic eruptive rocks.
    - Acidic eruptive rocks.
    - Doré conglomerate.

Unconformity.

Archean system:
- Laurentian series .... Granites and gneisses intrusive into Keewatin series.
- Keewatin series ("Lower Huronian" of Coleman and Willmott).
  - Eleanor slate.
  - Helen formation (iron-bearing).
  - Wawa tuff.
  - Gros Cap greenstone.

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[a] Coleman, A. P., Iron ores of northwestern Ontario: Eleventh Rept. Ontario Bur. Mines, 1902, p. 130.

[b] The Michipicoten iron ranges: Univ. Toronto Studies, geol. ser., No. 2, 1902, 47 pp. See also Rept. Ontario Bur. Mines, 1902, pp. 152-185.

[c] Iron ranges of Michipicoten West: Rept. Ontario Bur. Mines, vol. 14, 1905, pt. 1, pp. 278-355, with geologic map.

[d] Report of the special committee on the Lake Superior region: Jour. Geology, vol. 13, 1905, pp. 89-104.

The geology of the Michipicoten district is remarkably similar to that of the Vermilion district of Minnesota in regard to lithology, succession, and structure.

ARCHEAN SYSTEM.

KEEWATIN SERIES.

GROS CAP GREENSTONE.

DISTRIBUTION.

The Gros Cap greenstone is well exhibited just west of Michipicoten Harbor and on the trail to the old fishing station at Gros Cap.

The most extensive area of the Gros Cap greenstones is the one extending from Gros Cap eastward to Magpie River and thence north from Michipicoten River to the eastward bend of the Magpie. Other large areas exist northeast of Eleanor Lake, including most of the shore of Loonskin Lake, and along the Josephine branch railway from mile 13½ to mile 17.

Numerous smaller areas have been mapped. There are bands of greenstone and green schist in the Wawa tuff that have the same characteristics.

PETROGRAPHIC CHARACTER.

The Gros Cap greenstone consists of ellipsoidally parted basic igneous rocks formed partly of lava flows, in all respects similar to the Ely greenstone of the Vermilion district of Minnesota.

Many parts of the greenstones do not show the ellipsoidal structure and are apparently greatly weathered diabases, while still other parts are distinctly schistose; but the three varieties run into one another and can hardly be separated in mapping. The chloritic schists are probably tuffs of the volcanoes which poured out the lavas. The whole series is greatly weathered and saussuritic in thin sections.

WAWA TUFF.

DISTRIBUTION.

The extent of the Wawa tuffs and their boundaries can be given only approximately, partly because of the sand plains covering them and partly on account of the intermixed later eruptive rocks. Beginning at the southwest is a narrow band of quartz porphyry schist and felsite schist along the northern boundary of the Dore conglomerate area, between the latter rock and the Laurentian. Where the Dore conglomerates narrow toward the northeast, the northern fringe of quartz porphyry schist seems to widen correspondingly, though greatly interrupted by later acid and basic eruptives. Still farther northeast the sand plains of the Magpie Valley hide the rocks almost completely, not to reappear until near Talbott Lake, where the Wawa schists are extensively developed. From here to the northeast end of the region mapped the Wawa schists are found on each side of the bands of the iron range as the immediately inclosing rocks, except where broken by masses of greenstone or later diabase, and they extend northeast to the end of the region mapped.

PETROGRAPHIC CHARACTER.

The Wawa tuff generally has the composition of quartz porphyry or felsite, and in some places evidently consists of mashed and rearranged rocks with crystals of quartz and feldspar still to be seen in them. In general, however, the formation apparently consists of tuffs or ash rocks, probably erupted in connection with the quartz porphyry and deposited in water, so that they have a more or less stratified character. A few of them are brecciated, some crushed breccias, others perhaps agglomerates formed of volcanic fragments larger than the ash. Some rare forms have much the appearance of water-formed conglomerates with rounded pebbles, one singular example of the sort occurring on a steep hill slope at the west end of Lake Wawa. In a general way this resembles a beach deposit with pebbles cemented by a finer-grained greenish or yellowish matrix, but on closer examination the apparent pebbles are found to be really concretions.

There is no sharp line between this phase of the rock, which occurs in smaller amounts at other points also, and varieties like ordinary quartz porphyry schist, so that one may suppose it to be merely a phase of the series of acid schists in which there has been concretionary action.

Since the materials forming the schists were laid down, or else during their deposit, important chemical changes have taken place in them, probably by circulating hot water, so that sheared and crushed quartz porphyry or porphyrite has been greatly silicified, at times even transformed into thick bands of pale-gray or green chert or chalcedony, with a small amount of sericite. This phase is similar to parts of the Palmer gneiss of the Marquette district. In other cases a considerable amount of siderite or of a carbonate like ankerite, dolomite, or calcite has been deposited with cryptocrystalline or microcrystalline silica, suggesting a change to the iron-range rocks which form the uppermost series of the lower Huronian. It is probable that this change went on at the time when the original iron-range rocks were deposited and under the same conditions.

In a general way it may be stated that the Wawa tuff is accompanied by lenses or bands of carbonates, including impure siderites, dolomites, and limestones. In most places some granular silica also is present, and it may be that these lenses or bands are chemical sediments.

In a general way the Wawa tuffs tend to be more siliceous and to contain more siderite as they approach the iron range, and to be somewhat coarser in grain and gneissoid in look on the sides toward the Laurentian, as though the proximity of these rocks had influenced their crystalline character and chemical composition. The boundary between them and the Helen iron-range rocks is sometimes quite sharp, a thin sheet of black slate occasionally intervening between the two, but in other cases there are schistose varieties of the siderite of the iron range which form a transition toward the quartz-porphyry schists.

STRUCTURE AND THICKNESS.

The Wawa tuffs have on the average a strike of 70° east of north, though with considerable local variations, and a dip toward the south of from 50° to verticality. Near the Helen mine they are shown to form a syncline pitching toward the east and inclosing in their trough the iron-range rocks. As the dip is much the same on each side of this synclinal axis, the fold must have been a closed one; and since it was formed erosion has eaten down the Archean surface until at various points, such as west of the Helen mine and south of Lake Eleanor, the iron range in the central trough has been completely removed, leaving the lower schists across the whole width.

The greatest measured thickness of the schists is to the south of Sayers Lake, where they are known to reach across Lake Wawa, a distance of about two miles and a quarter, which at a dip of 70° would give more than 11,000 feet.

HELEN FORMATION.

DISTRIBUTION.

Beginning at the southwest, several bands of the granular silica variety occur on the Gros Cap Peninsula, the largest being at the Gros Cap mine on the south shore of the peninsula.[a] The materials here are chert and granular silica interbanded with hematite, and the width is in all about 150 feet. To the east another narrower band of rusty siliceous rock is seen, and just around the eastern point, near the beacon, is a third still narrower band, differing from the others in containing magnetite and much pyrite. All of these bands of iron range run about northwest and southeast and have a dip of perhaps 50° to the southwest. A similar band is seen on the west shore somewhat south of the portage across the neck of the peninsula, probably an extension of one of the bands mentioned before. About 150 yards north of the portage are several narrow bands of the rock, usually very pyritous, associated with quartz porphyry schist and striking about east and west with a dip to the south. This belt probably extends to the east, where an outcrop of brown sandy-looking grained silica occurs a little inland from the old fishing station. The band just mentioned is nearly parallel to the great area of schist conglomerate to the north and is the nearest part of the iron range to it, so that it may have furnished part of the pebbles of granular silica in the conglomerate.

Two or three small patches of the iron range are found in the greenstone east of Michipicoten Harbor, after which no more is known for about 8 miles, when the Helen iron range begins. All of the outcrops mentioned thus far appear to be inclosed in the greenstones as if swept off eruptively.

The principal belt outcrops near the Helen mine.

Beginning on the west, the iron range as found at the Helen mine is in two long fingers reaching the shore of Talbott Lake, but not crossing it. The southern finger, long and narrow, possibly reaches a short distance into the water of the lake, but does not appear on the opposite side. It extends eastwardly up the valley of a small creek until it reaches the main body of the formation near Sayers Lake. Following the boundary northward are several minor folds which are seen to rest on Wawa tuffs. Then crossing the railway track near the outlet of the lake, the range extends westward down to the shore of the lake, where it comes to an end within a few feet of the shore, being bottomed by Wawa tuffs.

A comparatively recent development has been the finding of a large band of iron-bearing formation within 2 miles to the northwest of the Helen mine in an area which was supposed to have been carefully explored. It is associated with a thick belt of black slate, but most of the inclosing rock is of the Gros Cap and Wawa formations.

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[a] Rept. Geol. Survey, Canada 1863-1869, p. 131; also Eighth Rept. Ontario Bur. Mines, pp. 145, 254.

On the north side the range seems to extend quite regularly toward the east, the formation standing almost vertically. [From the Helen mine the range] runs for a mile and three-quarters a little north of east, when another interruption occurs, thought by some to be caused by a fault. The evidence for this does not seem conclusive, and more careful exploration may bring to light in the heavily wooded region to the east some links connecting it with the Lake Eleanor band, which commences after a gap of a mile and a half and runs northeast to the Grasett road between Lakes Wawa and Eleanor. The road follows a depression between hills that probably represents a line or zone of faulting, for the iron range here jogs three-eighths of a mile to the north and then continues the usual strike of about 60°. Between the two main outcrops and just east of the road are two small ridges of rusty granular silica pointing a little east of north, perhaps remnants left during the dragging of the strata in faulting.

The iron range south of Lake Eleanor gives the best exposure of the range between the Helen and Josephine mines. In a general way it suggests that of the Helen mine, though on a smaller scale.

The strike of the iron-range rocks at the extreme southwest end is not far from north and south, with a dip running from 30° to 90° to the east, pointing toward the two hills of granular silica to the east of the road. Less than 100 paces eastward along the top of the ridge the strike becomes 60° to 80° and keeps this direction until the east end of the little lake is passed, when it changes to 45° for a short distance, and the range ends abruptly in a mass of greenstone. Beyond this it has not been traced, but the country is very mossy and forest covered, so that it is hard to say positively that there may not be exposures of the iron range yet undiscovered.

The next point at which the iron-bearing rocks have been found is 2¼ miles to the northwest of the Lake Eleanor range, where they begin just east of a long unnamed lake and run about 60° east of north past the north side of Brooks Lake almost to Bauldry Lake, a distance of about 2 miles. Here again a fault of great magnitude has been suggested, the plane of faulting running northwest and southeast; and there is much in favor of this view, though it can not be said to have been proved, since very little work has been done on the geology of the country between the two iron ranges. The only rocks known to exist between them are greenstones and green schists.

The iron-bearing formation appears again near the south side of Bauldry Lake and extends eastward past the south side of Long Lake. Beginning at Goetz Lake and running east through Brooks Lake and Kimball Lake is a considerable belt of iron formation, on which the Josephine mine is located. Ore has been found here in small amount by drilling, but has not been mined.

STRUCTURE AND THICKNESS.

In a general way the rocks of the Helen iron formation, though so narrow, rarely exceeding 1,000 feet in width, are the most distinctive features of the lower Huronian, since they are very easily recognized and nearly always rise as sharp ridges above the surrounding region. Except on Gros Cap, where the bands strike about northwest and southeast, the different ridges have a surprising uniformity of strike, about N. 60° to 70° E., the same direction as one finds prevalent in the adjoining schists. Though the general strike is so uniform, it is evident that along with the other rocks of the region the iron formation has been interrupted frequently by eruptive masses, and apparently also by faults of great magnitude, the effect always being to shift the part east of the fault plane toward the north.

It is probable that the bands of iron range are not simple tilted strips of rock but closely folded sheets, only the lower portion of which is still preserved, and it may be that the apparent gaps between the ranges are really due to the erosion of the general rock surface so far down as to cut off the folded upper part of the lower Huronian altogether, leaving only the schists beneath. If this is the case the depth to which the iron-bearing rocks descend may be quite limited, though the amount of mining and diamond drilling done on the range does not give very certain evidence in this respect.

The iron-bearing formation at the Helen mine underlying the Boyer Lake basin is peculiar in that the lake bottom is much below the outlet. The origin of this is discussed elsewhere (p. 158).

PETROGRAPHIC CHARACTER.

Five species of rock may be distinguished in the iron-bearing Helen formation—banded granular silica or ferruginous cherts with more or less iron ore, black slate, siderite with varying amounts of silica, grünerite schist, and pyritic quartz rock. All are found well developed at the Helen mine, and all but the grünerite schist have been found in the Lake Eleanor iron range also; granular silica and siderite occur in large quantities in every important part of the range, though small outcrops sometimes show the silica alone. The ferruginous cherts are in many places soft and sandy, like the ferruginous cherts or taconites of the western Mesabi. Jaspery varieties have not been found on this range, but they occur only a few miles to the north.

RELATIONS TO OTHER FORMATIONS.

The Helen formation is very closely related to the Gros Cap greenstone and Wawa tuff. Its relations to the associated rocks of the Keewatin series are almost identical with the relations of the Soudan formation of the Vermilion district of Minnesota to the adjacent Keewatin rocks. In general the iron-bearing formation from its structure seems to be at upper horizons of the Keewatin and to rest on the other rocks, being folded in with them; but the formation has been also intruded by basic rocks which have been mapped as Gros Cap greenstone, and some of them may be interbedded with the surface flows of the Gros Cap greenstone. For a discussion of the problem the reader is referred to the chapter on the Vermilion district and also to the discussion of the origin of the ores. (See Chapters V, pp. 118 et seq., and XVII, pp. 460 et seq.)

ELEANOR SLATE.

In addition to the slates of the Wawa formation, slates of a distinctly sedimentary kind occur as thin bands in the northeastern part of the region near Eleanor Lake and elsewhere. Slate or shale of the kind described is traceable at intervals for a mile along the north shore of Parks Lake, and is found underlying the Doré conglomerate north of Eleanor Lake on the Grasett road. They are buff to dark-gray or black rocks with slaty cleavage, sometimes forming an angle of 25° with the well-marked bedding. Some varieties of them are carbonaceous, and at a point east of Wawa Lake such a slate was taken up as a coal mine. Whether the black graphitic slate often connected with the iron ranges belongs with Eleanor slates is not certain, nor has it been determined positively whether the slates are older or younger than the adjoining iron-bearing rocks.

LAURENTIAN SERIES.

The Laurentian series includes various types of granite, quartz porphyry, quartz porphyrite, felsite, and quartzless porphyry. They are intrusive into the Keewatin series and in part into the overlying lower-middle Huronian sediments, but in large part also they lie unconformably below the Huronian, as is shown by the numerous pebbles of Laurentian gneiss and granite included in the basal conglomerate of the Huronian. It is not desirable that all these intrusives should be classed with the Laurentian, as that term is properly applied only to the pre-Huronian rocks, but they have not been sufficiently well discriminated and mapped to warrant a separate classification.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER-MIDDLE HURONIAN.

DORÉ CONGLOMERATE.

DISTRIBUTION, TOPOGRAPHY, AND STRUCTURE.

The conglomerate occurs from point to point along the shore as far as Dog River, 10 miles to the west, and eastward to about the third milepost on the railway from Michipicoten Harbor to the Helen mine, a distance of 4 miles; while the greatest width measured during last summer's work is about a mile and a half, on a line due north of the harbor.

In general the topography of the conglomerate band is very rugged and hilly, with numerous successive ridges running parallel to the strike, which averages about 70°; and with very steep slopes on each side, but especially toward the north, where the narrow hills often drop off vertically or even overhang. The cause of this is to be found in the unequal resistance of the different layers to weathering and in the fact that the dip is usually very steep, from 60° to 90°, averaging about 75° to the south. Dips to the north have only rarely been noticed. The steep cliffs formed in the way described often have a height of 50 or more feet, and on the north side are frequently unscalable for considerable distances. Perhaps the most rugged portion of the region is directly north of Michipicoten Harbor, where within 2 miles of the shore there are several of these ridges, with valleys between, rising finally to over 600 feet above Lake Superior.

While the general strike is about 70° there are great local variations, especially in the vicinity of eruptive masses. Near the second mile on the railway the strike is nearly north and south for more than 400 yards, but on each side the usual directions of from 70° to 75° are found. There is good reason to believe that in general the strike of the schistosity corresponds to that of the sedimentation, for bands of rock free from pebbles follow the same direction, but in a few cases the schistose structure seems to cross the direction of sedimentation, having a bearing of about 45°, while the general course of the ridges is 70° to 80°.

PETROGRAPHIC CHARACTER.

The conglomerates are for the most part large and well rounded. They consist of dark-green schist, granite, ferruginous chert, spotted gray-green schist, porphyry, felsite, and conglomerate or breccia. All have been more or less flattened during the development of schistosity in the rock.

The conglomerate is in many places penetrated by dikes of quartz porphyry, or sometimes quartzless porphyry, running parallel to the stratification as a rule, and in many cases squeezed or sheared into felsite schist in which the porphyritic structure is almost lost.

In addition to the porphyry dikes there are numerous masses and dikes of diabase rising through the conglomerate, apparently later in date than the porphyries, since they are seldom squeezed into schists so far as observed. The diabase seems to be the most resistant rock of the region with the exception of the iron range of the Helen mine, and accordingly forms in many cases the tops of the highest ridges.

THICKNESS.

The general attitude of the large area of schist conglomerate just described suggests a continuous series of strata, as supposed by Logan, since in most cases the dip and strike are fairly uniform; and any marked variations may be accounted for by the presence of eruptive rocks. This would give them a thickness of about 7,500 feet, for the greatest width is 8,000 feet, with an average dip of about 75°.

However, it is not easy to imagine the mass as tilted bodily, and it is more natural to think of the series as forming a close fold, most probably a syncline with the two sides closely squeezed together, and tilted slightly against the Laurentian mass to the north. In this case we may suppose that the schists were to some extent pulled asunder at the base of the fold, which was in tension, allowing the felsites and diabases to penetrate parallel to the cleavage. There is no doubt, however, that some of the diabase dikes are later in age and cut diagonally across the schistose structure.

One feature of the arrangement of the conglomerates supports the view that they form a syncline. Toward the western end of the series of rocks we find bands of well-defined conglomerate along each side with gray and green schists showing few or no pebbles between, as if there was an upper layer of finer sediments nipped in between the two sides of the conglomerate. The absence of pebbles in this central area may, however, be due merely to a greater amount of compression, flattening them beyond recognition. Toward the eastern end there are very few gaps where pebbles have not been seen.

RELATIONS TO UNDERLYING ROCKS.

The Doré conglomerate near Michipicoten Harbor is nowhere found in contact with undoubted Archean rocks, though what look like Wawa tuffs and have been mapped as such occur as a narrow band to the north between the conglomerate and the Laurentian; and schists with some granular silica, certainly lower Huronian, are found near the north end of the peninsula of Gros Cap, though a small sand plain separates them from the conglomerate. The Laurentian eruptives have not been seen in actual contact with them on the north, though some belts of green schists in the Laurentian a little way from the hidden contact may be greatly metamorphosed conglomerate swept off at the time of eruption.

The relationship to the south is more distinct, and the Gros Cap greenstones appear to be the underlying rock folded into a syncline with them; so that south of the railway half a mile from the harbor the greenstone seems to overlie the conglomerate, both having a dip of about 70° to the south.

The pebbles, however, are clearly derived from the rocks of the adjacent Keewatin and Laurentian. Their variety and large size characterize the conglomerate as a basal conglomerate marking a great unconformity.

MICHIPICOTEN EXTENSIONS.

Many areas of iron-bearing rocks near the Michipicoten district have been reported and mapped by Coleman, Bell, and others. Their lithology and association are similar to those of the Michipicoten district. No attempt will be made here to describe in detail the individual belts. None of them are productive and in few of them have detailed geologic maps been made.

J. M. Bell[a] has reported on the iron ranges of Michipicoten West, covering the northern and western extensions of the producing Michipicoten iron-range district, adjacent to Michipicoten Bay. The northern range lies between Magpie River and the western branch of Pucaswa River, practically continuous with the old Michipicoten range. The western range, separated from the other by granite, lies between Otter Head and Bear River, on the Lake Superior shore, and extends but a short distance north of Lake Michi-Biju. The lithology and succession are essentially the same as in the Michipicoten district. The Helen formation consists of sideritic and pyritous cherts, jaspers, amphibolitic schists, siderite, iron ores, quartzite phyllites, and biotitic and epidotic schists. For the most part the iron-bearing bands are lean ore. Exploration has been carried on somewhat extensively at Iron Lake, Frances mine, and Brotherton Hill,

[a] Iron ranges of Michipicoten West: Rept. Ontario Bur. Mines, vol. 14, 1905, pt. 1, pp. 278-355.

at the Leach Lake bands in the northern range, and in Laird's claims, the Julia River bands, the David Katossin claims, and the Lost Lake claims in the western range, but no important ore deposits have yet been found.

THE IRON ORES OF THE MICHIPICOTEN DISTRICT.

By the authors and W. J. Mead.

GENERAL STATEMENT.

The Michipicoten district has one producing mine, the Helen. The Helen ore body lies in a great amphitheater opening westward on Boyer Lake, the east wall of which is formed by iron carbonate, the north by ferruginous cherts, and the south by Wawa tuff. The tuffs and ferruginous cherts stand vertical. Boyer Lake has been drained, and the basin, a quarter of a mile long and 130 feet deep, is apparently cut out of solid rock. A dike of diabase crosses the basin from north to south near its east end, as shown by mining operations, and its outcrop on the edge of the basin can now be seen. Most of the ore mined is east of the dike, but ore is known west of it. Mining operations are 300 feet below the original level of Boyer Lake. The ore body seems to dip eastward as if passing under the siderite hill. A drift under this hill has developed several hundred thousand tons of iron pyrites. Along the south margin of the ore body ocher or paint rock marks the limit against the green schists. To the north the ore runs gradually into lean material, with too much white silica to be worth mining.

CHEMICAL COMPOSITION.

Following is the average analysis of all ore shipped from the Michipicoten district in 1907:

Average composition of all ore shipped from the Michipicoten district in 1907.

Moisture (loss on drying at 212° F.)	5.70
Analysis of dried ore:	
Iron	58.20
Phosphorus	.127
Silica	4.40
Manganese	.165
Alumina	.88
Lime	.23
Magnesia	.14
Sulphur	.127
Loss by ignition	10.40

Chemically the ore most closely resembles some of the more hydrous Mesabi ores. It is low in alumina and high in combined water, which makes almost all of the loss on ignition.

MINERAL COMPOSITION.

Mineralogically the ores are made up of hydrated iron oxide and silica, with small amounts of clay and other minor constituents. The following approximate mineral composition was calculated from the above average analyses:

Mineral composition of Michipicoten ores, calculated from above analyses.

Hematite	23.60
Limonite	69.60
Quartz	3.36
Kaolin	2.23
Iron sulphide	.24
Apatite	.41
Miscellaneous	.56
	100.00

The hydrated ferric oxide is calculated as hematite and limonite in order to afford comparisons with other ores similarly calculated. It is known that hydrated iron oxides other than limonite are present, and it is probable that practically all of the ore is more or less hydrated; hence the amount of hematite present is probably less than is indicated above. No phosphorus minerals have been identified, but the presence of calcium suggests calcium phosphate (apatite). Calculation shows, however, that sufficient calcium is not present to account for all the phorphorus as apatite. Iron sulphide is locally abundant in the ores, occurring in pockets of "pyritic sand."

PHYSICAL CHARACTERISTICS.

Color and texture.—In color the ore ranges from light-yellow ocher, suitable for paint, through a variety of shades of red and brown to dark brown or nearly black. In texture the ore varies from soft earthy material to rough, slaglike limonitic ore, and locally hard blue hematite is found.

Density.—The average mineral density of the ore, calculated from the average mineral composition given above, is approximately 3.85.

Porosity.—The porosity of the ore varies to an extreme degree, ranging from a minimum of less than 5 per cent in the dense ore to a maximum of over 50 per cent (locally 60 per cent) in the limonite. The average is rather difficult to estimate, but is probably between 30 and 40 per cent.

Cubic feet per ton.—Owing to the extent to which it varies in density, porosity, and moisture, the cubic content of the ore ranges within wide limits. The average is approximately 13.5 cubic feet a ton.

SECONDARY CONCENTRATION OF THE MICHIPICOTEN ORES.

The Helen mine has impervious walls, but the direction and nature of the concentrating waters are not yet clear.

The iron-bearing formation was originally cherty iron carbonate. The hill east of the ore body exhibits one of the largest masses of unaltered carbonate known in the Lake Superior region. The alteration of the iron carbonate can be seen in all its stages, first into ferruginous chert and then into ore, and locally directly into ore. The bottom of the lake basin is partly covered with large masses of yellow ocher dissolved from the carbonate and redeposited.

The iron carbonate is thoroughly impregnated with sulphide minutely disseminated through the carbonate and in veins in it. During the alteration of the iron carbonate to the iron ore this sulphide has remained relatively intact, for it is included with the oxides of iron in large masses. In the deeper levels of the Helen mine the iron sulphide is in such large masses as to constitute a great obstacle to mining. Nevertheless, some of the sulphide has been altered and is represented in the limonite forming the lake bottom. The waters of the lake are highly charged with sulphuric acid, which has a strong deleterious effect on the pipes.

Associated with the limonite in the lake bottom is a peculiar green mud, the composition of which is as follows:

Analysis of dark-green mud from lake bottom.

SiO_2	47.58
Fe	11.23
Mn	.14
CaO	.95
CO_2	3.19

Embedded in this mud was found a glacial bowlder consisting largely of serpentine, showing peripheral alteration to a depth of several inches. Analyses made by R. D. Hall of the center and outer portions are as follows:

Analyses of altered bowlder from bottom of Boyer Lake.

	Center of bowlder.	Altered portion.	Altered portion, assuming Fe_2O_3 constant.
SiO_2	39.36	37.80	28.30
Al_2O_3	3.48	3.76	2.82
Fe_2O_3	6.84	9.13	6.84
FeO	6.82	7.76	5.81
MgO	31.64	28.02	21.00
CaO	3.22	3.50	2.62
Na_2O	.11	.06	.04
K_2O	.99	.10	.07
H_2O-	.20	.62	.46
H_2O+	7.44	8.58	6.41
TiO_2	.13	.38	.28
SO_3	.18	.40	.30
CO_2	Trace.	.10	.07

The inner portion of the bowlder was a dense dark-green rock and the altered portion a lighter-green earthy material. The alteration appears to have been brought about essentially by solution. Oxidation has been practically nil, as has also carbonation. The ferric iron occurs essentially as magnetite. If this mineral is assumed to have been unaltered, it follows from a comparison of the first and third columns in the above table that there has been a loss of all constituents except ferric iron, SO_3 and CO_2. The nature of the alteration differs essentially from typical weathering.

The abundant evidence of decomposition of the substances of the lake bottom and the presence of sulphuric acid in the lake waters have suggested to Coleman and Willmott[a] that Boyer Lake represents a solution basin. The bottom of the lake is considerably below its outlet. Though decomposition has undoubtedly aided in the erosion of the lake bottom, there is also evidence, summarized by Martin (see pp. 430–431), that the lake basin is a glacial cirque developed largely by mechanical means.

[a] The Michipicoten iron ranges: Univ. Toronto Studies, geol. ser., No. 2, 1902, p. 23.

CHAPTER VII. THE MESABI IRON DISTRICT OF MINNESOTA.[a]

GENERAL DESCRIPTION.

The Mesabi iron district lies in the part of Minnesota northwest of Lake Superior. In shape and trend it is similar to the other iron districts of the Lake Superior region. (See Pl. VIII, in pocket.) It extends from a point west of Pokegama Lake, in T. 142 N., R. 25 W., east-northeast to Birch Lake, a distance of approximately 110 miles, with a width varying from 2 to 10 miles. Its area is about 400 square miles. To the east from Birch Lake to Gunflint Lake and beyond are small patches of iron-bearing rocks, constituting remnants of an eastward extension of the Mesabi district.

The main topographic feature of the district is a ridge or "range" parallel to the longer direction of the district, known as the Giants or Mesabi Range.[b] Mesabi (spelled also Mesaba and Missabe) is the Chippewa Indian name for "giant." In the west end of the district the Giants Range merges insensibly into the level of the surrounding country, about 1,400 feet above sea level, or 800 feet above Lake Superior. Toward the east the elevation with reference both to Lake Superior and to the surrounding country increases; from range 18 to range 12 elevations of 1,800 and 1,900 feet above sea level, or 400 and 500 feet above the level of the surrounding country, are reached. For many miles both north and south of the range there is a comparatively low, flat area, and the Giants Range, particularly its eastern portion, is a conspicuous feature in the landscape.

While the general trend of the range is east-northeast, there are many gentle bends in the crest line, and in range 17 a spur known locally as the "Horn" projects in a southwesterly direction for 6 miles. The crest of the range is in places broad and flat, in others comparatively narrow and sharp. The southern slope is very gentle; the northern slope is somewhat less so. At short intervals both crest and slopes are notched by drainage channels.

The Giants Range for the most part forms a drainage divide, although it is crossed by drainage channels at several places. The drainage of the district is apportioned among three of the great river systems of the country—the Mississippi, St. Lawrence, and Nelson.

The succession of formations in the Mesabi district appears in the following statement:

Quaternary system:
- Pleistocene series.............Deposits of late Wisconsin age.

Unconformity.
Cretaceous system.
Unconformity.
Algonkian system:
- Keweenawan series............Great basal gabbro (Duluth gabbro) and granite (Embarrass granite), intrusive in all lower formations.
- Unconformity.
- Huronian series:
  - Upper Huronian (Animikie group)..............
    - Acidic and basic intrusive rocks.
    - Virginia slate.
    - Biwabik formation (iron-bearing).
    - Pokegama quartzite.
  - Unconformity.
  - Lower-middle Huronian..
    - Giants Range granite, intrusive in lower formations.
    - Slate-graywacke-conglomerate formation (equivalent to the Ogishke conglomerate and Knife Lake slate of the Vermilion district).

[a] For further detailed description of the geology of this district see Mon. U. S. Geol. Survey, vol. 43, and references there given. Mining men and others have cooperated cordially in the preparation of this chapter, but we would acknowledge particularly our indebtedness to Mr. J. U. Sebenius, who, having been in charge of explorations in the Mesabi district since its discovery and being now chief engineer of the United States Steel Corporation, has perhaps closer knowledge of the geology of the iron-bearing rocks here than any other person.

[b] For the use of the terms "Giants Range" and "Mesabi range" in this report, see footnote on p. 41, also Mon. U. S. Geol. Survey, vol. 43, 1903, p. 21.

Unconformity.
Archean system:
Laurentian series.................Granites and porphyries.
Keewatin series.................Greenstones, green schists, and porphyries.

The core of the Giants Range is made up principally of granite of lower-middle Huronian and Keweenawan age and subordinately of Archean igneous rocks. To the south of the igneous core, for a part of the district, are lower-middle Huronian sedimentary rocks, with bedding approximately vertical. Against the southern boundary of the lower-middle Huronian, or, where the lower-middle Huronian is lacking, against the igneous core, lie the upper Huronian sedimentary rocks (Animikie group). They dip gently to the south and underlie the greater portion of the southerly slopes of the range. On the southeast the Huronian rocks are limited by the Keweenawan Duluth gabbro, the north edge of which cuts across the Huronian formations diagonally from southwest to northeast. The Archean, lower-middle Huronian, and upper Huronian are separated from one another by unconformities. Glacial drift covers the district so thickly that rock exposures are rare on the lower slopes of the range and only fairly numerous near the crest.

ARCHEAN SYSTEM OR "BASEMENT COMPLEX."

DISTRIBUTION.

The Archean rocks of the Mesabi district are confined to its central portion. They are found north and northwest of Nashwauk; northwest of Hibbing; north and northeast of Mountain Iron; in the southerly projection of the Giants Range known as the "Horn," bounded by the cities of Virginia, Eveleth, Sparta, and McKinley; north of Biwabik; and eastward nearly to the east line of R. 16 W. With the exception of the portion of the Archean area east of Embarrass Lake, exposures are sufficiently common to allow a fairly close determination of the boundaries. East of Embarrass Lake the mapping is based on the presence of abundant Archean fragments in the drift.

Included in the areas mapped as Archean north of Mountain Iron are several small patches of lower-middle Huronian rocks. Exposures are so few, they are so mixed in the same exposure with Archean rocks, and they are metamorphosed to such difficultly recognizable forms that their accurate delimitation on the general map is not possible.

KINDS OF ROCKS.

The Archean is represented, about in order of abundance, by micaceous, chloritic, and hornblendic schists, basalts, dolerites, porphyritic rhyolites, granites, and diorites. The basic rocks have commonly a green color and are usually referred to locally as greenstones or green schists. They are given one color on the general map of the Mesabi district and are to be correlated with the Keewatin series (Pl. VIII). The acidic igneous rocks, consisting of the porphyritic rhyolites and the granites, are mapped under another color and are correlated with the Laurentian.

All these rocks have their counterparts in other iron districts of the Lake Superior region. In the Vermilion and Crystal Falls districts, where especially well developed, Clements has described each phase in great detail. For details of petrography the reader is referred to the description of the Archean rocks in the monographs on the Crystal Falls and the Vermilion districts.[a]

Nowhere in the district have sediments been found which are demonstrably of Archean age, but slate fragments in the basal conglomerate of the lower-middle Huronian point to the former existence of Archean sediments.

[a] Mon. U. S. Geol. Survey, vols. 36 and 45.

STRUCTURE.

Most of the Archean rocks show some cleavage, and perhaps about half have enough cleavage to warrant calling them schists. In general the plane of cleavage is nearly vertical and strikes parallel to the range, about N. 60° E. The hornblendic schists north of Mountain Iron have a cleavage of a linear parallel type, and the lines of the cleavage dip steeply to the northeast. In addition to cleavage, there are many joints and faults with displacements of a few inches or feet, but no regular systems have been determined.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER-MIDDLE HURONIAN.

DISTRIBUTION.

Sedimentary rocks of lower-middle Huronian age appear in two considerable areas in the Mesabi district. One with an average width of perhaps a mile extends from Eveleth northeast to Biwabik; the other, somewhat less than a mile in width, extends from near the Duluth and Iron Range Railroad northeast to near the center of sec. 11, T. 59 N., R. 14 W. In the former belt there are areas of green schist forming the cores of the hills. One of them has been mapped, but others, though their presence is known by isolated exposures, are not sufficiently exposed to warrant their separation on the map. A number of small patches of lower-middle Huronian sediments are known also in other parts of the district.

Granite of lower-middle Huronian age forms most of the core of the Giants Range and, except north of Mountain Iron, where it is interrupted for a short distance by Archean hornblendic schists, is exposed continuously along the crest to where it is succeeded on the east by the younger Embarrass granite in R. 14 W. This lower-middle Huronian granite, known as the Giants Range granite, thus bounds on the north the other formations for most of the district. Detailed work has not gone farther north than the granite boundary.

GRAYWACKES AND SLATES.

The interbedded graywackes and slates form the greater part of the lower-middle Huronian sediments. They are dull dark-gray and dark-green rocks which usually weather to a somewhat lighter green or gray or to a dirty light yellow. The grain is usually fine, although it varies considerably. The bedding, shown by both color and texture, is conspicuous. Parallel to the bedding a secondary cleavage has been developed. As a result of variation in texture, bedding, and secondary cleavage, there appear all gradations between metamorphosed coarse graywackes, banded graywackes, and finely fissile slates. Along the parting plane of some of the graywackes and slates may be seen glistening plates of mica or chlorite, conspicuous because of the fact that they appear in separate spangles on the dark background rather than in continuous layers, although, indeed, some of the more fissile slates show mica and chlorite in the continuous layers characteristic of slates.

The graywackes and slates above described have resulted from the alteration of fine mud and feldspathic sand deposits. Some of the mica, especially that in separate clear-cut plates, may have been originally deposited in its present position, but most of it, and especially that in continuous sheets on the parting surfaces, is undoubtedly a secondary development due to dynamic movement in the rock.

The intrusion of granite below described has further greatly metamorphosed the graywackes and slates. In approaching the granite they become more chloritic, hornblendic, and micaceous, and a marked and usually much contorted schistosity obliterates the bedding. Under the microscope may be seen abundant development of secondary chlorite and hornblende and a lesser development of secondary biotite and muscovite. Accessories include tourmaline, staurolite, garnet, rutile, ilmenite, magnetite, and apatite. The alteration of the ilmenite and rutile to sphene (titanomorphic) is well exhibited.

CONGLOMERATES.

The conglomerates are abundantly and typically exposed in a belt running from the cut along the Duluth and Iron Range Railroad, in sec. 22, T. 58 N., R. 17 W., southwest through secs. 22 and 21 into secs. 20 and 29, T. 58 N., R. 17 W. Similar conglomerates are known in small patches bordering the greenstones north of the Genoa mine at Sparta.

The conglomerates are massive rocks for the most part, with various shades of green on fresh surface and a lighter green on the weathered surface. The pebbles vary in diameter from 6 inches to a small fraction of an inch. In kind they are, for the most part, identical, both macroscopically and microscopically, with the rocks of the Archean above described, including diabases, basalts, and granite porphyries. The more basic pebbles are in greater quantity than the acid ones.

The conglomerates, in common with the rest of the lower-middle Huronian rocks, have suffered metamorphism, but the extent of the alteration varies greatly from place to place. East of Mariska, in the railway cut referred to, the rocks show only recrystallization of the mineral particles, without marked development of schistosity. The alteration of the minerals is the same as that described above for the various rocks of the Archean. To the southwest of this cut the conglomerates have been much squeezed and are now very schistose. The recrystallization accompanying the squeezing has made the rocks very chloritic and micaceous, and, in many places at least, has completely obliterated the clastic texture in the finer-grained portions. The pebbles have been elongated in the plane of schistosity (vertical and striking N. 60° E.), and on the weathered surface stand out in lenticular and oval forms from the finer, more schistose, and more easily eroded matrix. Rocks of this character may be traced into schistose rocks in which, in pebbles and matrix alike, nearly every vestige of sedimentary texture has been lost.

GIANTS RANGE GRANITE.

At Birch Lake the lower-middle Huronian granites are coarse gray and pink hornblende granites. From the east line of R. 14 W. to the neighborhood of Mountain Iron the granites are similar to those on Birch Lake. It is noticeable that the coarser phases appear in the eastern end of this area. The hornblende varies in abundance, but is usually conspicuous. Rarely, as near the Mallman camps, the dark constituent is augite instead of hornblende, or, again, it may be partly biotite. In places the rock becomes very slightly gneissic, and immediately next to its contact with the lower-middle Huronian sediments it becomes very fine grained. Next to the contact of the granite with the Keweenawan Duluth gabbro on Birch Lake is a metamorphic rock resembling granite, which is described in connection with the gabbro.

From the neighborhood of Mountain Iron westward to the west end of the district the preponderating granite is somewhat finer grained than the granite to the east, possibly somewhat more gneissic, and usually of a pink color. Certain phases of this finer granite are similar to the hornblende granite to the east, but by far the larger portion shows a considerably greater content of quartz and a smaller content of the basic minerals.

Associated with these two prevailing types are dikes of exceedingly fine-grained pink granite showing very little biotite. They may be well observed in the cuts along the main line of the Duluth and Iron Range Railroad. Other dikes are pegmatitic granite consisting of a pink feldspar with very abundant quartz, and with the ferromagnesian minerals almost totally lacking. They may be seen to advantage at the upper falls of Prairie River.

RELATIONS OF GIANTS RANGE GRANITE TO THE LOWER-MIDDLE HURONIAN SEDIMENTS AND OF BOTH TO OTHER ROCKS.

The Giants Range granite is throughout intrusive into the lower middle Huronian sediments. Actual intrusive contacts are to be observed in a number of places. The lower-middle Huronian sedimentary rocks show the metamorphic effects of the intrusion, and near the contacts no conglomerates are to be observed. The contact of the granite and the sediments is well exposed northwest of Mesaba station.

Though the evidence is conclusive that the great mass of the granite is intrusive into the lower-middle Huronian sediments and not into the upper Huronian (Animikie group), it is likely that in minor areas the granites here mapped and described as lower-middle Huronian may contain granite of later date, which is known to be present in the district.

The conglomerate forming the great part of lower-middle Huronian sediments affords conclusive proof that the lower-middle Huronian sediments rest unconformably upon the Archean rocks. Every kind of pebble found in this conglomerate, with the possible exception of a few cherty slate pebbles, can be matched among the Archean rocks.

Both the lower-middle Huronian sediments and the Giants Range granite are unconformably underneath the upper Huronian (Animikie group), as shown both by structure and by conglomerates at the base of the upper Huronian sediments. This unconformity is described in connection with the upper Huronian.

STRUCTURE AND THICKNESS.

The lower-middle Huronian beds now stand on edge, the dip seldom varying more than 5° or 10° from vertical. Superposed upon the original bedding structure is an excellent secondary cleavage. The cleavage planes, for the most part, are approximately parallel to the bedding planes. The strike of both bedding and cleavage is uniform, about N. 60° E., though locally varying 10° to 20° from this direction.

Both the lower-middle Huronian sediments and the Giants Range granite are jointed, the sediments particularly so. The sediments, moreover, show conspicuous faulting and brecciation. The breccias at some places might be mistaken for conglomerate. A thickness of 3,000 to 5,000 feet is probably as great as can safely be assigned to the lower-middle Huronian sediments of the Mesabi district.

CONDITIONS OF DEPOSITION.

It is suggested in Chapter XX (pp. 603 et seq.) that the lower-middle Huronian deposits of the north shore may be in part subaerial continental deposits.

UPPER HURONIAN (ANIMIKIE GROUP).

GENERAL CHARACTER AND EXTENT.

The sedimentary rocks of upper Huronian age occupy practically all the southern slopes of the range from one end of the district to the other and extend also an unknown distance south beneath the glacial drift. The surface width of the Animikie group in the area included in the district described varies from less than 1 mile to 5 miles or more. The beds have a flat dip to the south. Their upper edges being truncated, they appear in belts winding along parallel to the range, the northerly belts representing the lower beds and the southerly belts the higher beds of the series.

The exposures of the upper Huronian, particularly on the lower slopes, are so widely separated that the mapping of the rocks would have been an impossibility had it not been for numerous drill holes and pits sunk in search for ore, which were bottomed in the upper Huronian. These are particularly numerous along the central portion of the range and have enabled the distribution of the upper Huronian rocks to be indicated within rather close limits for this part of the range.

The upper Huronian comprises from the base up (1) the Pokegama quartzite, consisting mainly of quartzite but containing also conglomerate at its base; (2) the Biwabik formation, consisting of ferruginous cherts, iron ores, slates, greenalite rocks, and carbonate rocks, with a small amount of coarse detrital material at its base; and (3) the Virginia slate. Between the Pokegama quartzite and the Biwabik formation there is a slight break indicated by conglomerate. The Biwabik formation grades conformably into the Virginia slate both vertically and laterally.

POKEGAMA QUARTZITE.

The Pokegama quartzite is the basal formation of the upper Huronian (Animikie group). Because of the southerly dip and truncation of the rocks, the quartzite appears as a belt immediately south of and contiguous to the lower-middle Huronian and Archean formations. The belt, varying from a few steps to half a mile or more in width, extends from the west end of the Mesabi district continuously to a point north of Mountain Iron. From here on to the east end of the range data are insufficient for mapping the quartzite as a continuous belt, and it is accordingly mapped as a number of discontinuous areas of varying width and length. It is likely that future exploration, as in the past, will result in extending and connecting some of these areas, but it is also certain that some of them are really cut off from one another because of the overlapping of the iron-bearing formation.

The Pokegama consists of vitreous quartzites of various colors and textures, with some micaceous quartz slates and conglomerates.

The thickness of the Pokegama quartzite ranges up to 200 feet.

BIWABIK FORMATION.

DISTRIBUTION.

The Biwabik formation extends along the slopes of the range for its entire length, from T. 142 N., R. 25 W., west of Grand Rapids, to Birch Lake, a distance of nearly 110 miles. The width of exposure averages perhaps 1¼ miles, but is in places as great as 3 miles and in others as little as a quarter of a mile. The total area is approximately 135 square miles. The bounding formation on the north is for the most part the Pokegama quartzite, but where this is lacking the Biwabik formation comes into contact with the lower-middle Huronian and Archean rocks. To the south the iron-bearing formation is bounded by the Virginia slate, except in range 12 and a part of range 13, at the east end of the range, where the Keweenawan Duluth gabbro laps up over the formation. On the east the iron-bearing formation is cut off by the overlapping Duluth gabbro; on the west it gradually thins out, the overlying slate and underlying quartzite coming together.

On account of the covering of glacial drift, exposures of the iron-bearing formation, except in the eastern end of the district, are few. But the formation has been reached and pierced in thousands of places by drills and mining excavations, and it is therefore possible, particularly along the part of the range at present productive, to delimit it with a fair degree of accuracy.

Much attention has been paid in recent years to following up the westward extension of the iron-bearing formation, which, in the vicinity of Grand Rapids and westward, becomes deeply buried under glacial drift. By drilling a large number of holes it has been possible to follow the formation into T. 142 N., R. 25 W., where it becomes thin and apparently disappears, the slate and quartzite coming together. These results have not seemed to warrant continuation of drilling in this direction, but until sufficient drilling has been done to demonstrate clearly what the structure and distribution are there it can not be said that the possibilities at this end of the district have been exhausted. Folding or faulting or changes in sedimentation might easily cause variations which would make it difficult to follow the formation. Twelve miles to the northwest of the westernmost Biwabik formation (iron-bearing) of the Mesabi district there begins a magnetic belt which extends from T. 144 N., R. 26 W., through Leech Lake to T. 142 N., R. 35 W., a distance of about 50 miles. This belt has not been proved. The few holes that have been put down seem to indicate that the formation is of Vermilion type, but the continuity and the breadth and length of the belt are exceptional for Vermilion iron-bearing rocks. It has been thought possible that this belt might represent an extension of the Mesabi district thrown to the north by a fold or a fault. Whatever it is, its trend indicates that the same general lineaments of structure of the Vermilion and Mesabi districts are following out here to the west, and even if the belt ultimately proves to be Vermilion it would then serve to limit the distribution of the Animikie (including the Biwabik iron-bearing formation) on the north, and thus serve as a guide to further exploration.

The iron-bearing formation in general occupies the middle slopes of the Giants Range, and its north and south boundaries have fairly uniform altitudes for considerable distances. By an examination of the map, however, it may be seen that the elevation of the formation increases from the west end of the district to the east, the total difference amounting to as much as 500 feet. This corresponds with the increased elevation of the range as a whole in this direction, although the higher elevation of the southern limit of the formation at the east end of the range is in part due to the fact that the lower parts of the formation are overlapped by gabbro. It may be further seen that the elevations of the north and south boundaries show local fluctuations as great as 200 feet, due to the folding of the formation and to differences in depth of erosion.

KINDS OF ROCKS.

The great bulk of the Biwabik formation is ferruginous chert more or less amphibolitic, calcareous, or sideritic and gray, red, yellow, brown, or green, with bands and shots of iron ore. It is analogous to the jaspers of the other iron ranges, but differs in certain particulars, as is shown on pages 461–462.

Associated with the chert, mainly in the middle zone, are the iron ores. Their surface area is only about 5 per cent of the total area of the iron-bearing formation, and the proportion of their bulk to that of the iron-bearing formation is much less. Near the bottom of the Biwabik formation is a small amount of conglomerate and quartzite—that is, coarsely clastic sediments. A minute conglomeratic layer has also been observed in the Mahoning mine, in about a central horizon of the formation. In thin layers and zones throughout the iron-bearing formation, and particularly in its upper horizons, are layers of slate and of paint rock, the paint rock usually resulting from the alteration of the slate. Between the slate and the paint rock and the ferruginous chert are numerous gradational varieties, most of which come under the head of ferruginous slate. Associated with the slaty layers in the iron-bearing formation or closely adjacent to the overlying Virginia slate are green rocks made up of small green granules of ferrous silicate which are here called greenalite, in a fine-grained cherty matrix. It will be shown later that these are the original rocks from which most of the other phases of the iron formation, including the ores, have resulted by alteration. Finally, certain calcareous and sideritic rocks are present in small quantity, particularly near the upper horizons, associated with the greenalite rocks. The rocks of the iron-bearing formation are described below, beginning with the original type—the greenalite rock.

The origin of the ores and iron-bearing rocks is discussed in Chapter XVII (pp. 499 et seq.).

GREENALITE ROCKS.

In moderate quantity, just below the Virginia slate or associated with some slate layer in the iron-bearing formation, are dull dark-green rocks of rather uniform fine grain and conchoidal fracture. Layers of slate, iron ore, and other phases of the iron-bearing formation usually mark their bedding. On close examination, particularly when the surface is wet, there may be observed numerous ellipsoidal granules of a green substance of a very slightly lighter green than the matrix in which they lie. They are so small and of a color so nearly like that of the matrix that they are likely to be overlooked unless especially searched for. An occasional one is of much greater size than the average and looks like a conglomerate pebble in the rock.

Under the microscope the granules are conspicuous. Their cross sections are round, oval (in some cases with much elongation), crescent-shaped, lens-shaped, gourd-shaped, or even sharply angular. Here and there a curved "tail" seems to connect one granule with its neighbor. Where in contact with a layer of iron carbonate or calcium carbonate, as many of them are, the granules are more irregular in shape and project into or are included in the carbonate layers as irregular filaments and fragments. The carbonate is largely secondary and clearly replaces the granules, but some of it is perhaps original, and in this case the variation in shape of the granules where associated with the carbonate layers has a bearing on the origin of the ores, which is discussed elsewhere (p. 187). One hundred and twenty measurements of the granules show an average greater diameter of 0.45 millimeter and an average least diameter of 0.21 millimeter, with average ratio of greatest to least of 100 to 47. The diameters rarely reach 1 millimeter and few are below 0.1 millimeter. Occasionally certain of the granules may be seen to be aggregated into larger granules with well-rounded outlines, making the conglomerate-like fragments above mentioned. The greater diameters of the granules, for the most part, are parallel to the bedding, and in fact this arrangement largely determines the bedding. In ordinary light the granules are green, greenish yellow, brown, or black. The green and yellow ones are transparent and the brown and black are nearly or quite opaque. Under crossed nicols the granules are either entirely dark or show a very faint lightening, hardly sufficient to disclose a color. Here and there incipient alterations to chert, grünerite, cummingtonite, or actinolite, scarcely discernible in ordinary light, give low polarization colors in minute spots and make the term "aggregate polarization" applicable. In reflected light the transparent green and yellow granules appear black, dark green, or dark yellow, while the opaque brown and black granules exhibit a rough light-green surface. Were it not for the light-green surface in reflected light, certain of the opaque dark-brown granules would be mistaken for iron oxide in ordinary and polarized light.

The matrix of the rocks containing the unaltered green granules varies widely in amount, from a mere interstitial filling to an abundant mass in which granules are widely separated. The matrix may be almost pure chert; it may be nonaluminous, monoclinic amphibole, actinolite, grünerite, or cummingtonite; it may be largely iron or calcium carbonate, although where the carbonate is abundant the granules are usually sparse and irregular; it may consist of any combination of chert, amphibole, and carbonate with a small amount of accessory iron oxide.

Originally the matrix may have had a somewhat different character. In the rocks containing the least altered granules the matrix is predominantly chert and subordinately light-colored amphiboles and carbonate. As the rocks become altered they contain more iron oxide and dark amphiboles, which will be shown on a subsequent page to develop from the alteration of the granules. The lighter amphiboles are themselves known to be a secondary development from chert and carbonate rocks. It seems likely, therefore, that the original matrix of the green granules was largely chert and in small part carbonate. In the freshest rocks now found the chert is much recrystallized and the original carbonate is largely leached out or replaced by actinolite.

The specific gravity of the unaltered granules can not be satisfactorily determined because of the practical impossibility of separating the granules from the matrix. Determinations of the specific gravity of the rock as a whole give results ranging from 2.7 to 3. As the matrix is largely quartz in the form of chert, which is known to have a specific gravity in the neighborhood of 2.65, the figures above given for the unaltered rock are too low for the granules themselves, although their incipient alterations to iron oxide and amphiboles tend to raise the specific gravity. So far as the matrix is colorless amphibole it is apparent that the specific gravity of the green granules is lower than the figures obtained for the rock, for the specific gravity of the colorless amphiboles is above 3. One exceptionally fresh specimen in which the granules lie in a matrix of chert gave a result of 2.7. The matrix in this case makes up something more than half of the rock mass, and it therefore seems probable that the true specific gravity of the granules is a little above 2.75.

Four analyses of rocks containing the least altered granules observed have been made by George Steiger, of the United States Geological Survey. He found that by treatment with hot concentrated hydrochloric acid most of the granules and their associated alteration products dissolved out, leaving a residue of almost clear silica, which probably mainly represents the matrix.

Analyses of greenalite rocks.

	1.		2.		3.		4.
	Soluble.	Insoluble.	Soluble.	Insoluble.	Soluble.	Insoluble.	
SiO_2	13.45	48.45	[a] 19.30	36.50	33.11	13.01	[b] 50.96
Al_2O_3	.37		.61		.56		1.09
Fe_2O_3	15.00	.64	13.83	.76	6.44	2.60	5.01
FeO	10.28		17.57		30.93		30.37
MgO	2.33	....	3.22	....	5.35	....	5.26
CaO	.28	....	None.	....	None.	....	.04
Na_2O	None.	....	None.	....	None.	....	None.
K_2O	None.	....	None.	....	None.	....	None.
H_2O-	2.50	....	2.38	....	1.34	....	.75
H_2O+	4.17	....	5.74	....	6.13	....	6.41
TiO_2	None.	....	None.	....	None.	....	None.
CO_2	2.04	....	None.	....	None.	....	None.
P_2O_5	None.	....	None.	....	None.	....	None.
S	....	....	....	....	....	....	Trace.
MnO	....	....	....	....	....	....	None.
BaO	....	....	....	....	....	....	None.
Carbon in organic matter	....	....	....	....	....	....	.21
Undetermined	....	.52	....	.15	....	.38	....
	50.42	49.61	62.65	37.41	83.86	15.19	100.10
	49.61	....	37.41	....	15.99	....	....
	100.03	....	100.06	....	99.85	....	....

[a] Of which 3.3 was found in the rock upon treatment with HCl (probably opal). [b] Of which 23.96 is soluble.

1. Specimen 45758. From 250 paces west, 83 paces north, of the west quarter post, sec. 35, T. 59 N., R. 15 W. The finely ground rock was evaporated on the water bath to dryness with 50 cc. of 1-1 HCl, taken up with water slightly acidified with HCl, and filtered. Soluble silica was then determined in this residue by boiling with 5 per cent solution of Na_2CO_3. A determination of soluble SiO_2 was then made in the rock before treatment with HCl and subtracted from the first soluble SiO_2 found, which gave the figure for SiO_2 in the soluble portion.

2. Specimen 45765. From test pit in Cincinnati mine. The soluble portion was found by evaporating to dryness on the water bath with 50 cc. of 1-1 HCl, and taking up with water slightly acidified with HCl. The residue was then boiled fifteen minutes with a 5 per cent solution of Na_2CO_3 to dissolve any soluble silica, this silica determined and placed with the soluble portion. The residue was ignited and finally heated for fifteen minutes over the blast lamp, weighed, and then a rough analysis made, which is found in the second column. The small amount of iron shown in the insoluble portion could easily have been carried down mechanically. A determination of soluble silica was then made in the rock before treatment with HCl and found to be 3.3 per cent. Subtracting this from the total soluble silica, 16 per cent of soluble silica remains for the part dissolved in HCl.

3. Specimen 45766. From test pit in Cincinnati mine. The finely ground rock was evaporated on the water bath to dryness with 50 cc. of 1-1 HCl, taken up with water slightly acidified with HCl, and filtered. Soluble silica was then determined in this residue by boiling with 5 per cent solution of Na_2CO_3. A determination of soluble SiO_2 was then made in the rock before treatment with HCl and subtracted from the first soluble SiO_2 found, which gave the figure for SiO_2 in the soluble portion.

4. Specimen 45180. From 500 paces west, 100 paces north of the southeast corner of sec. 22, T. 59 N., R. 15 W. Owing to presence of organic matter, the determination of ferrous iron is probably high.

From the detailed consideration of these results, which is not repeated here, it appears that the ferric iron occurs in the rock mainly as sesquioxide, for the soluble silica is accounted for by the ferrous iron and magnesia present, leaving none for the ferric iron; that in three slides of the four of the rocks analyzed the ferric oxide may be observed to be present and to be probably secondary, and hence that the iron oxide shown by the analyses is mainly secondary and not to be considered as belonging with the substance of the unaltered granules. It appears further that the alumina and lime are in such small quantity as to be practically negligible. It appears still further that there is far more than enough combined water to combine with the ferric iron to form ferric hydrate, and thus that a considerable portion of combined water shown by the analyses may be taken to belong to the green granules. Finally, it appears that the substances which can not be accounted for in any other way and which clearly belong with the green granules are silica, ferrous iron, magnesium oxide in small proportions, and water. It is therefore concluded that the substance of the green granules is essentially a hydrous ferrous silicate with a subordinate amount of magnesium, and that if ferric iron is present at all as an original constituent of the green granules it is in small quantity.

This conclusion is essentially in accord with that reached by J. E. Spurr in his report on the Mesabi district published in 1894.[a]

Having concluded the substance of the green granules to be mainly silica, ferrous iron, magnesium oxide, and water, we may ascertain whether or not there is any uniformity in the proportions of these elements. The ratios of the silica, ferrous iron, and magnesium in the four analyses, calculated on the basis of 100, appear in the table on page 168. The percentage of water is not included for the obvious reason that, while it is certain that much of it belongs with the granules, no quantitative estimate can be made of its amount because of the uncertainty as to the portion which belongs with the ferric hydrate.

[a] Bull. Geol. Nat. Hist. Survey Minnesota No. 10.

	1.	2.	3.	4.	Average.
SiO_2	55.1	43.7	47.7	40.2	46.8
FeO	42.1	47.5	44.6	50.9	46.3
MgO	2.8	8.8	7.8	8.9	7.1

The relative proportion of the ferrous iron and silica above shown suggests a combination of the two on the basis of one molecule of each. Theoretically the percentages of the two in such a combination would be—

Silica	45.62
Ferrous iron	54.38

The average of the ferrous iron, 46.3, is about 8 per cent less than the theoretical percentage. The magnesium oxide, which has a higher combining power than the iron, more than makes up for this deficiency.

On a subsequent page is given an analysis of a rock in which the green granules have been altered to a dark-green and brown amphibole, probably grünerite, apparently through simple recrystallization and dehydration. The alteration has occurred under deep-seated conditions, and it is probable that little if any addition or subtraction of material has taken place other than that involved in dehydration. The composition of the amphibole ought to give a clue to the composition of the original green substance. It is there found that the principal constituents of the amphibole are silica and ferrous iron in the following proportions:

SiO_2	47.5
FeO	52.5

The correspondence of these percentages with those above given is evident.

The above results are not sufficiently accordant to show that the substance under discussion has a definite and uniform composition. On the other hand, the impurities and alterations cause such variations that it can not be said that the green granules do not have definite chemical composition. If the granules do have a definite composition, the above results indicate the most probable formula to be $Fe(Mg)O.SiO_2.nH_2O$.

Dr. Spurr, after his study of the green granules, concluded to call them "glauconite." In view of the fact that potash is by most mineralogists insisted upon as one of the essential constituents of glauconite, the entire absence of potash in the substance under discussion is taken to preclude the application of the term "glauconite." The substance apparently corresponds to no known mineral species. As a convenient term by which to refer to it the name "greenalite" was coined for use in the monograph on the Mesabi district and is used in this report also.

The origin of greenalite and the details of the similarities and differences between greenalite granules and granules of glauconite, concretions of iron oxide and chert, and other granule and concretionary structures are discussed in Chapter XVII, on the origin of the iron ores.

FERRUGINOUS, AMPHIBOLITIC, SIDERITIC, AND CALCAREOUS CHERTS.

The following description applies to the normal types of chert occurring through the central and western portions of the range. The highly metamorphosed chert characteristic of the east end of the range is given a separate description on a subsequent page.

The cherts are gray, yellow, red, brown, or green rocks, with irregular bands and shots and granules of iron oxide varying in quantity from predominance almost to disappearance. A slight brecciation thoroughly recemented may be occasionally observed, and a pitted surface, due to the solution of certain of the constituents, is not uncommon. The iron oxide is mainly intermediate between hematite and limonite, and to a subordinate extent is magnetite, and its color accordingly ranges from red to yellow or to black. The variety of colors of the chert and the iron oxide, their irregular association, and their variation in relative abundance give the cherts most highly varied aspects; yet no phase of the cherts is likely to be mistaken for any other rock by anyone reasonably familiar with the iron-bearing rocks of the Lake Superior region. To the casual observer the massive lighter-colored cherts, containing little iron oxide, resemble quartzite, and indeed have been frequently so called. However, the splintery fracture of the chert and the absolute lack of rounded clastic grains, aside from the usual content of iron oxide in layers or spots or minute grains, are unfailing criteria for the discrimination of the two. The ferruginous cherts differ from the jaspers or jaspilites of the old ranges of Lake Superior in lacking their even banding and brilliant red color as well as the microscopic features described below.

When studied under the microscope it appears that all the rocks here described as chert are genetically connected. In looking over 250 slides but few have been observed which do not show some evidence of the derivation of the rock from the greenalite rocks above described. The granule shapes are still largely preserved,[a] but the alterations have tended in some places to make the shapes more irregular and partly or wholly to obliterate them. The alteration of the granules has been almost entirely metasomatic, for there is little evidence of dynamic movement resulting in the breaking up of the constituents of the rock.

The greenalite has been replaced by cherty quartz, magnetite, hematite, limonite, siderite, calcite, grünerite, cummingtonite, actinolite, epidote-zoisite, or any combination of them. The extent and nature of the alteration replacement vary within wide limits. The granule may be mainly greenalite, showing incipient crystallization of quartz, grünerite, or actinolite, visible only under crossed nicols. The granules may be represented almost wholly by hematite, limonite, magnetite, intermediate varieties, or any combination of them. The oxides may be arranged irregularly or concentrically. In the iron ores the granules are entirely represented by iron oxide, although their shapes are in part obliterated. The granules may be represented almost wholly by chert, which may be distinguished from that of the matrix by its coarser or finer texture, or, if not by texture, by distribution of pigment. In ordinary light chert granules may be marked by the pigments which in parallel polarized light are completely obscured by the crystallization of the chert, or the granules may not be seen in ordinary light and be conspicuous under crossed nicols because of the crystallization. Or the crystallization of the chert may have entirely obliterated the granules for much of the slide, both in ordinary and polarized light. The granules may be represented entirely by green, yellow, and brown grünerite, cummingtonite, or perhaps actinolite, or all, which in ordinary light may be scarcely distinguishable from the unaltered greenalite granules but which become apparent under crossed nicols by their double refraction. The granules may be represented by calcite or siderite in rhombs or irregular grains, sometimes showing zonal growth, which for the most part are clearly replacements of the granules. Most commonly the granules are represented by a combination of any or all of the minerals above named. Of these combinations, that of chert and iron oxide stands first. The two substances occur in all proportions with a great variety of arrangement. The two may be irregularly intermingled, or the iron oxide may form a rim about a cherty interior, or, though not commonly, the chert and iron oxide may be in concentric layers in the manner of normal concretions, or polygonal areas of fine chert may contain spots of iron oxide in the center of each as well as a rim of iron about the periphery, suggesting an organic structure. The alteration and replacement of the greenalite and the conditions favoring the development of the different minerals are discussed under the origin of the ores (pp. 187 et seq.).

In addition to the derivatives of the greenalite granules, there are present a few concentric concretions of iron oxide and chert about quartz, which may have been secondarily developed from some substance other than the greenalite. These are similar to concretions in the iron-bearing formation of the Penokee-Gogebic district, where they have developed from the alteration of an iron carbonate. The secondary concretions in the Mesabi district may also be developments from iron carbonates, which are now associated with unaltered portions of the formation and probably existed formerly in the portions which are at present altered. The secondary concretions are different from the greenalite granules in their beautifully developed concentric

[a] Spurr (Bull. Geol. and Nat. Hist. Survey Minnesota No. 10) has applied to this texture the term "spotted granular."

structure. Though a few of the granules themselves have a concentric structure resulting from zonal alteration, this is usually poorly developed and there is ordinarily little difficulty in distinguishing it from that of the secondary concretion, though in some places it is possible that some of the supposed secondary concretions formed from carbonate may be really secondary alterations of original granules.

Spherulites of epidote, rarely to be observed, though in part replacements of the granules, are also clearly secondary developments in the matrix.

The matrix of the chert may be a sparse interstitial filling between the granules or it may form most of the rock mass and contain but few isolated granules. The matrix is similar to that of the unaltered greenalite rocks in that it is mainly chert, but it differs in containing far more actinolite, grünerite, cummingtonite, iron oxide, calcite, and siderite, and rarely epidote-zoisite in spherulitic form. Sometimes also green chloritic substances are abundant, either irregularly distributed through the matrix or forming a definite rim about the granule. In the latter case the chlorite is in part in the fibrous form known as delessite and much resembles uralite. The recrystallization of the rock has in some places made the chert in the matrix coarser than that of the granules and in other places the reverse. The leaching out of the carbonates and greenalite from the matrix has occasionally left cavities which give the pitted character to the weathered surface of the cherts.

Accompanying the recrystallization of the chert has been its frequent adoption of radial or sheaf-like forms, giving black crosses under crossed nicols. These sheaves, as well as the sheaves of actinolite, grünerite, and cummingtonite, and rarely epidote, frequently lie with their butts against the outlines of the granules and send their points outward until they interlock with similar projections from adjacent granules. Commonly also one or more of the constituents of the matrix may be observed to lie partly in the matrix and partly in the granule, thus helping to obliterate the granule. Indeed, under crossed nicols the granules may not be observed, while in ordinary light their position may be indicated by the distribution of the fine pigment.

All of the constituents in the matrix are secondary except, perhaps, a part of the chert, and even this has been thoroughly recrystallized. The amphiboles and iron oxide may be observed to have developed by the alteration of the granules and some of the lighter amphiboles by the alteration of carbonate and chert in the matrix. The carbonate is largely though not entirely replacement from without, for it may be observed replacing nearly all the other constituents of the rock and occurring in minute veins crossing the rock.

The composition and origin of the ferruginous cherts are discussed on pages 186–187.

SILICEOUS, FERRUGINOUS, AND AMPHIBOLITIC SLATES.

Under this head are grouped a variety of slaty rocks which are interstratified with the other phases of the iron-bearing formation. They include dense black, dark-gray, green, or reddish rocks with a tendency toward conchoidal fracture and the slaty parting poorly developed, if at all; rocks showing banding of dark-green, black, gray, red, or brown layers parallel to the bedding and a well-developed cleavage parallel to the same structure; gradational varieties between these two, between them and the ferruginous cherts, and between them and the iron ores. Any of them may be hard or soft, carbonaceous or noncarbonaceous, fine grained or medium grained.

Under the microscope the slates are seen to contain principally cherty quartz, iron oxide, either hematite or magnetite, usually in octahedra, or some hydrated oxide, monoclinic amphibole which may be grünerite, cummingtonite, or actinolite, and possibly even common hornblende, a small amount of carbonate of calcium or iron, a little zoisite, and possibly also a little chlorite. From the optical properties and from the analysis of the rock it is thought that the amphibole is mainly grünerite and cummingtonite. There is much variation in the relative proportion of the principal constituents. Some of the slates consist almost entirely of fine cherty quartz, with subordinate quantities of dark amphibole in radial aggregates or in irregular masses, and of the iron oxides. Others are composed mainly of iron oxide, showing but small quantities of the quartz and dark amphibole. Others are composed of a tangled mass of yellowish, brownish, and greenish amphibole fibers containing minute particles of iron oxide, silica, and other subordinate constituents. The grünerite is far more abundant than the actinolite. The banding shown in many specimens is due to the segregation of the above-named elements into layers. While it may be convenient in description to refer to this or that slaty rock as a ferruginous slate, a siliceous slate, an amphibolitic slate, or an actinolite slate, depending upon the relative abundance of the constituents, usually all three constituents are present in one rock, and the rocks are really amphibolitic, siliceous, and ferruginous slates. Perhaps the most characteristic feature of the slates as a group is the abundance of the dark amphibole.

PAINT ROCK.

Throughout the iron-bearing formation, and particularly adjacent to the ore deposits, are thin seams of paint rock, which have resulted from the alteration of the slates above described. The paint rocks are essentially soft red or yellow or white clay. They retain the original bedding of the rocks from which they were derived, the structure being marked by alternation of bands of different color. In place the paint rocks are moist and soft. When taken out and dried they become harder but retain a soft, greasy feel.

The alteration of the paint rocks from slates is proved by the numerous intermediate phases to be observed. For analyses of paint rock see page 191.

SIDERITIC AND CALCAREOUS ROCKS.

Associated with the slaty layers in the iron-bearing formation, and particularly with the greenalite rocks, are carbonates of iron and calcium in small quantity. Most of the carbonate reacts readily with cold dilute hydrochloric acid and is certainly limestone, which, from the analysis of rocks containing it, is doubtless magnesian. Some of the carbonate, however, is certainly siderite, as shown by analysis. The carbonates occur in minute clear-cut layers interbedded with the other rocks of the iron-bearing formation, in veins cutting across the bedding, and in irregular aggregates and well-defined rhombohedral crystals in the layers of the iron formation. In the carbonate bands are small quantities of iron oxide, ferrous silicate, and chert, and in the bands of these minerals are small quantities of the carbonate. In some places the carbonates are coarsely crystalline and fresh and clearly have resulted from the replacement of the other constituents in the rock, particularly the ferrous silicate, or from infiltration along cracks and crevices. In other places, especially where in distinct layers interbedded with unaltered ferrous silicate phases of the formation, the carbonate layers seem certainly to be original. At the top of the iron-bearing formation and closely associated with the basal horizons of the Virginia slate are several feet of clear calcium carbonate, which is described in connection with the Virginia slate.

CONGLOMERATES AND QUARTZITES.

At the base of the iron-bearing formation is a thin layer of fairly coarse fragmental material consisting in places of conglomerate alone and in other places of conglomerate and quartzite.

THICKNESS.

The average thickness of the iron-bearing Biwabik formation is about 800 feet. This figure is based on average dips of the formation, width of outcrop, and drill records. Local averages are likely to be either larger or smaller. In both the east and west ends of the district the thickness diminishes somewhat, the iron-bearing formation apparently giving way along the strike to slate.

ALTERATION BY THE INTRUSION OF KEWEENAWAN GRANITE AND GABBRO.

Through ranges 12 and 13, near Birch Lake, the Biwabik formation is intruded on the north by granite and on the south by the Duluth gabbro and has undergone considerable metamorphism in consequence. This metamorphism has extended even farther west, for, though the gabbro does not come into actual contact with the iron-bearing formation through range

14, it abuts against the overlying Virginia slate and has metamorphosed both the slate and the iron-bearing formation in this area.[a]

In general through the western and central portions of the Mesabi district the iron oxide of the iron-bearing formation is mainly hydrated hematite, and magnetite is in subordinate quantity. Eastward from Mesaba station the iron oxide is mainly magnetite, and hematite is in subordinate quantity. Westward from Mountain Iron the amphiboles are almost entirely lacking; from Mountain Iron eastward to Mesaba station the amphiboles are present in the iron-bearing formation but are not abundant until Mesaba station is approached; eastward from Mesaba station they become abundant and make up an important constituent of the formation. In the eastern portion of the range the chert is correspondingly less abundant than in the western and central portions of the district, and in some places is almost entirely absent. The chert becomes also distinctly coarser in this area. In range 12 the grains commonly reach a diameter of 3 or 4 millimeters, and there are a few smaller particles, and in the central and western portions of the district they are seldom greater than 0.1 millimeter and almost invariably are associated with smaller particles. Toward the east there is a tendency for the texture to become more even, although there are many wide variations from uniformity. The chert grains, instead of being in irregular, roundish, and scalloped cherty forms, as in the central and western portions of the district, are in roughly polygonal shapes and united in a fairly uniform mosaic. Accompanying these changes is a more pronounced segregation of the magnetite and the amphibolitic chert into irregular layers and lenses, with the result that the iron-oxide layers, instead of containing various other minerals, are comparatively free from them. The characteristic granules of the ferruginous cherts are still conspicuous in the east end of the district, but in the most highly metamorphosed phases of the rocks, as in range 12, they have entirely disappeared, being obscured by magnetite, amphibole, and chert. In the phases not showing the maximum alteration they are marked by magnetite, either as a rim about the granule, as a solid mass filling it, or in evenly disseminated particles through it. Not uncommonly the granules may be observed only in ordinary light and then by distribution of the magnetitic particles; in parallel polarized light they are obscured by the polarization of the amphibolitic and cherty constituents. Finally, in the eastern portion of the district certain minerals have developed which have not been found in the less altered rocks of the central and western portions of the Mesabi district. In the latter areas the amphiboles are entirely grünerite and actinolite, with little or no hornblende. In the eastern portion of the district the amphiboles include grünerite and actinolite, and in addition green and brown hornblende in considerable quantity. Associated with these minerals are small quantities of biotite, glaucophane, andalusite, zoisite, and garnet. Though hypersthene, augite, and olivine are abundant and characteristic in the true gabbro of range 12 and westward, these minerals are nearly if not quite lacking in the Biwabik formation.

Although to the east toward Gunflint Lake the gabbro alone has been able to produce even greater metamorphic effects on the iron-bearing rocks, it is probable that the metamorphism of the iron-bearing rocks in the region under description has been produced jointly by Keweenawan gabbro and granite.

VIRGINIA SLATE.

DISTRIBUTION.

The Virginia slate bounds the iron-bearing Biwabik formation on the south from the west end of the district nearly to the east side of secs. 5 and 8, T. 59 N., R. 13 W., where the slate is overlapped by the gabbro. Still farther east, in the SW. ¼ sec. 25, T. 60 N., R. 13 W., drilling has shown altered slate to lie between Keweenawan Duluth gabbro on the south and Keweenawan diabase on the north, but whether it is an isolated mass at this point in the Keweenawan area or is continuous with the slate to the west explorations or exposures do not yet tell. The slate underlies the lower slopes of the Giants Range and continues south under the low-lying swampy

[a] The metamorphism of the Biwabik formation by the Duluth gabbro in the area adjacent to Birch Lake and to the east in the vicinity of Akeley and Gunflint lakes has been described in detail by U. S. Grant, W. S. Bayley, and Carl Zapffe and has been briefly considered or mentioned by N. H. Winchell, H. V. Winchell, A. H. Elftmann, J. E. Spurr, J. Morgan Clements, C. R. Van Hise, and others. The reader is referred to Chapter VIII, on the Gunflint district (pp. 198–204), for a fuller account of the alterations near the gabbro.

area south of the Giants Range for an unknown distance. The area overlain by slate is so thickly covered with drift that exposures of the slate are almost entirely lacking; its presence and distribution have been determined by drilling and test pitting in the search for iron. Through the central portion of the district enough of such work has been done to show the position of the slate boundary with a fair degree of accuracy, although even here there are considerable stretches where records of the occurrence of slate are wanting. In the western and eastern portions of the district the distribution of the slate is less well known, particularly in the western end of the district. In drawing the slate line on the map of this portion of the area all that can be done is to connect the separated explorations which reveal slate. Wherever exploration has been detailed it is found that the slate boundary is not straight but in gentle curves, and it is reasonable to expect, therefore, that future work will show numerous additional undulations in the slate boundary for the area at present not completely explored.

SLATE.

The normal Virginia slate is usually a gray rock, though in part black, reddish, or brown, with bedding shown by alternating bands of varying color and texture. Some of the beds are almost coarse enough to be called graywackes. Indeed, in the field the rock has been called a banded slate and graywacke. Some of the slate is hard and siliceous; other phases, especially the nonsiliceous and carbonaceous ones, are soft and can be whittled with a knife. Near the contact of the slate with the iron deposit in the underlying iron-bearing formation, as at Biwabik and in sec. 3, T. 58 N., R. 15 W., the slate becomes iron stained and soft and grades into paint rock. The slate in general has a very poor parting parallel to bedding planes, and there is little or no development of secondary cleavage. What there is of secondary cleavage has been developed parallel to the bedding planes and is marked by minute particles of mica there found. The rock in general aspect and mineralogical and chemical composition looks like slate, but it differs from true slate in lacking a true cleavage, and as this is one of the essential characteristics of slate it may be doubted whether the term "slate" ought to be applied to the rock. Yet the rock is not a shale, for it is too much metamorphosed and has too poor a parting parallel to the bedding. In the Cuyuna district the same formation shows the characteristics of a true slate, and the formation both there and in the Mesabi district proper has been known locally and in geologic literature as slate. Hence the term is here retained.

Analyses of Virginia slate.

	1.	2.
SiO_2	62.26	56.61
Al_2O_3	16.89	17.76
Fe_2O_3	1.76	3.29
FeO	4.55	5.15
MgO	2.95	4.10
CaO	.42	1.60
Na_2O	2.29	1.26
K_2O	3.02	4.04
H_2O-	.70	.25
H_2O+	3.88	4.18
TiO_2	.60	....
CO_2	None.	.68
P_2O_5	.20	....
Organic undetermined	....	....
C and c	....	.63
	99.52	99.55

1. Analysis by George Steiger, of the United States Geological Survey, of a composite sample of the Virginia slate made up by assembling several specimens from two localities (specimen 45767 from excavation for water tank of Eastern Railway of Minnesota, at Virginia; specimen 45463 from a point south of the Biwabik mine).
2. Analysis of Virginia slate by R. D. Hall, University of Wisconsin, of a sample representing 900 feet of drill core from a drill hole at the southeast corner of sec. 8, T. 58, R. 15.

CORDIERITE HORNSTONE RESULTING FROM THE ALTERATION OF THE VIRGINIA SLATE BY THE DULUTH GABBRO.

In approaching the Duluth gabbro, which overlaps the Virginia slate in ranges 14 and 13, the slate becomes more crystalline, harder, and characteristically breaks with a conchoidal fracture, and the color becomes darker and in many places is a bluish black. The rock, indeed, becomes a hornstone. Moreover, there appear minute light-colored specks which on the weathered surface are likely to have disappeared and to be represented by pits. Under the microscope the white specks are found to be cordierite in typical development, standing as numerous phenocrysts in a fine-grained matrix of biotite, feldspar, magnetite, and certain doubtful microlites which may be actinolite or sillimanite, or both.[a]

RELATIONS TO THE BIWABIK FORMATION.

Reference has already been made to the fact that the relations of the Virginia slate to the underlying Biwabik formation are those of gradation, both lateral and vertical. It remains to discuss this gradation somewhat fully. The iron-bearing formation contains slate layers throughout. At upper and middle horizons they are perhaps more numerous than at lower horizons. Just below the solid black Virginia slate there is a zone in which there are many interlaminations of iron-bearing formation and slate, the layers varying in thickness from several feet to a fraction of an inch. This zone is of varying and uncertain thickness. In many places at least the zone of minute interbanding is thin, not more than 15 or 20 feet, but, as already noted, layers of slate are found well down in the iron-bearing formation and layers of the iron-bearing formation are found well up in the slate, so that in a broad way the gradation zone may be several hundred feet.

Drilling shows much irregularity in the alternation of layers. Slate layers are more abundant in the eastern end of the district, and westward from Grand Rapids the iron-bearing formation rapidly thins, its place being taken by slate in T. 142 N., R. 25 W. Whether the iron-bearing formation extends indefinitely southward under the slate or gives place to slate in that direction is not known. All drill holes put down near the northern margin of the Virginia slate in the Mesabi district have shown the Biwabik formation below. For reasons cited on pages 517–518, however, it is regarded as not impossible that farther south the iron-bearing formation thins and becomes discontinuous, its place being taken by the black slate.

An examination of the map will show the Virginia slate to encroach on the south margin of the iron-bearing formation to greatly varying distances, with the result that the surface outcrop of the iron formation ranges in width from 2 miles or more to less than a quarter of a mile. This is due in part to steeper dips at the narrow places than at the wide places in the iron-bearing formation, erosion having thus uncovered less of the iron formation where the dips were steep; it is due in part to faulting, as at Biwabik and eastward; it is due in part to the greater dip of the present plane of surface erosion, either atmospheric or glacial, in places where the formation is wide than where narrow, the greater dip of the surface bringing it more nearly parallel with the dip of the iron-bearing formation, and thus uncovering more of it; but so far as present evidence goes these factors are not adequate to account for the observed variations in width of the iron formation. The known irregular alternation of iron-bearing formation and slate both across and along the beds is therefore regarded as a cause of the varying widths of the iron-bearing formation.

STRUCTURE.

Opportunities for studying the structure of the Virginia slate in place are so few that if the observer were dependent upon such observations alone he would be unable to make any statements concerning the structure of the formation beyond the fact that it dips at low angles away from the high land adjacent.

THICKNESS.

The thickness of the Virginia slate can not be determined in the Mesabi district. The drift covering is thick, mining exploration stops to the south where the slates are encountered, and the southerly extent of the slate belt is thus unknown.

[a] Cordierite in this formation was first noted and described by N. H. Winchell, Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 5, 1900.

STRUCTURE OF THE UPPER HURONIAN (ANIMIKIE GROUP).

As a whole the upper Huronian (Animikie group) is a well-bedded series of sediments. The bedding is most pronounced in the middle and upper horizons. The beds have gentle dips, averaging between 5° and 20°, though locally greater or less, in southerly and southeasterly directions away from the older rocks forming the core of the Giants Range, but locally the dips show much variation both in degree and direction. About the southerly projecting tongue of the Giants Range, in the vicinity of Virginia, Eveleth, and McKinley, the dips are westerly on the west side of the tongue, southerly at the end of the tongue, and southeasterly on the southeast side—that is, throughout approximately normal to its periphery. Even more conspicuous than the change of dip at such a place are the minor variations between exposures. Seldom is it possible to get two identical readings in dip at exposures of rock separated by even short intervals, although the direction and amount of the dip come within the above limits. These facts indicate that the upper Huronian beds are tilted away from the core of the Giants Range in directions normal to its trend and that the gently tilted beds are not plane surfaces but are gently flexed. By tabulation and comparison of the dips it becomes further apparent that the greater flexures are not random ones but generally have their axes normal to the trend of the range. On examination of the attitudes of the beds still more in detail it appears that the great flexures themselves are not simple but have many subordinate flexures, some of them transverse to the major ones. The complexity of the structure may be likened to that of water waves. On the great swells and troughs there are smaller waves, on the smaller waves there are still smaller ones, and so on down to the tiniest disturbance of the surface. Though perhaps the majority of the minor flexures in the upper Huronian rocks have attitudes similar to the larger ones, many of them vary greatly in direction. They may be observed at almost any single exposure of the upper Huronian.

The great flexures are very gentle, involving very small changes in degree and direction of dip. Many of the minor flexures superimposed upon the greater ones are sharp and conspicuous. The local dips may vary as much as 50° within a few hundred feet and change their direction considerably. Dips as high as 45° or even 60° may be seen in the layers of the iron-bearing formation in some of the open pits of the mines, as at the Stevenson, the Sauntry-Alpena, the Kanawha, and the Sparta. At the Hawkins and Agnew mines the iron-bearing formation exhibits steep, sharp folds. The iron-bearing formation shows more minor contortions than the rest of the upper Huronian rocks, because of the great chemical changes which it has undergone, but it is not probable that there is any great difference in the major folding.

The prevailing gentle southern tilt of the upper Huronian and the manner in which it laps around the salients in the older rocks suggest that the major features of upper Huronian structure may be due partly to initial dip as well as to subsequent folding—in other words, that the upper Huronian sediments are essentially in the position in which they were deposited against an old shore and have undergone minor deformation since.

Accompanying the tilting and minor folding of the upper Huronian there has been a very considerable amount of fracturing, especially in the comparatively brittle Pokegama and Biwabik formations. Indeed, it seems likely that the folds of the two lower formations of the upper Huronian are mainly the result of relatively small displacement along fractures, and only to a small degree the result of the actual bending of the strata without breaking. The ponding of water beneath the Virginia slate would seem to indicate that this formation has been less fractured than the iron-bearing formation because of its less brittle character, and has thus yielded to deformation by actual bending rather than by breaking. On almost every exposure of Pokegama and Biwabik formations joints and minute faults are to be observed cutting almost perpendicularly across the bedding. In each case the joints seem to make up two or more systems crossing each other at various angles, but such sets have little constancy of direction in widely separated exposures, unless we except a set of joints which at a number of places have an average direction of somewhere between N. 60° and 70° E.—that is, approximately parallel to the trend of the range. In the massive rocks the joints are clear cut and continuous for considerable distances. In the well-bedded rocks—as, for instance, in the thin-bedded portions of the iron-bearing formation—the joints are usually more irregular, less continuous, and less conspicuous. In such places each individual bed may be more or less jointed without reference to the layers above or below.

The displacement or faulting along joints has been, in general, small. The displacement is rarely 3 or 4 feet, and commonly it is measured by a few inches.

There is a displacement of about 200 feet along a nearly vertical fault strike running eastward along the north side of the Biwabik mine parallel to the northern margin of the upper Huronian past Embarrass Lake. The south side of the fault has dropped, with the result that the layers of the iron-bearing formation are somewhat tilted along the contact and the width of the outcrop lessened. The eastward extension of this fault carries it through the peculiar point of Pokegama quartzite projecting eastward into the iron-bearing formation east of Embarrass Lake. Though the structure has not been worked out in detail east of Embarrass Lake, it seems not unlikely that the peculiar features of the distribution of the quartzite and iron-bearing formation there may be partly explained by faulting, though original configuration of the shore line in upper Huronian time may have something to do with it. Other great faults are almost certainly present in the district, but evidence for them has not been correlated.

Certain of the joints and faults have been filled with vein quartz and others have not. It is rather surprising that so little vein quartz is to be observed. In the harder rocks, where the joints are clear cut and continuous, the quartz veins also appear so. In the well-bedded portions of the iron-bearing formation, where the joints are irregular and discontinuous, the distribution of the vein quartz is also irregular and discontinuous, being rather in a confused zone than in a well-defined plane.

After the upper Huronian was tilted and folded the upper edges of the beds were eroded away, with the result that the rock surface is now irregular, with dips corresponding roughly in direction but not in degree with those of the underlying rock strata, being in general less steep.

RELATIONS OF THE UPPER HURONIAN (ANIMIKIE GROUP) TO OTHER SERIES.

The upper Huronian lies unconformably upon the Archean and lower-middle Huronian rocks. The proof of unconformity is as follows:

1. The conglomerates at the base of the upper Huronian[a] contain fragments derived from the underlying rocks.

2. There is discordance in dip. The underlying formations, where they have any parallel structure at all, are almost vertical. The upper Huronian is well bedded, with a low dip. Moreover, in approaching the contact no change of dip is to be observed either in the upper Huronian or in the underlying rocks.

3. There is a difference in the amount of minor folding, fracturing, secondary cleavage, and further consequent metamorphism of the two bodies, the upper Huronian being much less affected than the older rocks.

4. The upper Huronian belt overlies Archean and lower-middle Huronian rocks indiscriminately. Near Biwabik, for instance, the northern edge of the upper Huronian lies diagonally across the contact of the Archean and lower-middle Huronian rocks.

5. The lower-middle Huronian sediments are intruded by the Giants Range granite, which composes most of the core of the Giants Range. The upper Huronian is not intruded by the Giants Range granite, and, moreover, in the conglomerate at its base it bears fragments of this granite. The upper Huronian in ranges 12 and 13 is in eruptive contact with the Keweenawan granite and gabbro.

CONDITIONS OF DEPOSITION OF THE UPPER HURONIAN (ANIMIKIE GROUP).

The conditions under which the upper Huronian (Animikie group) was deposited are discussed for the Lake Superior region in Chapter XX. It may be noted here that the rocks of this group are believed to be subaqueous deposits grading upward into delta deposits. The Mesabi

[a] Listed in Mon. U. S. Geol. Survey, vol. 43, pp. 94-98.

district may represent shore conditions of deposition as contrasted with the Cuyuna district farther south, which may represent offshore conditions. The well-assorted sands at the base of the group in the Mesabi district seem to show variation in thickness and area corresponding to the configuration of the older rock surface. For instance, the point of Pokegama quartzite extending eastward from Embarrass Lake suggests a sand spit, though distribution may be complicated by faulting. The peculiar conditions determining the deposition of the iron-bearing formation are discussed on pages 499 et seq.

KEWEENAWAN SERIES.[a]

DULUTH GABBRO.

A portion of the great mass of Keweenawan gabbro of northern Minnesota comes within the limits of the Mesabi district. The northern edge of the mass lies diagonally across the eastern end of the district, extending from near the Duluth and Iron Range track, in range 14, northeastward through ranges 13 and 12 to Birch Lake. Through range 14 the gabbro is in contact with Virginia slate; in ranges 13 and 12 it is in contact with the Biwabik formation, and north of Birch Lake it is in contact with lower-middle Huronian granite. The northern edge of the gabbro forms a conspicuous northward-facing escarpment overlooking the low-lying area of the Virginia slate and of iron-bearing formation immediately to the north. To this the name "Mesabi Range" was first applied. In the neighborhood of Birch Lake the gabbro comes well up on the crest of the Giants Range, and here it does not stand above the adjacent rocks.

DIABASE.

There are in the Mesabi district certain rocks associated with the Duluth gabbro which are not covered in the above general account. In range 13 exposures of fine-grained diabase appear in the SW. ¼ sec. 25, T. 60 N., R. 13 W., and in the central and northern portions of sec. 35, T. 60 N., R. 13 W. Bowlders of the same material indicate its extension for several miles east and west, and, taken together with the exposures, indicate a belt with a possible width of somewhat less than a mile, a length of at least 3 miles and probably much more, and a trend northeast and southwest—that is, parallel to the general strike of the formation boundaries in this part of the district. The diabase is a fine-grained dark-gray rock which under the microscope shows a well-developed ophitic arrangement of plagioclase feldspar crystals and the presence of abundant hornblende and less abundant ilmenite and magnetite. The diabase corresponds lithologically to the diabase sills intruded in the iron-bearing formation in the neighborhood of Gunflint Lake, and there supposed to be either offshoots of the gabbro or intrusives both in the gabbro and adjacent rocks. The trend of recent opinion is toward the former conclusion. In the SW. ¼ sec. 25, T. 60 N., R. 13 W., south of the diabase, drill holes have recently penetrated altered slate (cordierite hornstone). The relations of the slate to the surrounding rocks are unknown because of lack of exposures and exploration. If the slate is continuous with that to the west, which had not heretofore been known to extend farther east than secs. 5 and 8 of the same range, the diabase must be a sill intruded in the upper Huronian (Animikie group). If the slate is not continuous with the main belt of slate to the west, it must be an isolated mass in the Keweenawan rocks, and the diabase would belong with the main mass of the Keweenawan. From the analogy of its lithologic character with that of the diabase sills to the east, from its distribution, and from the occurrence of slate to the south it is thought that the diabase is probably a sill, but lack of exposures and of sufficient exploration makes it quite impossible at present to show its boundaries on the map. The area south of the diabase, including that in which the slate has been found, is therefore mapped as Keweenawan.

A little southeast of the northwest corner of sec. 34, T. 59 N., R. 14 W., E. J. Longyear found diabase at the depth of 984 feet, in a drill hole which had passed through 16 feet of drift, 392 feet of black slate, and 576 feet of iron-bearing formation. Diabase was penetrated for 309

[a] For a general account of the Keweenawan series of Minnesota see Chapter XV (pp. 366 et seq.)

feet before the work was stopped. The iron-bearing formation is bounded on the north by lower-middle Huronian graywackes and slates, upon the eroded edges of which lies the iron-bearing formation, with perhaps a thin layer of Pokegama quartzite between. The fact that the diabase rather than the Pokegama quartzite or lower-middle Huronian graywacke and slate was reached by the drill below the iron-bearing formation would be in accord with the supposition that the diabase formed a sill intruded into the iron formation at this place.

In the NE. ¼ SE. ¼ sec. 13, T. 57 N., R. 22 W., drilling has penetrated 20 feet of diabase with iron-bearing formation both above and below.

EMBARRASS GRANITE.

Through ranges 12 and 13 and as far west as sec. 2, T. 59 N., R. 14 W., a distance of 15 miles, the granite forming the core of the Giants Range is intrusive into the upper Huronian. Whether it was intruded at the close of the upper Huronian epoch or during the succeeding Keweenawan is a matter of doubt and indeed is a matter of small consequence. The fact that granite dikes cut the Keweenawan series in other parts of northern Minnesota makes it a plausible assumption that the granite was intruded in Keweenawan time, but no relations of the granite to the Keweenawan have been observed in the Mesabi district. The granite is named the Embarrass granite from its lithologic similarity to granite exposed at Embarrass station on the Duluth and Iron Range Railroad, just north of the Giants Range.

The Embarrass granite is a pink hornblende granite. It is usually of coarse grain but shows much variation. In general the grain becomes finer toward the west. The characteristic feature of the granite is its large content of quartz in small and large grains, which are very conspicuous, especially on the weathered surface. The quartzes range in diameter from a few millimeters to more than a centimeter. The large ones have a characteristic purplish-blue color. In its content of quartz the Embarrass granite is readily distinguished from the lower-middle Huronian granite (Giants Range granite) in the central and western parts of the range, in which the quartz is exceedingly rare or entirely lacking. Other constituents are pink orthoclase feldspar, which sometimes occurs as porphyritic crystals almost an inch long, and a rather small amount of hornblende. The relative abundance and coarseness of all the constituents of the granite of course show the usual variations of a large granitic mass.

Cutting the granite are a few dikes of finer-grained, lighter-colored quartzose granite, which under the microscope is found to differ from the one just described only in lacking hornblende and the rare elements mentioned.

In the Mohawk mine and elsewhere near Aurora granite forms the foot wall of the ore bodies, in one place coming within 16 feet of the rock surface. From this vertical dikes cut across the formation. The relations seem to be those of intrusion of granite principally parallel to the bedding but partly across it. These relations may be correlated with those of the Embarrass granite at the east end of the range.

CRETACEOUS ROCKS.

Distribution and character.—Recent explorations have shown Cretaceous conglomerates, shales, or iron ores as a thin mantle over most of the western part of the district and in isolated patches as far east as Embarrass Lake. It is therefore thought inadvisable to attempt to show Cretaceous deposits on the map. Especially noteworthy is the discovery of small conglomeratic Cretaceous ore bodies overlying the contact of the iron-bearing Biwabik formation and the Virginia slate. From the distribution of the remnants now known it is certain that Cretaceous rocks once overlay all of the district west of range 16, that they may have extended farther east, and that erosion has largely removed them from the area they did occupy. It is not unlikely that some of these remnants have been protected because faulted down in post-Cretaceous time.

The rocks consist of conglomerate and shale. The conglomerate in the occurrences known overlies iron-bearing rocks and in some places iron ore. As would be expected, therefore, the fragments of the conglomerate are derived from the iron-bearing formation; in the western part of the range the conglomerate is locally rich enough to mine. The conglomerate fragments consist mainly of heavy ferruginous chert and iron ore, both hematite and limonite. Except locally, and especially where the pebbles are of hard material, they are not well rounded. There are present in the conglomerate also fossils which are described below. The fragments are but loosely cemented. When broken out of the ledge the rock is fairly compact, but on being exposed to weathering it soon disintegrates. The cement is largely ferruginous, but there is present also a considerable amount of white or yellow substance which A. T. Gordon, chemist of the Mountain Iron mine, found to consist of silica and alumina and hence to be essentially a clay. Occasionally there may be observed also minute greenish-yellow particles in the cement which may be glauconite grains, so common in the Cretaceous. Analyses disclose abundant phosphorus. The general appearance of this Cretaceous iron-ore conglomerate is very like that of "canga" or rubble ores formed subaerially on the surface of iron formations in the Minas Geraes district of Brazil.

The shales are soft, thin-bedded rocks of a bluish-gray color when fresh but in many places are of a light color due to bleaching. These, too, contain fossils.

Fossils.—Selected specimens of the shale and conglomerate containing fossils were submitted to T. W. Stanton, paleontologist, of the United States Geological Survey, for examination. He pronounced them to be "unquestionably Upper Cretaceous forms, not older than the Benton and probably not younger than the Pierre."

In addition to the fossils above noted, the Cretaceous of the Mesabi district has been found to contain small shreds of lignitic material. The presence of this material well up on the Mesabi range suggests the possibility of finding lignite deposits in the low area to the west, north, or south of the Mesabi range.

PLEISTOCENE GLACIAL DEPOSITS.

The Mesabi district is covered by a mantle of glacial drift, of the late Wisconsin epoch, which effectually conceals the greater part of the underlying rocks. On lower slopes the drift is thick, sometimes reaching 150 to 200 feet, and here of course rock exposures are rare: on middle slopes the thickness commonly does not exceed 50 or 60 feet, and 20 to 50 would measure much of it; on the upper slopes of the range the drift is thin or altogether lacking and rock exposures are correspondingly abundant. In the eastern portion of the district also, where the Giants Range granite has a higher elevation than to the west, the drift is thin and allows numerous rock masses to project through; toward the west, as the elevation of the Giants Range decreases, the drift becomes thicker, until westward from Grand Rapids it buries even the crest of the Giants Range to a depth of more than 100 feet.

The Pleistocene deposits are fully discussed in Chapter XVI (pp. 427–459).

THE IRON ORES OF THE MESABI DISTRICT.

By the authors and W. J. Mead.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The iron-bearing Biwabik formation rests on the middle south slope of the Giants Range, with a low dip to the south, 4° to 20°, affording an exposure of considerable width at the surface. The elevation of this exposure varies between 1,400 and 1,600 feet. The distribution of the Biwabik formation and the possibilities of westward extension are discussed on pages 164–165. Possibilities of extension southward are mentioned on page 174. The ore bodies are in patches along the erosion surface of the iron-bearing formation, generally less than 200 feet thick, but reaching 500 feet at greatest.

The aggregate area of all the iron-ore deposits of present commercial grade known at this writing at the surface is about 15 square miles, constituting a little less than 8 per cent of the exposed surface of the iron-bearing formation in its productive portion between the east line of range 14 on the east and west side of range 26 on the west. If low-grade ores were counted the area would be approximately doubled.

East of range 14 the nature of the formation is influenced by the great Keweenawan Duluth gabbro mass overlying the east end of the district. The ore bodies are few and small and are more largely magnetitic and amphibolitic than hematitic. Toward the west end of the district also the ores become lower in grade, owing to increasing content of loosely disseminated chert, locally called sand, so abundant in certain of the ores that they require washing to attain the present commercial grade.

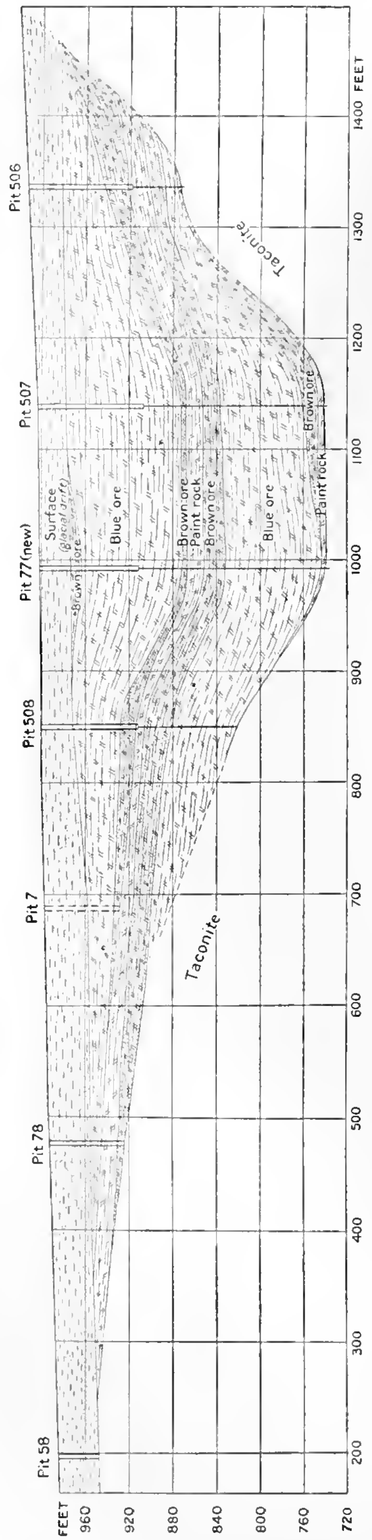


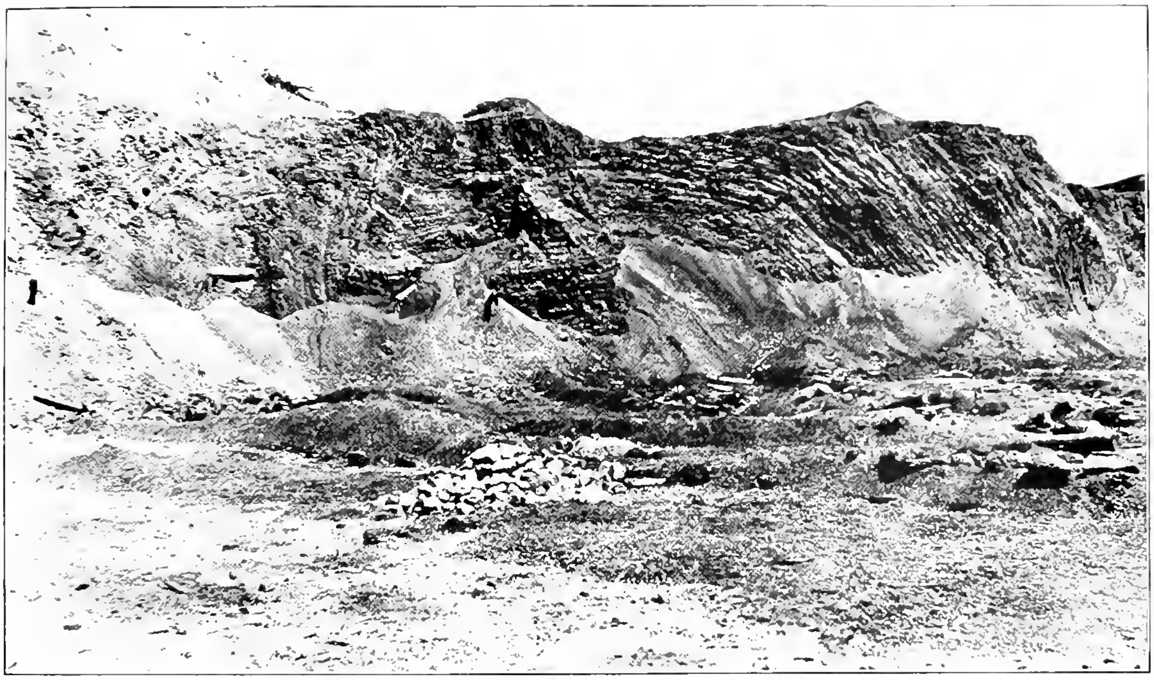
FIGURE 16.—North-south cross section of an ore deposit on the Mesabi range near Hibbing, Minn., looking west, illustrating shape of ore body, interbanding of blue ore, brown ore, and paint rock, and especially slump of ore due to secondary concentration.

The rocks immediately associated with the ores are mainly ferruginous cherts, locally called "taconite," forming both the walls and basements of the deposits. The ores usually do not rest directly upon the quartzite underlying the iron-bearing formation. Their lower limits are locally marked by thin layers of paint rock a few inches thick. A horizontal plan of the Mesabi ore deposits is exceedingly irregular both in major outline and in minor features. The deposits are in many places bounded by intersecting plane surfaces of joint or fault planes. In vertical section the ore deposits in general are widest at the top and narrow below, in the form of a shallow basin. The slopes of the basin are rarely symmetrical and few slopes are uniform; a slope is generally a series of steps, some of them overhanging the ore or projecting into it. The bedding of the iron ores is continuous with that of the adjacent ferruginous cherts of the iron-bearing formation except where there has been local slump or faulting at the contact. The slump is sometimes accompanied by close crumpling of the layers of the iron-bearing formation (Pl. IX). It will be shown later that the slump results from the leaching of silica. Obviously the layers have been originally too long for their present positions and have crumpled to accommodate themselves to the new conditions. The bedding of the ores is thus essentially parallel to that of the upper Huronian of this district—that is, sloping gently southward at angles from 4° to 20°, with minor gentle folds whose axes pitch in that direction. A good general conception of the structural relations of the Mesabi ores may be obtained by thinking of the ores as irregular rotted upper portions of the slightly tilted and beveled iron-bearing formation, the rotting having been favored in certain spots, as will be shown later, by the fracturing of the formation or by the minor folds in which the formation rests. (See fig. 16; Pl. X, which is a north-south cross section; and Pl. XI.)

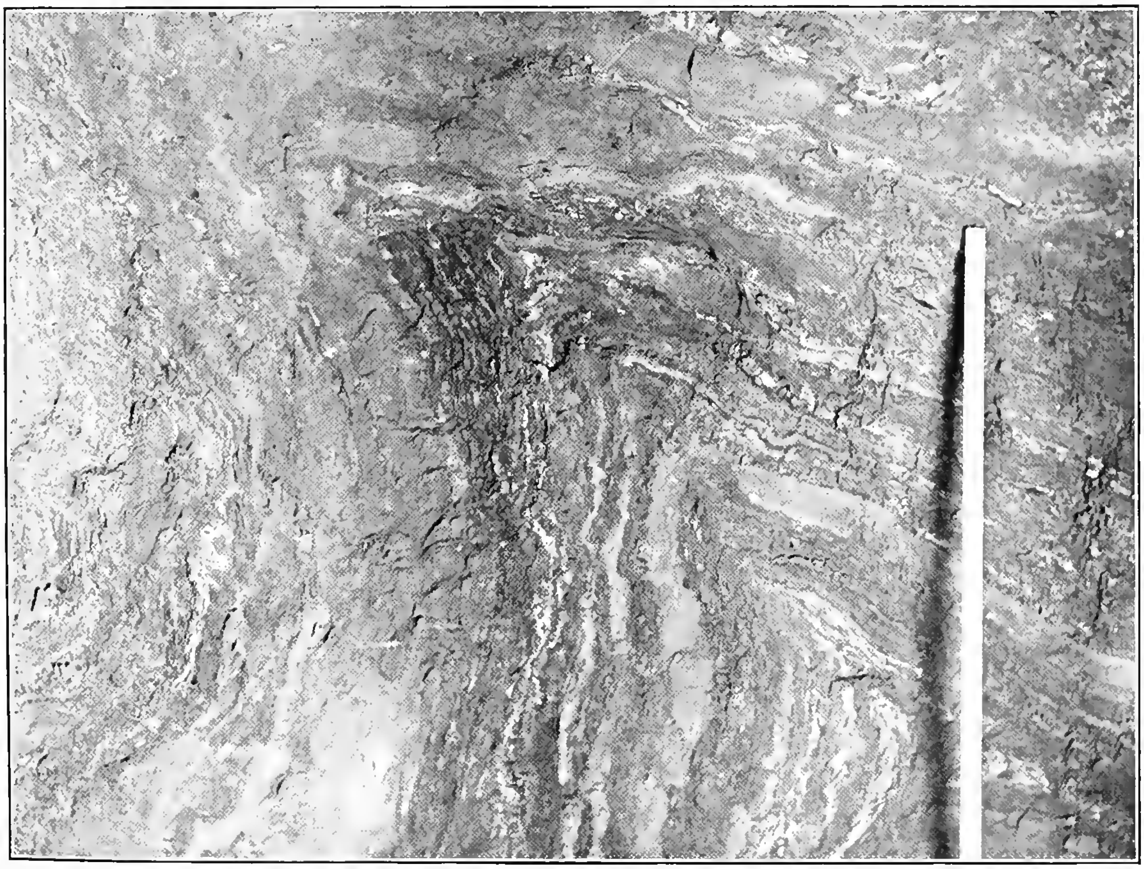
CHEMICAL COMPOSITION OF FERRUGINOUS CHERTS AND ORES.

ANALYSES.

The chemical composition of the ores and related rocks is here exhibited by partial and complete analyses from various sources. A large number of the analyses employed were kindly furnished by the several mining companies. All the other analyses except those previously published were made by Lerch Brothers in their laboratories at Hibbing and



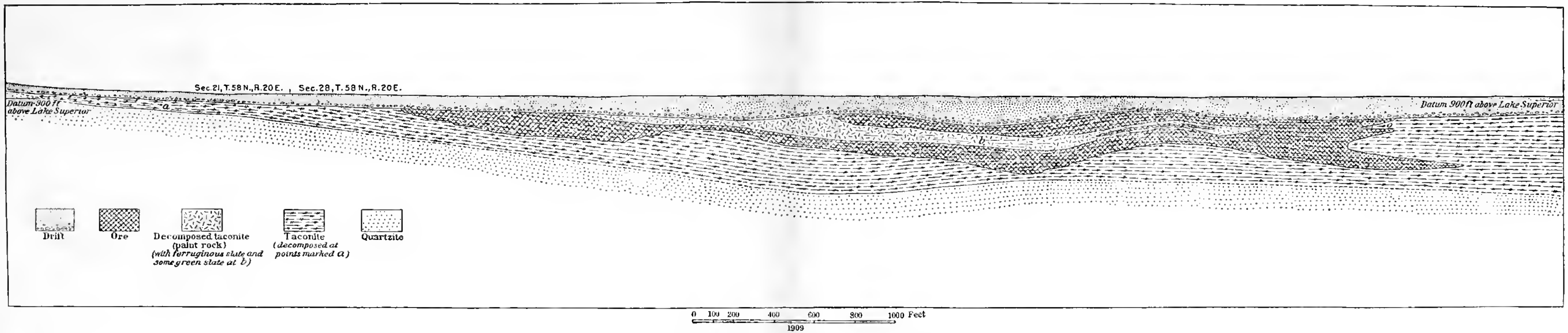
A. HAWKINS MINE.



B. MONROE MINE.

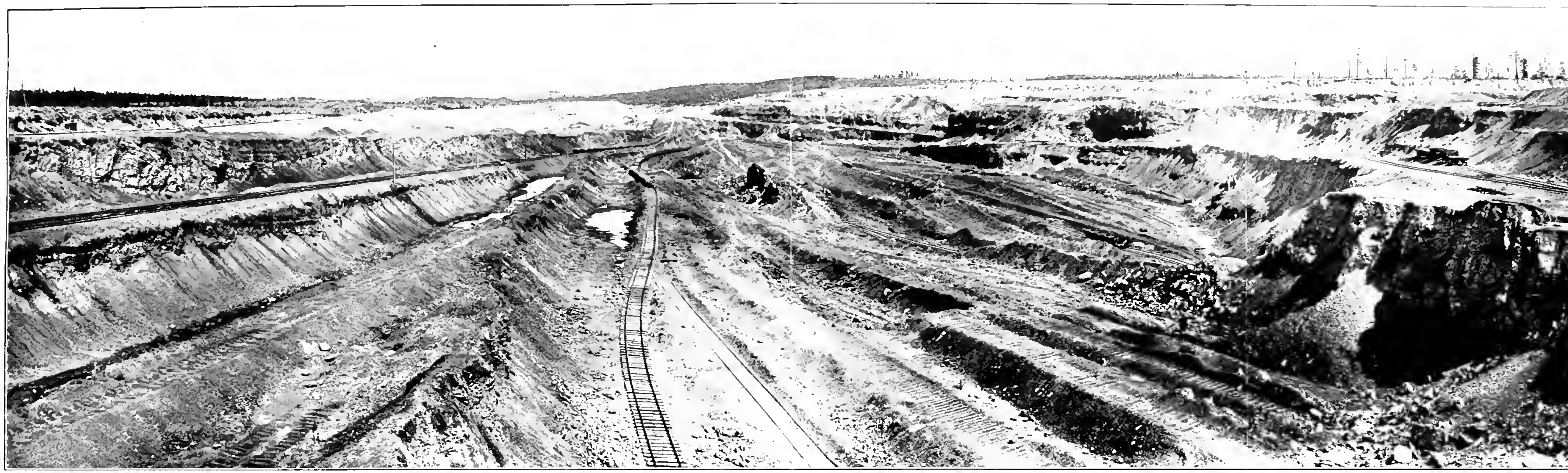
SHARP FOLDING OF BEDS OF IRON-BEARING BIWABIK FORMATION IN MESABI DISTRICT, MINN.

See page 180.



NORTH-SOUTH CROSS SECTION THROUGH IRON-BEARING BIWABIK FORMATION, MESABI DISTRICT, MINNESOTA.

Compiled by O. B. Warren from drill records.



A. PANORAMIC VIEW OF THE MOUNTAIN IRON OPEN-PIT MINE, MESABI DISTRICT, MINN.

Looking east. From photograph presented by J. F. Lindberg, Hibbing, Minn. See pages 180, 497.

B. PANORAMIC VIEW OF THE SHENANGO IRON MINE, MESABI DISTRICT, MINN.

See pages 180, 497.

Virginia, Minn. The average cargo analyses for the various grades of ore were obtained from the list published by the Lake Superior Iron Ore Association.

Nine typical analyses of taconite are given in the following table. These analyses include carefully selected samples from several drill holes giving complete sections through the formation.

Partial analyses of ferruginous chert (taconite) from the Mesabi range.

[Samples dried at 212° F.]

	Fe.	SiO_2.	P.	Al_2O_3.	Loss on ignition.
La Rue mine, sec. 29, T. 57 N., R. 22 W.	32.24	51.48	0.021	0.37	0.62
Stevenson mine, secs. 7 and 8, T. 57 N., R. 21 W.	24.99	61.38	.024	.21	.60
Crosby mine, sec. 32, T. 57 N., R. 21 W.	11.79	81.38	.010	.29	.67
Do.	19.56	70.27	.013	.33	.25
Drill core from three holes in T. 57 N., R. 22 W., in all 800 feet	30.24	47.14	.038	.84	5.16
Drill core, 300 feet	23.80	50.90	.030	1.20	7.52
La Rue mine, sec. 29, T. 57 N., R. 22 W.	32.26	50.78	.018	.30	.45
Burt mine, sec. 31, T. 58 N., R. 20 W.	23.98	62.75	.013	.91	1.33
Do.	32.52	52.26	.020	.42	1.07
Average	25.71	58.70	.021	.51	1.96

The large loss on ignition in the drill-core samples is in part due to the presence of CO_2 in carbonates. The samples represent the hard phases of the formation, showing little concentration to ore. When all of the iron-bearing formation outside of the available iron-ore deposits is averaged, including both the hard lean parts shown in the above table and the partly concentrated portions of the formation, the average iron content runs higher. An average of 1,094 analyses, representing 5,400 feet of drilling in the district away from the available ores, gives 38 per cent. This does not include the ores. Because of the great mass of such rocks as compared with the ores, this figure of 38 per cent represents approximately the general average iron content of the entire formation.

The average composition of the Mesabi ore for the years 1906 and 1909 was obtained by combining average cargo analyses of all grades mined for each of those years in proportion to the tonnage represented by each grade. In this manner an average analysis was obtained which represents as exactly as possible the composition of all of the ore mined in the Mesabi district during the years 1906 and 1909.

Average composition of all ore mined in the Mesabi district during the years 1906 and 1909.

	1906.	1909.
Moisture (loss on drying at 212° F.)	....	12.27
Analysis of dried ore:		
Iron	60.70	58.83
Phosphorus	.0559	.062
Silica	5.58	6.80
Manganese	....	.816
Lime	....	.32
Alumina	1.58	2.23
Magnesia	....	.32
Sulphur	....	.069
Loss on ignition	4.57	4.72

Range in composition of ores mined in the Mesabi district, as shown by average cargo analyses for 1909.

Moisture (loss on drying at 212° F.)	7.15	to 15.79
Analysis of dried ore:		
Iron	52.40	to 64.05
Phosphorus	.019	to .105
Silica	2.50	to 19.90
Manganese	.20	to 2.84
Alumina	.16	to 5.67
Lime	0	to 1.82
Magnesia	0	to 2.06
Sulphur	.004	to .440
Loss on ignition	1.71	to 9.45

REPRESENTATION BY MEANS OF TRIANGULAR DIAGRAM.

In figure 17 the triangular method of platting is employed to show the chemical composition of the various phases of taconite and ore studied. Here actual percentage weights of the constituents are indicated, and no account is taken of volume or porosity. Each point, by its position in the triangle, indicates an individual analysis. The diagram consists of an equilateral triangle crossed by equally spaced lines, 100 parallel to each side. Distances measured perpendicularly from the three sides to any point within the triangle (by means of the divisions in the triangle) represent severally percentages of ferric oxide, silica, and the remaining constituents. Thus any point in the triangle indicates a certain definite combination of these three factors. The grouping of the points in the triangle shows that the principal variation in composition lies between the iron and the silica. In the process of concentration of ore from the ferruginous chert the percentage of iron increases in proportion to the decrease in silica, while the percentage of minor constituents remains practically constant; hence this concentration would be represented by a series of points in a line parallel to the right-hand side of the triangle. A taconite with a high content of alumina produces an ore high in kaolin, and conversely.

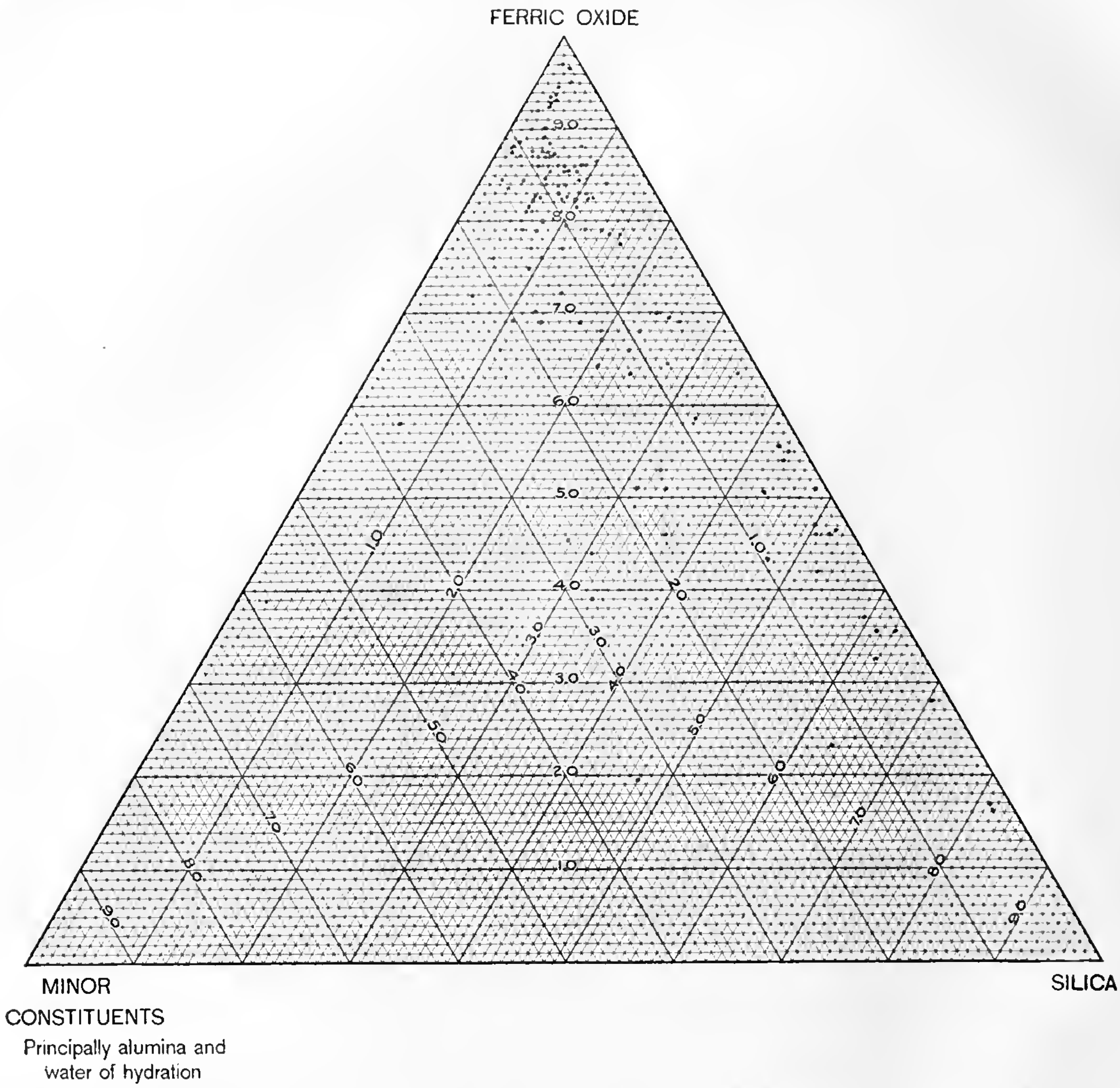


FIGURE 17.—Triangular diagram showing composition of various phases of Mesabi ores and ferruginous cherts in terms of ferric oxide, silica, and minor constituents (essentially alumina and combined water). The ores and cherts here represented are shown in figure 21 in terms of percentage volumes of iron minerals, silica, and pore space.

MINERALOGICAL COMPOSITION OF FERRUGINOUS CHERTS AND ORES.

Mineralogically both the cherts and the ores consist essentially of hydrated oxides of iron, chert, or quartz, aluminum-bearing minerals, usually kaolin, and a small amount of minor constituents. In the calculation of the approximate mineral composition of the various rocks and ores these minor constituents—alkalies, sulphur, phosphorus, etc.—were disregarded, the error thus introduced being small. The iron is present in the ores and cherts as a partly hydrated ferric oxide. To ascertain in each case the particular hydrated iron-oxide mineral present would be impracticable, but by calculating the iron as hematite and limonite the degree of hydration is expressed by relative amounts of the two minerals. The amount of limonite is found by assigning to the volatile matter or water of hydration available the proper amount of iron, the remainder of the iron being calculated as hematite. The practice of assigning to the iron mineral all the water of hydration not in aluminum silicates may introduce minor inaccuracies because of the possible slight hydration of the chert.

The mineralogical compositions of the ores and ferruginous cherts of the Mesabi range calculated from the average analysis by the methods described above are as follows:

Approximate mineral compositions of average ores and ferruginous cherts.

	Ferruginous cherts.	Ores.	
		1906.	1909.
Hematite	26.30	63.00	61.81
Limonite	12.22	27.00	25.95
Quartz	58.07	4.10	4.10
Kaolin	1.37	4.08	5.30
Miscellaneous	2.04	1.82	2.84
	100.00	100.00	100.00

PHYSICAL CHARACTERISTICS OF THE ORES.

TEXTURE.

The Mesabi iron ores are for the most part soft, somewhat hydrated hematite, though approximately pure limonite ores are present in subordinate quantity. The ores as a whole are of finer texture than those of any other Lake Superior district. Their texture varies from exceedingly fine-grained "flue dust" to a fairly coarse, hard, and granular ore breaking into parallelepiped blocks. Usually the ore needs but little blasting to allow the steam shovel to take it from the bed. The average texture of the Mesabi ores is shown by the following table, representing an average of screening tests on eight grades of typical Mesabi ore totaling 18,313,570 tons in 1909. These screening tests were made by the Carnegie Steel Company and represent the total year's output of each of the grades tested. The textures of the ores of the several Lake Superior districts are compared in figure 72 (p. 481).

Textures of Mesabi ores as shown by screening tests.

	Per cent.
Held on ½-inch sieve	25.98
⅛-inch sieve	26.24
No. 20 sieve	11.54
No. 40 sieve	9.90
No. 60 sieve	8.54
No. 80 sieve	2.16
No. 100 sieve	2.28
Passed through No. 100 sieve	13.68

The fineness of many of the ores has required mixture with coarser grades for blast-furnace charges. The average mixture is approximately indicated by the proportions of Mesabi to other Lake Superior ores, which has increased to 69 per cent in 1910.

DENSITY.

Several methods were employed in the determination of density—(1) determination of density of finely powdered specimen by means of specific-gravity bottle; (2) determinations of density from hand specimens by the common method of weighing in air and in water, the pores of the rock being filled with water by prolonged boiling before weighing under water; (3) calculation of specific gravity of the rock or ore from mineral composition by proper combination of the densities of the several minerals present. The density of the ores or cherts calculated by using the density of the iron minerals given by Dana was uniformly higher than the density found by gravity methods. The iron minerals in an earthy form have a lower density than those in the hard ores, and it was found that the two methods could be made to agree by assigning to hematite a density of 4.5 and to limonite one of 3.6.

By combining the specific gravities in proportion to the percentages of the minerals the average density of the ferruginous cherts is found to be 3.27.

Actual density determinations on eleven specimens of ferruginous cherts gave an average of 3.02. (See table below.) This figure is lower than the average figure computed above, for two reasons: The eleven specimens on which the determinations were made contained a smaller percentage of iron than the average analysis above. The close texture of the specimens prevented complete saturation by immersion in water and also prevented complete drying; hence both density and porosity determinations are somewhat lower than they should be. For these reasons it is believed that the specific gravity as calculated from the average analysis above (3.27) represents most closely the average specific gravity of the taconite.

The average specific gravity of the ore, as calculated from the mineralogical composition of the average ore, is found to be 4.10.

POROSITY.

In all rocks and ores of which hand specimens could be collected the porosity was determined by comparing the weight of the specimen when saturated with water with its weight when dried. This manner of determination is formulated as follows:

$$\frac{\text{Weight of water absorbed}}{\text{Weight of rock when saturated}} = \text{moisture of saturation} = M.$$

$$\text{Porosity} = \frac{M}{\frac{1-M}{G} + M}$$

where G equals specific gravity. From this formula it is obvious that a determination of density is necessary in connection with each porosity determination.

The porosity determinations on eleven specimens of ferruginous chert by the method described follow.

Porosity determinations of chert.

Specimen No.	Specific gravity.	Porosity (per cent of total volume).	Specimen No.	Specific gravity.	Porosity (per cent of total volume).
44051	3.25	6.5	45603	2.80	3.50
45588	3.04	2.3	45692	2.87	3.80
45309	2.86	9.45	45672A	2.96	6.45
45305	2.88	5.1	45590	3.07	3.55
40651	2.90	6.25			
45021	3.22	6.00	Average	3.02	4.72
45596	2.92	3.75			

To unconsolidated material, such as a large part of the Mesabi ores, the above method could not be applied. The porosity of such material was found by comparing its actual density when in place, including pore space, with the calculated mineral density, which does not include pore space. The actual density of the material in place was determined by weighing the amount removed from an excavation made on a leveled surface of the ore, the volume of the excavated material being determined by measuring the amount of grain necessary to fill the excavation. Another method for the determination of cubic content of the Mesabi ores is one employed by O. B. Warren, of Hibbing, Minn. Mr. Warren used a bottomless box 4 feet long, 3 feet wide, and 1 foot deep. These dimensions were chosen as representing the average volume of a ton of ore. This box is set up on a leveled surface and the ore removed from the inside of the box until the sides are sunk to the level of the surface. In this way exactly 12 cubic feet of ore are removed and weighed, a sample for analysis being taken at the same time.

The porosity of the ore may also be determined by saturating a portion *in place* by an abundant application of water. Placing a sample of the saturated material immediately in a closed vessel permits the determination of the moisture of saturation, from which the porosity may be calculated as shown above. Where the ore to be tested is in a vertical wall a small niche should be cut to afford a horizontal surface for the application of the water. It will be seen that this method does not differ essentially from the determination of porosity of hand specimens, except that the material is saturated *in place* and not after removal from the ground.

More than 100 determinations by the various methods show the average porosity of the ore to be approximately 40 per cent of the volume. (See fig. 21, p. 190.)

CUBIC CONTENTS.

Owing to the wide variation in the three essential factors, density, porosity, and moisture, there is a wide variation in the number of cubic feet per ton of the ores. This number ranges from 9 cubic feet per long ton in some of the highest-grade blue granular ores to 17 or 18 in the low-grade limonites. The average for the district is approximately 12 cubic feet per long ton. The method of calculation is discussed on pages 480–484.

MAGNETIC PHASES OF THE IRON-BEARING FORMATION.

OCCURRENCE.

Eastward from the town of Mesaba, on the Duluth and Iron Range Railroad, the iron-bearing Biwabik formation becomes progressively more magnetic, more coarsely crystalline, and the red or brownish tones of the ferruginous cherts give way to black and gray colors. Ore deposits are rare. Such as there are consist of mixtures of hematite and magnetite. In the most magnetic and crystalline parts of the formation ore deposits seem to be entirely lacking. In addition to the magnetite and quartz, there are present various anhydrous silicates, such as grünerite, actinolite, augite, and others. The parts of the formation rich in magnetite are concentrated into definite layers a few inches to a few feet in thickness and interlayered with layers less rich in magnetite. Mining would require not only hand sorting but presumably also crushing and magnetic concentration.

CHEMICAL COMPOSITION.

The chemical composition of the amphibole-magnetite rock is about the same as the average of the iron-bearing formation elsewhere in the Mesabi district outside of the iron-ore deposits, as is shown by the following average:

Average chemical composition of amphibole-magnetite rock in the Mesabi district.

SiO_2	60.51
Al_2O_3	1.20
Fe	25.22
MgO	.52
CaO	.67
H_2O	Small.
P_2O_5	.05
S	.59
MnO_2	.92
TiO_2	None.

The reasons for the lack of concentration of ore in this part of the formation are discussed on page 553.

SECONDARY CONCENTRATION OF MESABI ORES.

STRUCTURAL CONDITIONS.

In the Mesabi district waters falling on the south slope of the Giants Range have flowed southward, entered the eroded edges of the slightly tilted Huronian series, and flowed through the iron-bearing formation, following both bedding and joint planes. There are gently pitching rolls in the formation, but they are so light that their control of the circulation is small as compared with that of the bedding and joints. The result is the extreme irregularity in the shape and distribution of the Mesabi ore deposits.

On the south the iron-bearing formation is overlain by slate. The percolating waters undoubtedly permeate the iron-bearing formation beneath the slate, but it is altogether likely that there they are ponded and have a relatively slow movement. Drill holes put down through the slate into the iron-bearing formation occasionally meet water under artesian pressure. The principal zone of escape doubtless is the north edge of the slate—that is, the water overflows to the surface before passing far under the slate (fig. 18). This doubtless explains the comparative lack of alteration of the iron-bearing formation or the existence of ore deposits far under the Virginia slate.

The ponding effect of the slate also probably aids in diminishing any possible effect which the southward-pitching synclines in the iron-bearing formation might have on the localization of the ores, for the reason that near the slate flowage of water is controlled by the point of escape at the edge of the slate rather than by the configuration of the basin in which it might otherwise

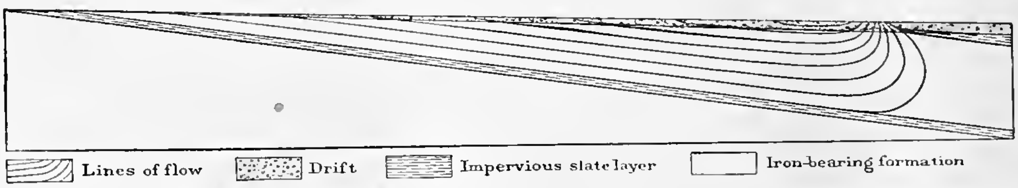


FIGURE 18.—Section through iron-bearing Biwabik formation transverse to the range, showing nature of circulation of water and its relations to confining strata.

flow, and this point of escape may be higher than the anticlines in the basement, thus allowing the waters to flow equally well over anticlines and synclines in the basement.

The impervious basement in the Mesabi district is usually some layer in the iron-bearing formation itself, commonly a shaly layer which has subsequently been altered to paint rock. In no place does the ore rest directly upon the underlying quartzite.

The greatest depth of the Mesabi ore deposits must be less than the depth of the iron-bearing formation, and as the greatest thickness of the formation is only near the slate margin, where the waters are escaping and are not doing their best work, it follows that the ore deposits are not likely to reach this maximum depth. The greatest depth thus far known in the Mesabi range is 500 feet. The common depths are less than 300 feet.

The Giants Range furnishes the head for the percolating waters. Toward the west end of the district the range becomes lower and the grade of the ore becomes correspondingly lower, suggesting that the circulation of the ore-concentrating solutions was less vigorous at the western end because of the lower elevation. The ores have no close relation to the minor hills on the Giants Range slope, though they tend to occur in the depressions, principally because in such places denudation is relatively deep owing to softness. Were it not for the irregular covering of glacial drift, their relations to minor valleys would be more apparent.

ORIGINAL CHARACTER OF THE IRON-BEARING FORMATION.

The iron-bearing Biwabik formation originally consisted dominantly of greenalite rocks and subordinately of cherty iron carbonate, the characters of which are described on pages 165–170.

The alteration of these rocks to the ore has been accomplished in two stages, mainly successive but partly overlapping—first, by alteration to ferruginous chert; second, by leaching of silica from the ferruginous chert.

ALTERATION OF SIDERITIC OR GREENALITIC CHERT TO FERRUGINOUS CHERT (TACONITE).

Chemical change.—The chemical change consists of oxidation of the iron according to the following reactions:

For greenalite—

$$2FeSiO_3.nH_2O + O = Fe_2O_3.nH_2O + 2SiO_2 \pm H_2O.$$

For siderite—

$$2FeCO_3 + nH_2O + O = Fe_2O_3.nH_2O + 2CO_2.$$

Mineral change.—The greenalitic cherts or greenalite rocks are composed essentially of rounded granules of greenalite in a matrix of chert. The tendency to banding is not as distinctive as in the cherty iron carbonates. The greenalite alters to hydrated iron oxide. The silica remains or goes out. Mineralogically the sideritic cherts consists essentially of siderite and chert more or less segregated into alternate layers. The siderite is changed to hydrated iron oxide. Either removal or retention of silica may accompany this change.

Secondary siderite, usually differing from original siderite in having coarser grain, is a minor product of alteration of both greenalitic and sideritic cherts.

Volume change.—Though the alteration is distinctly of a katamorphic nature, the change is from a light to a denser mineral, and hence involves a reduction in the volume of the iron mineral. Like the oxidation of the siderite, the oxidation of the greenalite involves a change from a lighter to a denser iron mineral and a decrease in the volume. The volume changes involved in the above alterations are as follows:

Alteration of siderite to hematite, 49.25 per cent loss.

Alteration of siderite to limonite, 18.30 per cent loss.

Alteration of greenalite to hematite and quartz, 24.50 per cent loss.

Alteration of greenalite to limonite and quartz, 9 per cent loss.

As the chert is at first unchanged in the alteration of the greenalite and carbonate to iron oxide, the volume change accompanying these alterations is effective on only a portion of the rock. Chemical analyses of both the sideritic cherts and the greenalitic rocks show that approximately 60 per cent of their volume is chert. Hence the change in volume is effective on only 40 per cent of the total volume of the rock. The loss in volume, then, for the entire rock, taking into account both the iron and the silica, ranges from 3.6 per cent to 19.7 per cent, according as the original rock bore siderite or greenalite and according to the degree of hydration of the resulting product.

Development of porosity.—This volume change, due to oxidation of greenalite or siderite, develops pore space. Determinations of porosity on eight typical specimens of greenalitic rock and sideritic chert showed the average porosity to be 0.96 per cent of the volume of the rock. An average of twelve determinations on type specimens of ferruginous chert (taconite), from which apparently no silica had been leached, gave a porosity of 4.72 per cent. The porosity resulting from the reduction in volume, due to the oxidation of greenalite, in a rock containing 40 per cent by volume of that mineral should be 9.8 per cent of the volume of the rock when the product is hematite and 3.6 per cent when the product is limonite. The ratio of hematite to limonite in the average taconite is about three parts of hematite by volume to two of limonite; hence the porosity resulting from the alteration of average greenalite rock to average ferruginous chert should be approximately 7.3 per cent of the volume of the chert. This figure does not differ greatly from the observed porosity of the ferruginous chert—4.72 per cent. It is to be expected that the observed porosity would be less than the porosity as calculated above, for several factors, such as cementation and mechanical agencies, would tend to close openings formed.

ALTERATION OF FERRUGINOUS CHERTS (TACONITE) TO ORE.

The alteration of ferruginous cherts (taconite) to ore consists essentially in removal of silica. It has already been shown that the alteration of ferruginous cherts to ores is essentially later than that of the original greenalite and carbonate rocks to ferruginous cherts.

During the change from the ferruginous cherts to ore the iron oxide remains essentially the same in absolute quantity (not in percentage) and in degree of hydration, as will appear from some of the following analyses and calculations.

VOLUME CHANGES.

At many places in the district the actual gradation from ferruginous chert to ore may be observed. In the following table are several series of analyses showing this gradation. Each series represents a series of specimens taken from the same layer of taconite. In no case were the members of one series taken from an area greater than 2 feet in extent, so that approximately uniform original composition was insured throughout each series.

The first member of each series represents the least altered phase, each successive member of the same series showing a greater degree of alteration.

Alteration of ferruginous chert.

	Chemical composition.					Approximate volume composition.			
	Fe.	SiO_2.	P.	Al_2O_3.	Loss on ignition.	Pore space.	Hematite + limonite.	Quartz.	Kaolin.
Series 1, Stevenson mine	29.47	52.89	0.016	0.62	2.92	8.00	32.35	57.90	1.74
	33.01	50.08	.016	.35	1.65	16.50	31.25	51.40	.93
	35.26	43.44	.013	.40	4.48	26.30	33.51	39.30	.92
	48.88	25.03	.015	.21	3.83	52.70	30.81	16.18	.34
Series 2, Stevenson mine	44.33	34.24	.013	.37	1.81	38.00	33.12	28.10	.77
	45.30	31.05	.014	.23	2.73	39.70	34.65	25.20	.48
	48.51	26.42	.013	.35	2.67	42.40	36.05	20.88	.70
	49.18	23.60	.016	.32	2.64	45.40	35.70	18.25	.65
Series 3, La Rue mine	32.26	50.78	.018	.30	.45	4.00	33.55	61.10	.90
	38.84	42.69	.012	.24	.74	23.20	33.73	42.50	.61
	44.49	34.33	.010	.22	.69	24.20	39.89	35.35	.57

Series 1 was taken near the top and to one side of the ore body; there was apparently no slump, as is shown by the constant volume of the iron mineral. Figure 19 is a graphic repre-

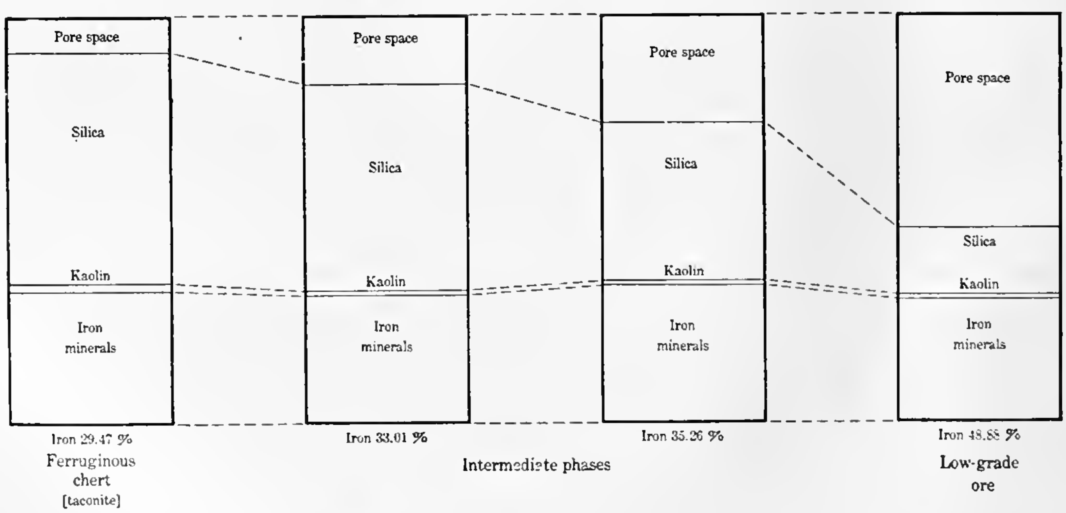


FIGURE 19.—Diagram showing volume changes observed in the alteration of ferruginous chert to ore. The four specimens represented were collected from a single band of ferruginous chert in the Stevenson mine, Mesabi district, Minnesota. (See analyses, above.)

sentation of the series. Both the other series showed slight evidence of slumping, the chert bands being thinner at the most altered end: consequently the increase in volume of the iron mineral was expected.

Figure 19 shows very well that the essential process in the alteration of the taconite is the leaching of silica. This removal of material causes an increase in pore space. The development of porosity beyond certain limits weakens the rock and results in slumping or crushing; hence the volume of silica removed may be greater than the porosity observed. In order properly to compare the various phases of taconite and ore studied, it is necessary to consider them in terms of volume composition rather than of weight. By so doing the factor of porosity is included in each phase studied, the volume composition being given in terms of hydrated iron oxide, silica, pore space, and minor constituents (principally kaolin). The alteration as shown by the average analyses of greenalite, taconite, and ore is expressed diagrammatically in figure 20.

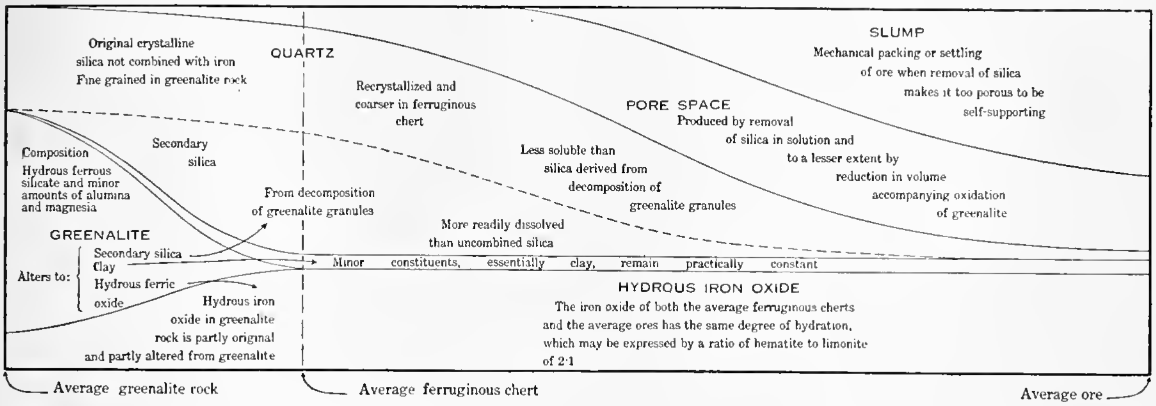


FIGURE 20.—Graphic representation of the changes involved in the alteration of greenalite rock to ferruginous chert (taconite) and ore, Mesabi district, Minnesota. The mineral composition of the various phases is represented in terms of volume by vertical distances. The mineral composition of the greenalite rock, ferruginous chert, and ore as represented was obtained by averaging a large number of analyses.

METHOD OF EXPRESSING VOLUME CHANGES BY TRIANGULAR DIAGRAM.

While the method of representation shown above (figs. 19 and 20) expresses well the average results, it is not a convenient way of handling a large number of detailed figures. In order that many individual comparisons may be made on a single diagram, the volumes of the principal constituents—silica, iron minerals, and pore space—are platted on a triangle (fig. 21) in which all these factors are indicated by position in the diagram. The triangular method of representing percentages of three constituents has been described on page 182. In figure 21 the same method is employed to represent the volume composition of the various phases of the iron-bearing formation studied. As is indicated on the triangle, distances measured from the three sides represent severally percentage volumes of iron minerals, silica, and pore space. Thus any point in the triangle represents amounts of pore space, quartz, and iron minerals totaling 100 per cent. In actual analyses, however, it is found that these three factors seldom total 100 per cent, a small percentage of minor constituents being present, principally kaolin, which makes it impossible to represent the volume composition by a single point in the diagram. This difficulty is obviated, however, by representing the percentage volume of each of the three principal constituents by a short line drawn parallel to each side at the proper distance, thus constructing a small equilateral triangle within the larger one. The altitude of this small triangle represents, by the divisions in the large triangle, the percentage volume of the minor constituents. We may then represent by the position and size of a small parallel triangle within the large equilateral triangle the volume composition of any chert or ore in terms of pore space, silica, iron minerals, and minor constituents.

DATA USED IN TRIANGLE.

Chemical analyses, together with density and porosity determinations, were procured for 120 taconite and ore specimens, including gradation phases between the taconite and ore, slaty phases of the taconite, and paint rock. These data, when platted on the triangular diagram, show the relations of the various phases of the iron-bearing formation and enable one to deal with a large number of individual cases as easily as with averages. Each of the small triangles within the large one represents an actual specimen or sample from the iron formation.

CONSIDERATION OF THE TRIANGULAR DIAGRAM.

The unaltered taconite is represented by the small triangles in the lower left-hand side of the triangle, where porosity is low and silica high. If the taconite represented by any one of these triangles is to be altered to ore, it is necessary that part of the silica be removed to permit an increase in the iron content. If silica is removed, there must be an increase in the percentage

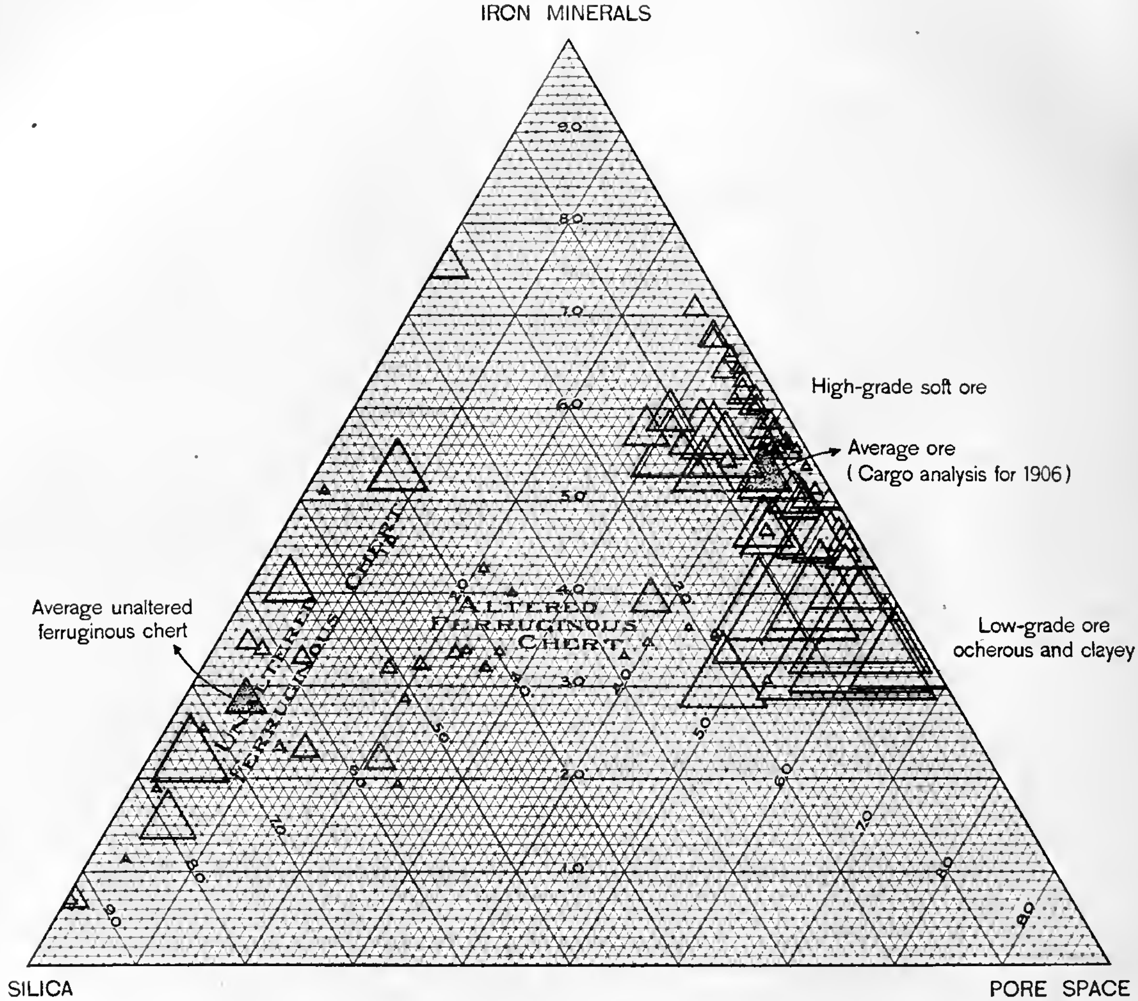


FIGURE 21.—Triangular diagram representing in terms of pore space, iron minerals, silica, and minor constituents (clay, etc.) the volume composition of the various phases of ferruginous cherts and iron ores of the Mesabi district. For detailed explanation see page 189.

of volume either of pore space or of iron. If we suppose the change to lie between silica and pore space, iron being unchanged, the alteration of the chert will be represented by a succession of triangles reaching across the diagram to the right at a constant distance from the base, silica decreasing and porosity increasing. If the sample selected is high enough in iron and low in silica, sufficient silica may be removed to produce ore without developing an impossible porosity. On the other hand, if the small triangle selected is near the base of the diagram, representing a taconite that is composed largely of silica and contains only a small amount of iron, it is evident that removal of sufficient silica to bring the percentage of iron up to the ore grade without slump would develop a very large porosity. It is probable that the porosity would increase until the material became too porous to support itself and the weight above, when slump would occur, decreasing the pore space and increasing the percentage volume of iron. This change would be represented on the diagram by an upward movement of the triangle selected. Actual infiltration of iron in solution would also cause decrease in porosity and increase in iron, but field observation shows that infiltration of iron is very slight in this district, and hence any shortage of pore space must be explained by slump. Calculations show that on an average this slump amounts to approximately 45 per cent of the volume of the original taconite, which would give a vertical slump of 82 feet for every 100 feet depth of ore. This figure, though apparently large, is well in accord with the observed facts. The degree of slump in an ore body may best be measured by observing the amount of sag in the paint-rock layers which have been bent downward by the slump of the underlying ore. Figure 16 shows a typical cross section of an ore deposit in the Hibbing district; the amount of slump in the ore beneath the paint rock is seen to be of the same magnitude as the above figures. The diagram (fig. 21) shows that where the original content of iron in ferruginous chert is high the amount of silica to be leached is small and the resulting pore space is small, but that where the iron is low the pore space is proportionally greater. It follows, then, that ferruginous cherts originally low in silica are much more easily and quickly altered to ore than those high in silica.

It is also seen from the diagram that the ores high in alumina or clay (represented by the larger triangles) have a greater porosity in rough proportion to the alumina content. The alumina is very largely in the form of kaolin, a substance characteristically very porous and not so easily affected by slump as the coarser and more granular ores; hence the larger porosity.

ALTERATIONS OF ASSOCIATED ROCKS CONTEMPORANEOUS WITH SECONDARY ALTERATION OF THE IRON-BEARING FORMATION.

The shaly layers in the original iron-bearing formation become transformed to paint rock or ferruginous slates during the ore concentration. Abundant phases of the formation intermediate between the shales and carbonates or greenalites become, after alteration, either ores or cherts with a pronounced shaly or slaty structure. These are variously called ferruginous slates, slaty ores, or paint rock, according to their iron and clay contents. The nature of the alteration is a leaching of silica and the more soluble bases, leaving a mixture of clay and iron oxide. Following are typical analyses of the phases mentioned above:

Typical analyses of unaltered slaty phase of iron-bearing formation and paint rock.

	Unaltered slaty phase of iron-bearing formations.			Paint rock.		
	1.	2.	3.	4.	5.	6.
SiO_2	37.11	53.86	23.80	9.54	20.94	55.57
Al_2O_3	2.41	9.14	7.95	7.00	19.01	3.28
Fe_2O_3	17.51		5.97	77.30		
Fe		15.90			30.88	25.60
FeO	26.13		32.21	.45		
MgO	3.70		5.89			
CaO	.75		4.67			
Na_2O	.09		.29			
K_2O	.62		.18			
H_2O-	.95		} 4.28		} 13.44	
H_2O+	2.57					
TiO_2	.22			.61		
Co_2	6.16	.14	11.84			
MnO	1.21					
C	.73					
Volatile			3.35			
P_2O_5	.09	.04		.20		

1. Specimen 45461 from Moss mine; analysis by George Steiger.
2. Specimen 45600 from point near the southeast corner of the NE. ¼ SW. ¼ sec. 21, T. 58 N., R. 20 W.; analysis by H. N. Stokes.
3. Specimen 112 (Chem. series No. 240), NE. ¼ SE. ¼ sec. 17, T. 58 N., R. 19 W.; analysis by A. D. Meeds for J. E. Spurr. (See Geol. and Nat. Hist. Survey Minnesota, Bull. No. 10, p. 10).
4. Specimen 40661 from Mahoning mine; analysis by George Steiger.
5. Dark portion of banded red and white paint rock (specimen 45646) from Mountain Iron mine; analysis by A. T. Gordon.
6. Paint rock (specimen 45594) from Penobscot mine, beneath ore; analysis by H. N. Stokes.

Where igneous rocks have been intruded into the formation before its alteration these have suffered similar alterations to the slate. Their bases have been leached and they remain essentially as clay, retaining the igneous textures.

PHOSPHORUS IN MESABI ORES.

DISTRIBUTION IN THE IRON-BEARING FORMATION.

The distribution of phosphorus in the various phases of the iron-bearing formation is as follows:

Phosphorus in iron-bearing formation.

	Iron.	Phosphorus.	Ratio of phosphorus to iron.
Greenalite rock, average of six typical specimens	25.05	0.012	0.000479
Ferruginous chert:			
Average	25.71	.021	.000820
Iron layers in ferruginous chert (Specimen 44051)	61.69	.074	.001200
Chert layers in ferruginous chert (Specimen 44051)	24.50	.019	.000770
Iron layers in ferruginous chert (Specimen 44050)	51.27	.035	.000680
Chert layers in ferruginous chert (Specimen 44050)	11.55	.010	.000870
Iron layers in ferruginous chert (Specimen 44071)	58.39	.052	.00089
Chert layers in ferruginous chert (Specimen 44071)	38.33	.018	.00047
Slate in iron formation, typical analysis	29.90	.098	.00328
Paint rock, typical analysis	40.80	.189	.00462
Amphibole-magnetite rock	23.56	.0394	.00167
Iron ore, average of 1906 output	60.70	.0559	.000920

There is a wide variation in the phosphorus content of the several grades of ore. In general it may be said that the more hydrous ores tend to run high in phosphorus but are not uniformly so. In figure 22 the increase of phosphorus with the degree of hydration of the ore is shown, the data being average cargo analyses of all grades of ore shipped from the Mesabi

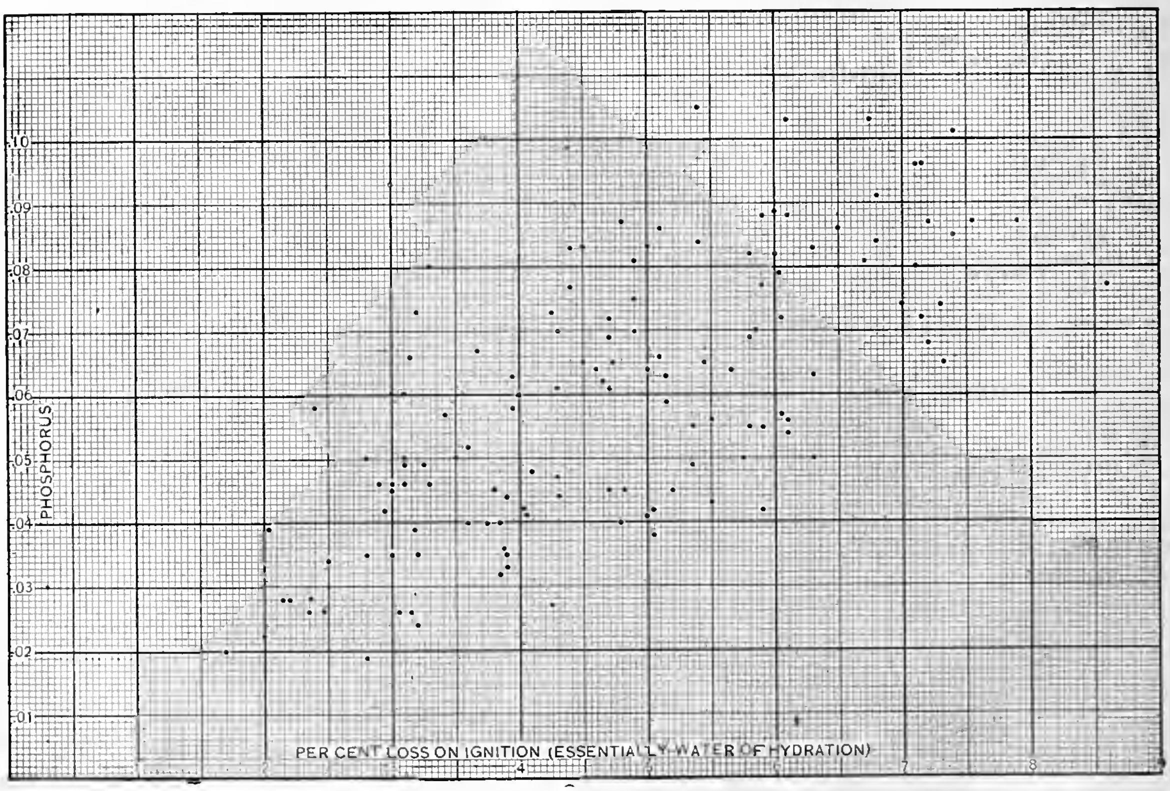


FIGURE 22.—Diagram showing relation of phosphorus to degree of hydration in Mesabi ores.

range in 1906. Percentages of phosphorus and of water of hydration are platted respectively as ordinates and abscissas. The arrangement of the points on the diagram seems to indicate that high phosphorus is in general associated with high content of combined water.

In the Mahoning open-pit mine large round concretions of rather hard yellow ore are found embedded in darker ore. The concretions contain in their centers crystalline and botryoidal quartz and yellow hydrated iron oxide. Analyses of the outer shell and of the core of the concretions were made from samples representing a number of individuals. The results of the partial analyses given in the following table show a marked concentration of phosphorus at the center of the concretion. As the concretions are of a distinctly geodal structure, the phosphorus in the interior was evidently one of the last constituents introduced.

Analyses of concretions from Mahoning mine.

	Iron.	Phosphorus.	Ratio of phosphorus to iron.
Outer shell of concretions	65.77	0.058	0.00088
Center of concretions	53.12	.143	.00269

In the Oliver open-pit mine, in 1899, a vein of limonite could be seen cutting down from the surface, clearly as a result of an alteration by percolating waters along a fissure, and the percentage of phosphorus within the vein was much higher than in the ore immediately adjacent. This occurrence of high phosphorus is similar to the high phosphorus in the Mahoning concretions, in that it occurs with a more hydrated iron oxide than the surrounding ore, and is evidently later than the concretion of the ore.

Another instance of the occurrence of high phosphorus with hydrated iron oxide was furnished by Mr. A. T. Gordon, who analyzed hard black hematite and soft yellow limonitic ore in the same hand specimen from the Mountain Iron mine with the following results: Hard ore, iron 61.00, phosphorus 0.077; soft ore, iron 57.98, phosphorus 0.118.

To obtain further data on the association of phosphorus with the more hydrated phases of the ore washing tests were made on samples of ore from the Sellers and Burt mines at Hibbing, Minn. Each sample was stirred with water in a pail and after the mixture had been allowed to settle for ten minutes the water was poured off and filtered and a very finely divided reddish-yellow sediment was obtained. A portion of the remaining ore was then thoroughly washed with water until free of coloring matter. Analyses made in Lerch Brothers' laboratory at Virginia, Minn., of the samples thus obtained gave the following results:

Partial analyses from washing tests on Mesabi ores.

	Iron.	Phosphorus.	Alumina.	Loss by ignition.
Ore from Sellers mine:				
1. Finely divided sediment held in suspension longer than 10 minutes	46.64	0.072	9.06	8.32
2. Intermediate between 1 and 3	57.92	.052	....	3.95
3. Dark-colored residue after washing with water	59.92	.049	1.34	3.54
Ore from Burt mine:				
1. Finely divided sediment held in suspension longer than 10 minutes	49.57	.073	8.31	7.34
2. Dark-colored heavy residue	60.65	.051	2.00	3.67

A calculation of the mineralogical composition of Nos. 1 and 3 from the Sellers mine and Nos. 1 and 2 from the Burt mine from these analyses shows that the material is of the same general composition as paint rock, being high in kaolin and hydrated iron oxide. The mineral compositions follow:

Mineral composition calculated from analyses in the table above.

	Sellers mine.		Burt mine.	
	No. 1 (fine material).	No. 3 (heavy material).	No. 1.	No. 2.
Hematite	36.40	67.60	45.00	69.00
Limonite	35.25	21.10	30.25	29.50
Quartz	5.45	7.90	3.75	5.45
Kaolin	22.90	3.40	21.00	5.05

In the Meadow mine, at Aurora, Minn., ore immediately above an altered granite dike was found to run higher in phosphorus than the ore farther from the contact. This fact suggests that either the alteration of the granite contributed phosphorus to the ore or the dike acted as an impervious layer above which the phosphorus was concentrated. The tests show that the phosphorus is in some manner associated with the kaolin and hydrated iron oxide and bear out the statement that high phosphorus is related to the degree of hydration of the ore.

Phosphorus content of rocks associated with iron-bearing formations.

	Iron.	Phosphorus.	Ratio of phosphorus to iron.
Virginia slate (Mon. 43, p. 170)	4.74	0.0885	0.01868
Giants Range granite, average twelve specimens		.087	
Basic intrusives in iron formation of Gunflint district		.120	
Granite dike in iron-bearing Biwabik formation:			
1. Kaolinized and much iron stained		.059	
2. Near No. 1 but farther from ore, less iron stained		.036	
3. Completely kaolinized but preserving granitic texture; color light pink		.020	

SECONDARY CONCENTRATION OF PHOSPHORUS.

Present differences in phosphorus content between various phases of the iron-bearing formation may be due (1) to original differences or (2) to secondary changes, producing differences in phosphorus content not due to original differences in composition. These secondary changes may be actual increase or decrease in phosphorus due to infiltration or leaching, or relative increase or decrease due to the introduction or removal of other constituents.

A comparison of the partial analyses of the three principal phases of the iron-bearing formation—greenalite rock, taconite, and ore—successively developed during the secondary concentration, shows a continuous increase in phosphorus and in the phosphorus-iron ratio during secondary concentration of the ore. The percentage of phosphorus increases from 0.012 in the greenalite to 0.021 in the taconite and probably to more than 0.0559 in the ore (the average ore shipped being lower in phosphorus than the average ore of the range). The corresponding increase in the phosphorus-iron ratio is from 0.00048 to 0.00082 to 0.00092. In spite of possible variance of these figures from true averages, the differences are so marked as to point very strongly to an actual increase in the percentage of phosphorus during the alteration of the greenalite rock to taconite and of the taconite to ore.

In the discussion of the secondary concentration of the ore it was shown that the concentration was accomplished by the removal of silica and that the amount of iron carried in solution was very small. If the phosphorus were as insoluble as the iron and if no phosphorus had been introduced, the ratio of phosphorus to iron would necessarily have remained constant during the concentration—in other words, both elements would have been concentrated to the same degree. As there is an actual increase in the ratio of phosphorus to iron during the alteration, it appears that phosphorus has been concentrated to a greater degree than the iron. As iron has not been largely removed, this increase in phosphorus may be explained only by actual introduction of that element in solution from sources outside of the iron-bearing formation or from other parts of the formation itself. All available evidence seems to indicate that at least part of the phosphorus in the ores is more soluble than the iron oxide; hence without the introduction of phosphorus we should expect an actual decrease in the ratio of phosphorus to iron during the concentration of the ores. This seems to show that the introduction of phosphorus from without was even greater than the increase in the phosphorus-iron ratio indicates.

Most of the ores were at one time overlain by Cretaceous sediments, patches of which still remain as far east as Virginia, Minn. Analyses from drill holes and test pits disclose a high phosphorus content in the Cretaceous beds overlying the ores. Furthermore, they show that there is a gradation in the phosphorus content from the Cretaceous down into the underlying ore. A typical series of analyses from a drill hole in the western part of the Mesabi district shows the phosphorus content of the Cretaceous shale to be 1.353 per cent, that of the ore immediately underlying to be 0.180 per cent, and that of lower levels to grade down to 0.045 per cent at a depth of 50 feet below the shale. It seems highly probable, then, that the most abundant source for the phosphorus introduced into the ores of the Biwabik formation was the Cretaceous rocks. As indicated in the table of analyses (p. 194), there are other sources for phosphorus in the granites and slates outside of the iron-bearing formation, and it is possible also that the slates of the iron-bearing formation itself have contributed phosphorus to the ore.

EXPLANATION OF PHOSPHORUS IN THE PAINT ROCK.

The paint rock of the Biwabik formation is a kaolinized alteration product formed by the alteration of interbedded slate layers or of the lower layers of the overlying Virginia slate. The change from slate to paint rock is of exactly the same nature as the alteration of taconite to ore, the soluble bases together with quartz being leached and leaving the insoluble residue of hydrated iron oxide and kaolin. As there are all gradations between slate and taconite, we find the same continuous gradation between paint rock and ore. The paint rock is characteristically high in phosphorus, the analysis in the table on page 194 being typical, though occasionally paint rock is found with comparatively low phosphorus content. Both the slate of the iron-bearing formation and the Virginia slate are high in phosphorus, so it is believed that the high phosphorus of the paint rock is to a large extent original, phosphorus remaining with the iron oxide and kaolin during the leaching of the silica and other constituents.

But it appears necessary also to account for at least part of the phosphorus in the paint rock as coming from outside sources, and the most obvious source is the Cretaceous, as already indicated for the iron ores.

PHOSPHORUS IN THE AMPHIBOLE-MAGNETITE PHASES OF THE IRON-BEARING FORMATION.

In the Gunflint district the Gunflint formation appears to be an eastern extension of the iron-bearing Biwabik formation, consisting almost entirely of silicated magnetite rock. An average analysis representing 834 feet of drill core in the formation showed the average iron and phosphorus contents to be 23.56 per cent and 0.0394 per cent respectively. This gives an average phosphorus-iron ratio of 0.00167. Comparison of these figures with the analysis of the other phases of the iron-bearing formation (p. 192) indicates that the average iron content is very close to that of both the greenalite and taconite phases. This phosphorus content of the silicated magnetite rocks is, however, much higher than that of either greenalite or taconite. The reason for this high phosphorus in the silicated magnetite phase of the iron-bearing formation may lie either in the original difference in phosphorus content between the different parts of the range or in the introduction of phosphorus from the closely associated intrusives. Present knowledge does not permit a more definite conclusion. The average phosphorus content of the intrusive gabbros is 0.12 per cent, which is much higher than the phosphorus content of the iron-bearing formation, so that it furnishes an abundant source for the introduction of secondary phosphorus.

MINERALS CONTAINING PHOSPHORUS.

So far as is known, no phosphorus minerals have been identified in any of the iron-bearing rocks of the Mesabi range. Obviously, then, discussion of the mineral occurrence of phosphorus is entirely a matter of conjecture based on chemical evidence and on the nature of phosphorus-bearing minerals which have been identified in the other Lake Superior iron-bearing formations. It is not unlikely that some of the phosphorus occurs in the form of apatite (calcium phosphate). It seems reasonable to suppose that this mineral may be found in the iron-bearing Biwabik formation, although careful search has not yet revealed it.

In figure 23 percentages of phosphorus in the various commercial grades of ore are platted as ordinates and percentages of lime as abscissas. The diagonal line crossing the diagram indicates the ratio of phosphorus to lime in apatite; hence all points above the line denote an excess of lime over the amount necessary to form apatite and all points below the line indicate a deficiency of lime. In other words, phosphorus in ore represented by points above the line may be combined with lime to form apatite, and ore represented by points below the line necessarily contains some phosphorus in forms other than apatite. This seems to show conclusively that, though there is sufficient calcium in a large part of the ore to form apatite, in some grades of ore a deficiency of calcium proves the existence of other phosphorus minerals, possibly of iron or aluminum. Another fact brought out by the diagram is that calcium is deficient only in the ores highest in phosphorus. This suggests the possibility that the original phosphorus

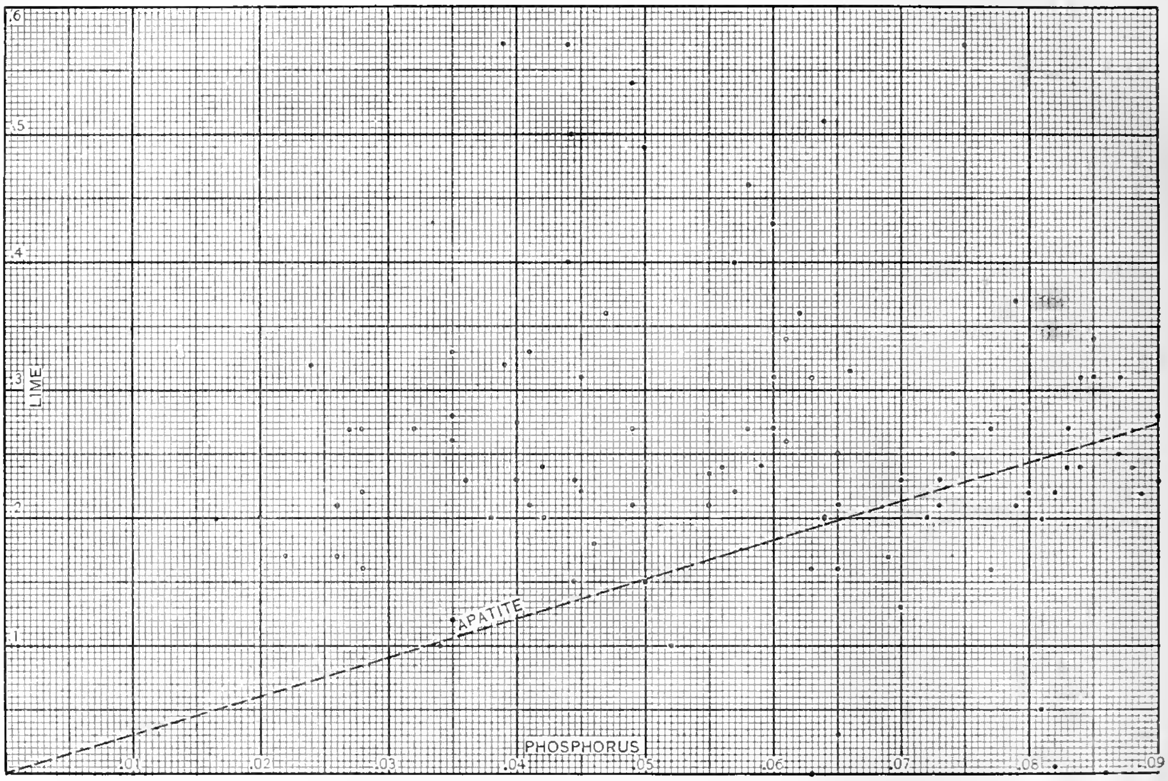


FIGURE 23.—Diagram showing relative amounts of phosphorus and lime in Mesabi ores.

of the ores may be in the form of apatite but that secondary phosphorus takes some other form. The association of high phosphorus with the hydrated forms of iron and aluminum suggests that this excess of phosphorus may be in phosphates of iron and aluminum. It is very probable that at least part of the phosphorus is combined with the iron and aluminum in no definite mineral form.

DETRITAL ORES IN THE CRETACEOUS ROCKS.

In the western part of the Mesabi district, in T. 56 N., Rs. 23 and 24 W., a considerable amount of detrital ore has been found in the Cretaceous rocks overlying the Biwabik formation and the northern margin of the Virginia slate. Drilling has shown up several million tons of this ore of the following average composition:

Average composition of Cretaceous ore from the west part of the Mesabi range.

[Samples dried at 212° F.]

Iron	54.41
Phosphorus	.118
Silica	6.18
Alumina	8.25
Manganese	.49

As the ore has not been opened up, the sources of information as to texture, moisture content, and other physical characteristics are limited to the results of drilling. The drilling shows that the ore is conglomeratic in nature, as is usual in detrital ores. There appears to be considerable opportunity for further discoveries of ore of this character.

SEQUENCE OF ORE CONCENTRATION IN THE MESABI DISTRICT.

The sequence of ore concentration in the Mesabi district is similar to that in the Gogebic district in that the upper Huronian (Animikie group) was but slightly tilted and eroded before the Keweenawan gabbro was intruded into it. The gabbro thus came into contact with the iron-bearing formation only at the east end of the district. Here it found in very small quantity soft ores and ferruginous cherts developed by weathering and changed them to hard ores and jaspers. The original greenalite rocks making up most of the iron-bearing formation were altered to amphibole-magnetite rock. The principal and present productive part of the district was protected from the gabbro by a great mass of slates. The erosion following the post-Keweenawan folding for the first time exposed the main mass of the iron-bearing Biwabik formation from beneath the slates.

By Cretaceous time the concentration of the ore was far advanced, for we find the basal detrital zone of the Cretaceous carrying abundant iron ore in the form of polished pebbles. Since Cretaceous time all the Cretaceous has been stripped off except parts of the western part of the Mesabi district, so that surface agencies have had opportunity to continue the concentration of the ore.

The amphibole-magnetite rocks of the east end of the district have resisted surface alteration, except local discoloration by oxidation in a thin film at the surface.

CHAPTER VIII. THE GUNFLINT LAKE, PIGEON POINT, AND ANIMIKIE IRON DISTRICTS OF MINNESOTA AND ONTARIO.

Under the three names Gunflint Lake, Pigeon Point, and Animikie is discussed the strip of territory extending from the east end of the Mesabi and Vermilion districts in the vicinity of Gunflint Lake to Port Arthur on Animikie or Thunder Bay and thence eastward to the Loon Lake district. The districts are geographically continuous and the principal geologic features in each, given by the Animikie and Keweenawan rocks, are much the same, but because of slight variations and because the districts have been studied from different standpoints by different men they are described under the above three headings.

GUNFLINT LAKE DISTRICT.[a]

GEOGRAPHY.

The Gunflint Lake district includes the lake of that name on the international boundary at the extreme eastern end of the Vermilion district of Minnesota, and extends in a narrow strip about 10 miles east and 10 miles west of the lake. The rock succession and structure are essentially the same as in the Mesabi district to the west and the Animikie district to the east. It is cut off from the Mesabi district by the great overlapping mass of Duluth gabbro. It is connected with the Animikie district by continuous exposure except for the drift.

SUCCESSION OF ROCKS.

The succession of rocks is as follows:

Quaternary system:
- Pleistocene series........................Glacial drift.

Unconformity.

Algonkian system:
- Keweenawan series......................Conglomerate, sandstone marl, diabase sills (Logan sills), and gabbro (Duluth gabbro).
- Unconformity.
- Huronian series:
  - Upper Huronian (Animikie group)..{Rove slate. / Gunflint formation (iron bearing).}
  - Unconformity.
  - Lower-middle Huronian.............Graywacke, with greenstone and granite intrusives.

Unconformity.

Archean system:
- Laurentian series..........................Granites and gneisses intrusive into Keewatin.
- Keewatin series.............................Green schists, greenstone, mashed porphyry.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

UPPER HURONIAN (ANIMIKIE GROUP).

GENERAL DESCRIPTION.

The district is occupied principally by the upper Huronian (Animikie group), dipping to the south at angles of 10° to 65° (fig. 24). The group laps from the south across the eastern end of the Vermilion district and thus rests on the north against the various older rocks of that district, including the granite of Saganaga Lake in secs. 23 and 24, T. 65 N., R. 4 W., the

[a] See Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903.

Ely greenstone west of the granite, and the Ogishke conglomerate and the Knife Lake slate still farther west. These rocks have already been described in connection with the Vermilion district and will not again be referred to.

The base of the upper Huronian (Animikie group) is marked by a thin conglomerate which in some places is almost lacking. The unconformity with the underlying rocks is determined principally by the general structure and distribution. The Animikie group has uniform strike and dip, differing widely from those of sedimentary beds to the north and contrasting with the igneous rocks in which no strike and dip are found. It also laps successively across several members of the older rocks without losing its continuity. Contacts are so poor in the Gunflint district that these alone fail to give sufficient evidence of unconformity. In view of the broader features indicated and also indubitable facts in the Mesabi district to the west and the Animikie district to the east, the unconformity may be regarded as certain.

The lowest formation is the iron-bearing Gunflint formation. Above this and outcropping in a belt south of it is the Rove slate, named from its abundant exposures on Rove Lake to the east. Intrusive sills of diabase (Logan sills) are found parallel to the bedding of the slate and the iron-bearing formation. Above and south of the Animikie group is the Keweenawan Duluth gabbro, closely related in age to the Logan sills. The gabbro at the western end of the district laps directly across the Animikie group upon the underlying lower-middle Huronian and Archean. Eastward it laps successively against the Gunflint formation and the Rove slate. Thus the outcrop of the Animikie group widens, V-shape, eastward. In the vicinity of Gunflint Lake itself only the iron-bearing formation is exposed. Eastward more and more of the slate appears.

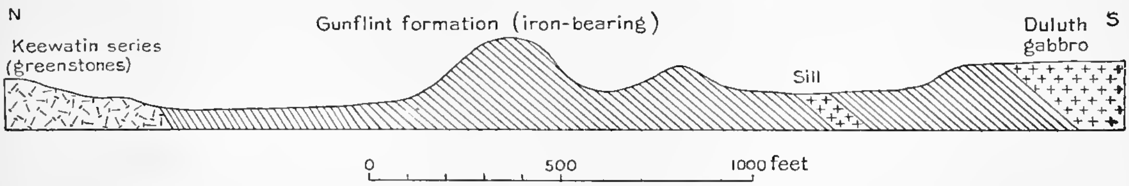


FIGURE 24.—Cross section of iron-bearing Gunflint formation east of Paulson mine, Gunflint district, Minn.

GUNFLINT FORMATION.

Distribution.—The iron-bearing Gunflint formation is exposed in a nearly east-west belt 600 feet to half a mile wide. Northeast of the Paulson mine, secs. 21 and 22, T. 65 N., R. 4 W., there is an east-west tongue of the Gunflint formation projecting westward into Ely greenstone. About three-fourths of a mile east of the Paulson mine, in sec. 27, T. 65 N., R. 4 W., where a great north-south valley cuts directly across the Gunflint formation, the narrow belt of iron-bearing formation joins a wider area of the same rock which extends over the greater portion of secs. 23 and 26, T. 65 N., R. 4 W. The Gunflint formation is widest in these sections, its great width being due chiefly to the fact that a fairly wide synclinal fold has here been stripped of higher formations, leaving exposed an unusually large area of the iron-bearing formation. East of these sections, toward the international boundary, the width exposed is less.

Structure.—The structure of the Gunflint formation is not very complicated. A small northeast-southwest trending area of Gunflint formation is exposed on the southeast shore of Disappointment Lake. Here the sediments have a strike corresponding very closely to the trend of the area itself—that is, northeast-southwest—and they dip to the south. In rocks of similar age on Gabimichigami Lake the structure is somewhat more complicated. Here the sediments have been folded, and as a result they form in the main a syncline plunging toward the northwest, but with a subordinate anticline near the center which has an axis plunging to the southeast. In the narrow belt extending from sec. 34, T. 65 N., R. 5 W., eastward to the great cross valley in sec. 27, T. 65 N., R. 4 W., the members of the formation rest upon the older rocks and uniformly dip to the south. The regularity of this dip is, however, interrupted by a number of minor flexures whose axes plunge southeast. As a result the amount of the dip varies considerably, ranging from about 10° to 65° to the south, all the greater dips occurring at the west end of the belt, the dips becoming flatter within short distances eastward. The gradual diminution in the angle of dip as the sediments are followed to the east corresponds to their less-folded condition in the eastern part of the area. Attention has already been called to the areal distribution of the sediments and the westward-trending tongue of sediments occurring in secs. 21 and 22, T. 65 N., R. 4 W., which is good evidence of an infolded syncline of the sediments at this place. The dip of the sediments as observed on the outcrop in this area gives further evidence of the existence of this syncline.

Some very considerable irregularities have been noted in a few places along the margins of certain enormous masses of dolerite which occur in the midst of the sedimentary area. These dolerites, it may be stated here, are intrusive in the sediments, and this fact sufficiently explains the contorted character of the adjacent sediments, for this contorted character is confined to their immediate vicinity, the uniform low southerly dip appearing at a short distance from such contacts.

Petrographic character.—Near Gunflint Lake the iron-bearing formation consists of sideritic cherts grading into ferrodolomites associated with minor amounts of ferruginous cherts and ferruginous slates. Westward toward the Paulson mine the rocks become black or dark-green, coarsely crystalline, banded rocks consisting essentially of magnetite, fayalite, cordierite, quartz, and iron carbonate, in varying proportions in different bands and in different parts. Where the iron carbonate is present the other minerals, aside from quartz, are absent. The iron carbonate is regarded as the original phase and the other minerals as their alteration products. (See p. 529.) In small and highly varying quantities are hedenbergite, bronzite, grünerite, pyrrhotite, anthophyllite, hypersthene, actinolite, biotite, apatite, diopside, hornblende, augite, perthite, pleonaste, and crocidolite. Fayalite is conspicuous in association with magnetite layers. Cordierite, so rare the world over, is perhaps the most conspicuous mineral of the whole series, in many places forming a third of the volume of the rock. It has the pseudohexagonal twinning and staurolite inclusions oriented in a definite manner with regard to the optic axes of the cordierite, which are characteristic of this mineral. The cordierite for some time has been recognized in the Huronian slates as an intrusive contact effect but has been discovered in the Gunflint formation only recently by Zapffe,[a] who has also distinguished a number of the minor minerals noted. The texture is xenomorphic and the minerals include one another in poikilitic fashion.

Contact metamorphism.—Perhaps nowhere else in the Lake Superior country is there so good an opportunity to study the metamorphic effects of the great gabbro intrusion and its associated sills. The iron-bearing formation has been coarsely recrystallized and silicated to such an extent that it can be distinguished from the intrusives only with great difficulty. Detailed study of this metamorphism has been made by Bayley,[b] Clements,[c] Grant,[d] and Zapffe.[a] Their conclusion in general has been that, though there has been minute intrusion of igneous masses parallel to the bedding, there has been no considerable transfer of solutions from the gabbro to the iron-bearing formation during the alteration. This subject is further discussed in connection with the origin of the ores. (See p. 548.)

Thickness.—The thickness, so far as it can be determined in this district, is approximately the same as that of the Biwabik formation in the Mesabi district—that is, somewhat less than 1,000 feet.

ROVE SLATE.

Distribution.—The westernmost exposures of the Rove slate in the Vermilion district are found in sec. 21, T. 65 N., R. 4 W., where the formation underlies a very narrow area in the south-central part of the section. Eastward it rapidly widens. The northern boundary of the

[a] Unpublished thesis, University of Wisconsin, 1908.
[b] Bayley, W. S., The basic massive rocks of the Lake Superior region: Jour. Geology, vol. 1, 1893, pp. 433–456, 587–596, 688–716; vol. 2, 1894, pp. 814–825; vol. 3, 1895, pp. 1–20.
[c] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 389–390, 419.
[d] Grant, U. S., Contact metamorphism of a basic igneous rock: Bull. Geol. Soc. America, vol. 11, 1900, pp. 503–510.

slate extends northeastward and is limited by the Gunflint formation and a great dolerite sill. The southern boundary, marked by the Duluth gabbro, trends east-southeast. At the eastern limit of the area mapped (Pl. VI, p. 118) the extreme width of the Rove slate area in the United States is only about 2 miles, and a great deal of this width is taken up by intrusive sills of dolerite. Beyond the limits of the district the slates have an enormous development in Minnesota and in the adjacent portion of Canada.

Structure.—The slates have a very uniform dip of from 5° to 25° SSE. As indicated by the variation in dip, the monocline is occasionally varied by minor southward-pitching rolls, which may be noted by close examination of almost any of the great cliffs that give good exposures.

Petrographic character.—Slates form the bulk of the Rove formation, but with them are associated graywackes, some slaty, others very massive, and also some fairly pure quartzite. These sediments have been divided by Grant,[a] of the Minnesota Survey, into a "black slate member" and an overlying "graywacke slate member." In our work no attempt has been made to discriminate between these two petrographic facies of the Rove slate. They are not separable by any time interval but represent merely slight changes in the conditions of deposition. Macroscopically they are very fine-grained black carbonaceous slates grading up into dark-gray graywacke of medium grain, with occasional bands of material almost sufficiently pure to be called quartzite. Nowhere were any conglomerates, even fine-grained ones, found associated with these. The slates are unquestionably the predominant kind of rock. These carbonaceous rocks are commonly very fissile, but in places they are fairly massive.

Contact metamorphism.—The sediments of this formation have been found within 3 feet of the gabbro—at the southeast end of Loon Lake—but not nearer. Here the rocks are interbanded slates and graywackes, quite crystalline and hard. Microscopic examination of them shows that the gabbro has effected a partial recrystallization of the sediments and disclosed in the sediments a large amount of secondary biotite and muscovite. Both of these occur in relatively large porphyritic plates inclosing grains of the other materials constituting the slate, recognizable quartz, and ferruginous material. Down the slope the rocks are less indurated, and near the bottom of the section, at the water's edge, about 50 feet below the gabbro, the sediments do not appear essentially different from the ordinary rocks of the same character and age.

Along the southern and southeastern shores of Loon Lake the slate shows a spotted character and is a spilosite, such as is fairly common in sediments near the contact with the great mass of gabbro and such as occurs also in other districts near great dolerite dikes. This spilosite contains a large amount of chlorite in spots in a matrix of quartz and presumably some feldspar. In the Mesabi range some of the slates near the gabbro contact show clearly recognizable cordierite, which forms the white spots; these slates have been metamorphosed to a cordierite hornstone.[b] In general the slate adjacent to these sills in the Gunflint district shows its normal characters, with at most a little metamorphism due to cementation.

Thickness.—Within the district only about 2,600 feet of the Rove slate is exposed beneath the gabbro, but eastward the thickness rapidly increases.

KEWEENAWAN SERIES.

DULUTH GABBRO.

The Duluth gabbro forms the southern boundary of the pre-Keweenawan rocks throughout the greater portion of the Vermilion district. The westernmost points at which the Duluth gabbro touches the district are in secs. 26 and 35, T. 63 N., R. 10 W., and sec. 3, T. 62 N., R. 10 W. From these sections on along Kawishiwi River the gabbro swings off to the northeast with a broad sweep, extending just within the area mapped on Plate VI (p. 118) as far east as the

[a] Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1894, p. 74; Final Report, vol. 4, 1899, p. 470.
[b] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 171-172.

vicinity of the Paulson mine, in sec. 28, T. 65 N., R. 4 W. From this place its edge trends to the southeast, passing beyond the limits of the area mapped toward Lake Superior. Two small isolated outliers have been found north of Gabimichigami Lake. The southernmost one is only a quarter of a mile from the northern edge of the main mass of the gabbro, northwest of Paul Lake, and the other is about three-fourths of a mile from the nearest point on the edge of the gabbro and lies in the NW. ¼ sec. 29 and the NE. ¼ sec. 30, T. 65 N., R. 5 W.

The petrographic character of the Duluth gabbro is described on page 372, in the chapter on the Keweenawan series.

LOGAN SILLS.

The Logan sills lie well within the district, at varying distances north of the edge of the gabbro mass. The first exposure of such a sill was noticed on the southwest side of Gabimichigami Lake, but this can not be traced far. The next one was seen near Bingoshick Lake. This sill has been followed to the east for several miles to a point east of the Paulson mine, having throughout this distance an almost continuous outcrop. Parallel to this sill several small and relatively unimportant sills have been observed. Beyond the Paulson mine the upper Huronian sediments (Animikie group) begin to widen, rapidly increasing in width eastward, as already described. Corresponding with this widening there is an increasing number of sills which in general trend east and west and lie approximately parallel to one another. During several trips to Gunflint Lake and to the country to the south a number of these sills were followed along their strike for short distances and were also crossed at right angles to the strike. Their relations to the sediments were thus clearly seen. No attempt was made to trace out the individual sills. This work has been done in previous years by Chauvenet[a] and Merriam,[b] of the United States Geological Survey, and in more recent years by U. S. Grant,[c] of the Minnesota Survey.

RELATIONS OF THE KEWEENAWAN ROCKS TO ONE ANOTHER AND TO ADJACENT FORMATIONS.

Geologic relations.—The general features of the relations of the Keweenawan rocks are described in Chapter XV, on the Keweenawan series. Here are described certain features of these relations especially well exhibited in this district. These are particularly the superposition of the Duluth gabbro upon all underlying rocks and the relations of the gabbro to the Logan sills intrusive in the Animikie group.

The gabbro and the sills are petrographically the same, and textural gradations have been observed which indicate their close relationship. The gabbro, though predominantly coarse-grained and granular, is locally fine-grained and poikilitic; in one place it was found as a dike in the Animikie and there graded into a porphyritic facies and even into a fine-grained ophitic dolerite. Locally in the midst of the thick sills the rock is a good granular gabbro in texture, and it ranges from this through ophitic poikilitic-textured dolerites into fine-grained aphanitic intersertal-textured basalts upon the selvage. Mineralogically they are the same, except that in the relatively few specimens from the sills which have been studied no olivine nor hypersthene has been observed, nor do the sills show such great mineralogical variation from titaniferous magnetite rocks to enormous anorthosite masses, though there are small anorthosite masses in the sills. Such differences in variation are, however, easily explicable as due to the enormous difference existing between the masses of magma forming the gabbro and that forming the individual sills. The gabbro and sills are therefore regarded as essentially contemporaneous and genetically related.

The gabbro is believed to be a great laccolithic mass which in general follows approximately the contact plane between the Animikie group and the Keweenawan. In the Vermilion district there are local departures from this relation. Over a great part of the southern edge of the

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[a] Chauvenet, W. M., manuscript notes.

[b] Mon. U. S. Geol. Survey, vol. 19, 1892, Pl. XXXVII.

[c] Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, 1899, pp. 487-488.

Vermilion district the gabbro followed essentially along the surface of unconformity between the upper Huronian (Animikie group) and the lower-lying sediments, uplifting thereby the upper Huronian sediments, for at several places on the edge of the Vermilion district and just south of it isolated patches of the lowest part of the Gunflint formation are found included in the Keweenawan gabbro.

In the eastern part of the Vermilion district the gabbro began to rise and cut across the upper Huronian (Animikie group), reaching higher and higher beds to the east, and then spread out essentially along the plane between the Animikie and the base of the Keweenawan, sending sills and dikes into the Rove slate (upper Huronian) and also into the Keweenawan rocks, as can be seen on Brule Lake.

Topography as related to geology.—The line of contact between the gabbro and the older rocks adjacent to it is fairly well marked by a slight topographic break. The gabbro normally has a steep north face, in some places showing an escarpment of varying height. It is nowhere very high but is considerably higher than any topographic features in the area extending a considerable distance north of it. The contact at many places is marked by a lake or a stream. This difference between the topography of the gabbro area and that to the north exists at the immediate contact, but in general the gabbro area is lower than that underlain by the older formation to the north. Locally the gabbro area has been reduced almost to base-level. In fact, this area may be described as very nearly a plain, with minor but pronounced irregularities. The uniformity of the surface is due in great part to the homogeneous character of the gabbro mass, owing to which it has been about equally affected by the various agents which have attacked it. Most of the minor pronounced irregularities are due to erosion, which has been controlled very commonly by the joints of the gabbro, and to differences in composition where they exist. For example, the anorthosite masses usually stand out conspicuously from the surrounding more basic and less resistant portions of the gabbro.

The lakes of the gabbro area are as a rule shallow, and they are also very irregular and can not be said to have uniform length in any one direction, as is so markedly true of the lakes of the other portions of the Vermilion district. On the contrary, they spread out in all directions, sending off numerous bays, of which some are very long and narrow and all are very irregular in shape.

The Logan sills exercise a very material influence upon the topography of that portion of the district north of the gabbro in which they occur. It will be recalled that the upper Huronian (Animikie) sediments in this vicinity have a monoclinal dip to the south. The sills have been injected essentially parallel to the bedding of the sediments, though occasionally they are found cutting across the beds at low angles. Erosion has been most active in this portion of the district in a direction parallel to the strike of the beds, and consequently most of the large valleys and lakes trend in agreement with these, approximately east and west. The resistant sills now form the caps of the ridges, the slates having been removed down to the sills. The massive rock forming the sills breaks off along the joint planes, and as a result perpendicular cliffs are formed below the foot of which talus from the sills and from the easily weathering Rove slate gives a gentle slope. These sills are sometimes very nearly concealed by the accumulated talus derived from them.

The effects of erosion have produced a series of hills with very nearly vertical north escarpments and a gentle slope from the crests to the south. This slope corresponds very closely to the dips of the Rove slate and the upper surface of the dolerite sills.

THE IRON ORES OF THE GUNFLINT LAKE DISTRICT.

In the vicinity of Gunflint Lake the iron-bearing formation (Gunflint formation) is mainly cherty iron carbonate more or less recrystallized and silicated and more or less oxidized and hydrated at the surface and next to fissures and certain bedding planes. No attempt at mining has been made here.

The principal hope for ore in the Gunflint formation has been centered in the vicinity of the Paulson mine, 5 miles west of Gunflint Lake. Here the formation consists of dark-green to black, coarsely crystalline rocks, consisting of magnetite, quartz, amphiboles, cordierite, fayalite, augite, pyrrhotite, etc., thinly interlayered in varying proportions. Fayalite is especially abundant in rocks rich in magnetite.

Titaniferous magnetites in the Duluth gabbro are described on page 561.

CHEMICAL COMPOSITION.

An analysis representing an average of the rock from a drill hole penetrating 245 feet into the iron-bearing formation and an analysis of a surface sample taken across the entire width of the formation give the following average:

Chemical composition of iron-bearing Gunflint formation.

SiO_2	60.51
Al_2O_3	1.20
Fe	25.22
MgO	.52
CaO	.67
Na_2O	.00
K_2O	.00
H_2O	Small.
P_2O_5	.05
S	.59
MnO_2	.92

This is almost exactly the composition of the ferruginous cherts or taconites of the Mesabi district. The significance of this resemblance is discussed in connection with the origin of the iron ores, in Chapter XVII (pp. 499 et seq.). Bands of the formation a few feet thick run as high as 50 or 55 per cent in iron. At the bottom, where it rests against the greenstone, a 3-foot layer is encountered running above 55 per cent in iron. The thinness of the ore bands, the highly crystalline, silicated, magnetic character of the ore, and the locally high sulphur preclude the use of the ore under present conditions. On the other hand, the total amount is large, the phosphorus content is low, and it lacks titanium, in this respect contrasting with the titaniferous magnetites within the gabbro mass immediately adjacent. Magnetic concentration may make these ores available for the future, though the tonnage of low-grade ores requiring no concentration, with which these would have to compete, is so large that the time may be distant, if it ever comes, when these ores can be concentrated and used with a profit.

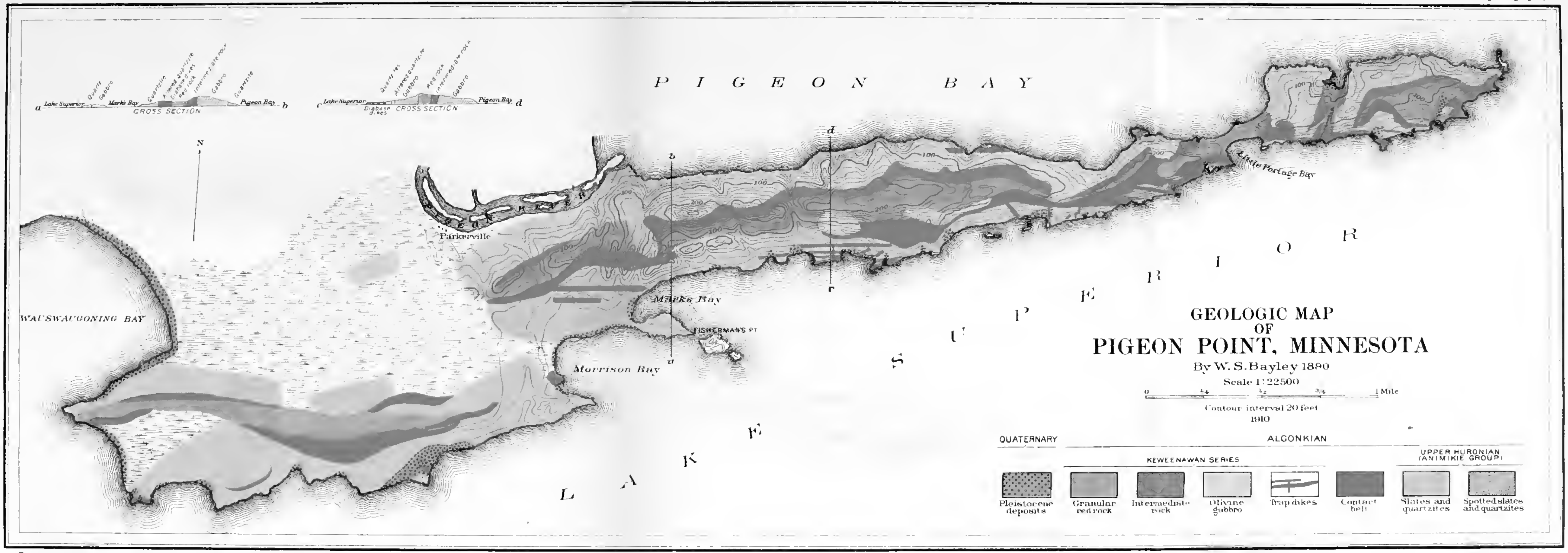
PHYSICAL CHARACTERISTICS.

The ores are in some places very coarse grained. The iron-bearing formation is medium to coarse grained, dense, and tough. The pore space is less than 1 per cent and usually almost zero. Specific gravity, determined by the pycnometer method, on a pulverized drill sample of 245 feet of the formation, is 3.62, and that for the ore layers is 4.08.

PIGEON POINT DISTRICT.[a]

The oldest rocks of the Pigeon Point district (Pl. XII) are interbedded slates and quartzites of the Animikie group (upper Huronian). Cutting the Animikie rocks is an olivine gabbro, which occupies all the higher portions of the point. It is in all probability the lower portion of a large dike whose upper part has been removed by denudation. Between the gabbro and the bedded rocks in many places are successively a coarse-grained red rock, a fine-grained red rock (quartz keratophyre), and a series of contact rocks. The main masses of the keratophyre occupy a position between the Animikie sediments and the gabbro. This rock has all the characteristics

[a] See Bayley, W. S., The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena: Bull. U. S. Geol. Survey No. 109, 1893.



Topography from U. S. Lake Survey

of an eruptive younger than the gabbro. The coarse-grained rocks between the gabbro and the keratophyre are intermediate in character between the two and grade into them. They are therefore regarded as a contact product formed by the intermingling of the gabbro and keratophyre magmas. Between the keratophyre and the slates and quartzites of the Animikie group there are three zones showing different grades of alteration of the sedimentary rocks due to the contact with the igneous rock.

ANIMIKIE OR LOON LAKE DISTRICT OF ONTARIO.

LOCATION AND GENERAL SUCCESSION.

The Animikie district proper includes the area about Animikie or Thunder Bay, on the northwest coast of Lake Superior, but detailed study has been made principally of the part of the district near Loon Lake, at the east end of the bay, about 25 miles east of Port Arthur (see Pl. XIII), and to this part of the district the following description applies. It is taken largely from descriptions by W. N. Smith [a] and R. C. Allen.[b]

The succession of rocks is as follows:

Quaternary system:
- Pleistocene series .... Glacial drift.

Algonkian system:
- Keweenawan series .... Conglomerate, sandstone, marl, diabase sills (Logan sills).
- Unconformity.
- Huronian series:
  - Upper Huronian (Animikie group) .. { Black slate. / Iron-bearing formation.
  - Unconformity.
  - Lower-middle Huronian .... Graywacke, slate, and conglomerate, with greenstone and granite intrusive rocks.

Unconformity.

Archean system:
- Laurentian series .... Granites and gneisses, intrusive into Keewatin series.
- Keewatin series .... Green schists, greenstone, mashed porphyries.

ARCHEAN SYSTEM.

The Keewatin series outcrops along Current River 5 or 6 miles northeast of Port Arthur, along the Canadian Pacific Railway, near milepost 119 and west of it about a mile. It comprises a variety of green schists and mashed porphyries. Evidence of the extreme deformation to which these rocks have been subjected is found in their folded and schistose structures. The schistosity is nearly vertical with strike N. 70° E.

Laurentian rocks are not present in the district itself, but form part of the granitic hills to the north.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER-MIDDLE HURONIAN.

KINDS OF ROCKS.

The lower-middle Huronian occupies the central part of the area between the upper Huronian (Animikie group) and the Keweenawan on the east and the Animikie and the Keewatin on the west. The detrital member of the lower-middle Huronian is represented mainly by a great thickness of graywacke, which is believed to be correlated with the Knife Lake slate of the Vermilion district of Minnesota. At the base of the graywacke is a considerable thickness of schistose conglomerate carrying fragments of black jasper and of a great variety of green schists. It marks the unconformity between the Keewatin and lower-middle Huronian.

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[a] Loon Lake iron-bearing district of Ontario: Rept. Ontario Bur. Mines, vol. 14, 1905, pt. 1, pp. 254-260.

[b] Unpublished thesis, University of Wisconsin. See also Silver, L. P., The Animikie iron range: Rept. Ontario Bur. Mines, vol. 15, 1906, pt. 1, pp. 156-172.

The conglomerate grades up into the graywacke, which in its lower horizons is quartzose. The actual contract between the lower-middle Huronian and Keewatin was not observed, the two usually being separated by a slight topographic depression, which near milepost 119 is but 14 paces broad.

The metamorphism of the graywacke has almost obliterated the bedding, but where bedding was observed it was found to be more or less discordant with the cleavage, which varies in dip from 65° S., a mile or more south of the Canadian Pacific Railway, through the vertical to 65° N. on and north of the graywacke ridge which runs parallel to and a short distance south of the Canadian Pacific Railway.

Near the base of the graywacke is found locally a considerable thickness of volcanic tuff and amygdaloid. This formation is best exposed about 1½ miles south of milepost 110 on the Canadian Pacific Railway, in a strip several hundred yards wide and a mile or more long. In places it appears to be conglomeratic, showing a decided banding which looks very much like bedding, and in other places it is vesicular, the vesicules being filled with secondary minerals.

The gradation was but imperfectly observed in a single outcrop, but these tuffs and amygdaloids seem to grade both parallel to the strike and across it into the normal phase of the graywacke.

INTRUSIVES.

The graywacke is intruded by a variety of granites and greenstones. All the granites and some of the greenstones are massive and cut across the strike of the cleavage in the graywacke. Near some of these intrusive masses the graywacke is decidedly more schistose, especially in the area north of the Canadian Pacific Railway, where the intrusion of the granites is more intimate than elsewhere. Here the graywacke locally becomes a hornblende schist.

The granite forms the hills north of the Animikie district and is correlative in age and topography with the Giants Range granite of the Mesabi district.

UPPER HURONIAN (ANIMIKIE GROUP).

GENERAL DESCRIPTION.

The iron-bearing Animikie group dips gently to the southeast across the steeply inclined structures of the underlying series at angles locally varying widely, but averaging from 2° to 7°. It outcrops in two main areas, the first between Loon Lake and the head of Thunder Bay, the second along the shores of Thunder Bay in the vicinity of Port Arthur.

The Animikie sediments comprise two distinct zones, as follows:

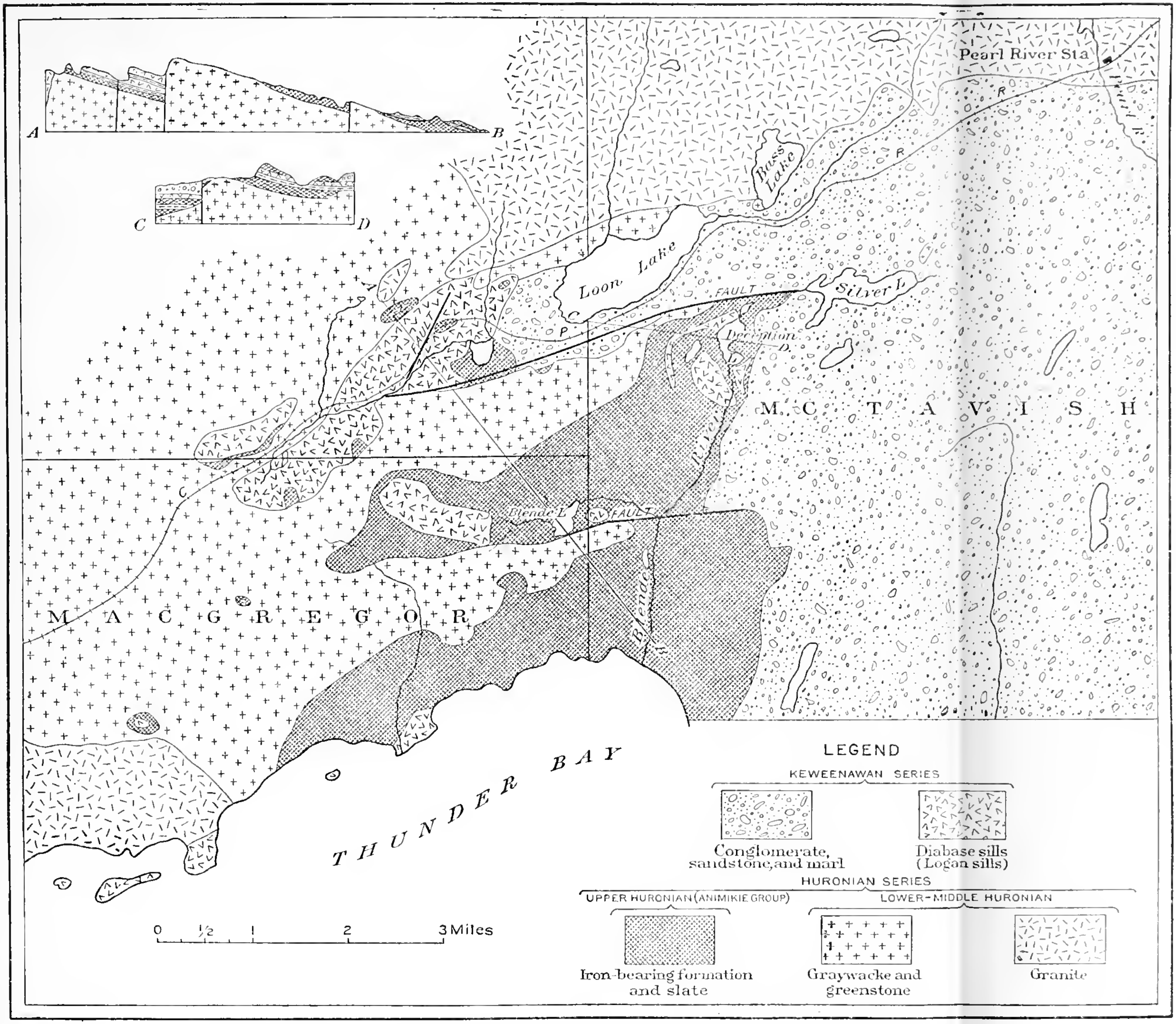
	Thickness.
A black slate formation (total thickness not present)	50 to 60 feet.
An iron-bearing formation, including:	
An upper iron-bearing member	250 to 300 feet.
An interbedded black slate	25 to 30 feet.
A lower iron-bearing member	50 to 60 feet.
A thin basal conglomerate	5 to 18 inches.

The sediments are intruded by diabase sills varying up to 35 or 40 feet in thickness.

IRON-BEARING FORMATION.

The iron-bearing formation of this district is believed to be the same as the Gunflint formation of the Vermilion district, for it has been seen in almost continuous exposure between this district and the Vermilion district.

Conglomerate.—The base of the Animikie group is marked by a thin but persistent layer of conglomerate, which, as shown in open pits and by drill cores from borings in the vicinity of Loon Lake, varies from 5 to 18 inches in thickness. The pebbles in the conglomerate are small and predominantly of vein quartz. Small patches of it found on the graywacke ridge east of McKenzie and on the Keewatin schists near Current River, about 5 miles northeast of Port Arthur, attest the original extension of the Animikie group over the entire area.



GEOLOGIC MAP OF THE ANIMIKIE IRON-BEARING DISTRICT, NORTH OF THUNDER BAY, ONTARIO.

By W. N. Smith and R. C. Allen. See page 205.

Lower iron-bearing member.—In appearance the lower iron-bearing member resembles the ferruginous chert or "taconite" of the Mesabi district of Minnesota, but it is peculiar in that it carries a large amount of calcium-magnesium-iron carbonate. The carbonate may be wholly secondary. It occurs in large part as coarsely crystalline siderite. A single hand specimen may be found to contain crystalline siderite, iron ore, and typical "taconite," which contains small granules embedded in a cherty matrix, thus closely resembling the altered greenalite rock of the Mesabi district. However, it may be that both the iron silicate and most of the iron carbonate were deposited simultaneously. In the Mesabi district the original iron-bearing rock was predominantly a ferrous silicate, in the Penokee-Gogebic district a ferrous carbonate with very subordinate ferrous silicate. The lower iron-bearing member in the Animikie district may have been originally made up of approximately equal amounts of the silicate and carbonate.

Certain of the layers of this member are sufficiently rich in iron oxide or low in siliceous bands to give thin zones of iron ore. Bands 6 to 8 feet thick contain 30 to 46 per cent of iron. The grade may be easily raised by sorting out the siliceous bands. The possible commercial value of these deposits is in their wide horizontal extent. Ores also appear in small irregular bodies, following the fault plane north of Deception Lake and extending eastward to Silver Lake and south and east of Bittern Lake.

Interbedded slate.—Near the top of the "taconite" zone is found a black slate interbedded at more or less irregular intervals with the "taconite" below and the iron carbonate above. The relations are those of gradation through continuous deposition.

Upper iron-bearing member.—The rock making up almost the whole of the upper iron-bearing member is a cherty iron carbonate similar in every way to the iron carbonate of the Penokee district. It exhibits all phases of alteration from iron carbonate to iron ore. Some of it is coarsely crystallized, as though from secondary metamorphism.

The iron ores occur principally along the fault zones already mentioned in connection with the lower iron-bearing member. These also cut the upper iron-bearing member.

UPPER BLACK SLATE.

In its normal phase the upper slate is made of thinly bedded layers, black but weathering to a rusty brown. Locally it bears an abundance of mica. Most of the mica plates lie with their greatest and mean diameters in the plane of bedding, but many of them cut across the bedding at various angles. This phase of the rock has not been studied microscopically, but the mica plates look more like detrital fragments than secondary minerals developed in place, for they occur in separated spangles and not in continuous layers, as commonly shown in rocks having a development of secondary mica. Furthermore, where outcrops of the micaceous slate occur there is no evidence of metamorphic conditions such as commonly develop mica; and where it occurs in contact with intrusive diabase sills the metamorphic effects of the intrusion are seen not to extend more than a fraction of an inch from the plane of contact, so the mica is probably not a product of metamorphism attendant upon the intrusion of the diabase. Therefore it is believed to be clastic in origin.

KEWEENAWAN SERIES.[a]

GENERAL DESCRIPTION.

Unconformably above the upper Huronian (Animikie group) is a succession of conglomerates, sandstones, and impure marls, to which the term "Nipigon" series has been applied by the Canadian Survey. These rocks, however, are now known to belong to the Keweenawan series, and the name "Nipigon" has been abandoned by the United States Geological Survey. This series is most fully developed east of Loon Lake. The unconformity between it and the underlying rocks is marked in various ways. At the base of the Keweenawan is a coarse conglomerate containing waterworn pebbles and bowlders of all the underlying rocks, among

[a] See Chapter XV (pp. 366-426) for general discussion of Keweenawan series.

which, however, granite and the iron-bearing formation are predominant. The Keweenawan series shows comparatively little metamorphism, even less than the Animikie group. The strikes and dips of the Keweenawan are always more or less discordant with the strikes and dips of the underlying formations. The strongest evidence of the great time interval represented by the unconformity is, however, the fact that the Keweenawan is found successively overlying both the Animikie group and the lower-middle Huronian rocks, thus showing that the entire Animikie group and part of the lower-middle Huronian had been truncated by erosion before the Keweenawan series was deposited.

LOGAN SILLS.

The Animikie group is intruded, mainly parallel to the bedding, by a series of diabase sills of Keweenawan age, which seem to follow preferably the slate horizons. By jointing, these sills have been broken up into great columnar blocks, the breaking off of which where the sills are exposed maintains vertical cliffs, a characteristic feature of the topography in this district. These sills are laccolithic in character.[a] At one locality about half a mile south of Deception Lake the diabase outcrops in the shape of a great flat dome, the overlying slates dipping away from it in all directions.

The metamorphic effect of the intrusion on the slates and iron-bearing formation is hardly perceptible more than a fraction of an inch away from the plane of contact. In certain localities the iron-bearing formation in the vicinity of the diabase is very slightly magnetic, indicating some development of magnetite. The slight metamorphic effect of the diabase intrusions may be ascribed to rapid cooling of the magma. The fineness of grain of the diabase suggests that the sills were not deep-seated intrusives. Thus, being thin and also near the surface, they cooled rapidly, the heat being conducted away from them by the cooler rocks adjacent.

The diabase which forms the laccolithic Logan sills of the Animikie group is also found both overlying and cutting the Keweenawan sediments.

STRUCTURAL FEATURES.

The main structural characteristic of the area is the general dip to the southeast; in this it conforms to its geographic position as a portion of the north side of the Lake Superior synclinal basin. The upper surface of the Keewatin series and lower-middle Huronian rocks shares in the general slope to the south, although, as previously noted, this does not apply to the bedding and schistosity of the rocks. The normal strike of the Animikie group is to the northeast, with an average dip of about 7° SE. Locally, however, the rocks have been closely folded and the resulting strikes and dips are widely divergent from the normal. The general strike of the Keweenawan is east of north, with flat dip to the southeast, although it also locally shows the same severe folding and fracturing as the Animikie.

Faulting has been an important factor in producing the present structural and topographic features of the district. The faulting is believed to have been caused by the same general forces that produced the Lake Superior basin. (See pp. 622–623.) The major fracturing occurred along certain approximately parallel zones, and in the vertical displacements that followed the several fracture blocks acted as independent units, in which the northern units became depressed relative to the southern units, thus producing a system of "block" faults.

The greatest vertical displacement definitely determined is about 300 feet, as shown from diamond-drill records and surface exposures along the east-west fault a short distance south of Loon Lake.

GENERAL TOPOGRAPHIC FEATURES IN THEIR RELATIONS TO GEOLOGY.

As seen from a point north of Loon Lake on the high range of hills extending from Pearl River station beyond McKenzie, the region as a whole presents a general slope toward Lake Superior. To the north the country rises, the granite hills towering one above another, and

[a] Lawson, A. C., The laccolitic sills of the northwest coast of Lake Superior: Bull. Geol. and Nat. Hist. Survey Minnesota No. 8, 1893, pp. 24–48.

to the south the lakeward slope is interrupted by the long, narrow McKenzie Valley, beyond the southern rim of which the general slope is continued down to the shores of Thunder Bay. East of Loon Lake the range of Keweenawan sandstone hills forming the southern side of the valley swings at a right angle to the southeast, and the valley emerges on a broad flat timbered with spruce and tamarack and sloping gently down to Black Bay. To the southeast the elevated and much dissected area of Keweenawan sandstone projects into the lake a distance of 20 or 25 miles, forming a peninsula separating the waters of Black and Thunder bays. This peninsula, crowned at its lakeward end by a great protective cap of diabase, terminates in a bold headland over 1,300 feet high, known as Thunder Cape. The great escarpment of sandstone 600 to 800 feet high forming the northwestern side of this peninsula and extending 2 or 3 miles inland is one of the most striking scenic features of the north shore. West of Thunder Cape, Pie Island, with its great flat protecting top of diabase rising 700 or 800 feet above the water, stands like a sentinel at the entrance to Thunder Bay. North of the island, on the mainland south of Fort William, McKays Mountain, another great flat sheet of diabase, supported on Animikie sediments, rises abruptly from the plain of Kaministikwia River to a height of over 1,000 feet. Thunder Cape, Pie Island, and McKays Mountain are magnificent examples of the mesa type of topography, which is a distinct characteristic of the Thunder Bay region.

The origin of this mesa-like topography is found in the prevalence of diabase sills underlain at varying altitudes by strata of weaker rocks, the sapping of which maintains a progressive undermining of the great columnar blocks above them, thus producing vertical cliffs with talus slopes beneath.

WESTWARD EXTENSION OF THE ANIMIKIE DISTRICT.

The Animikie group, containing the iron-bearing formation, extends westward from Animikie Bay to the Gunflint Lake district, with structural and lithologic features like those at its east end, although in the vicinity of Port Arthur and thence westward the amount of slate exposed to the south and above the iron-bearing formation is much larger. The slates with their intrusive sills are beautifully exposed in Pie Island and McKays Mountain and many of the hills to be observed along the line of the Port Arthur and Western Railway. The saw-toothed topography characteristic of both the Gunflint and the Loon Lake districts is everywhere to be seen, with its gently dipping slopes to the south, usually capped by diabase sills, and abrupt slopes to the north. The drainage for the most part follows parallel to the strike.

The older rocks on which the Animikie group rests include the same kinds as were observed in both the Animikie and Loon Lake districts, but they have not been mapped in detail for all of this intervening area.

THE IRON ORES OF THE ANIMIKIE DISTRICT OF ONTARIO.

OCCURRENCE.

Iron ores approaching commercial grade are known only in a small area near Loon Lake, 25 miles east of Port Arthur. The ore deposits are thin but extensive layers of hematite in the ferruginous cherts of the lower part of the formation. In one zone, and perhaps in others, ores have developed along fault and joint planes. The thickness of the ore layers which can be mined will depend on the grade which can be utilized and on the success with which chert layers may be eliminated by hand sorting. Eight feet is about the greatest thickness of a bed which would run as high as 45 per cent, but with a small amount of hand sorting two or three times this thickness could be used. The commercial importance of the ores obviously depends on their horizontal dimensions. The ores rest upon ferruginous cherts and grade into them laterally. One of the beds is capped by a diabase sill intruded parallel to the bedding.

CHARACTER OF THE ORE.

The ore is a lean, banded siliceous hematite, more or less hydrated. Analyses of samples taken every 3 inches from four exposures representing vertical distances of 6 to 8 feet each are given below. These are from the natural exposures which showed the greatest observed concentration and include both the hematite and associated siliceous material.

Analyses of Animikie ore.

Iron	45.81	45.22	30.76	30.21
Phosphorus	.020	.017	.160	.256
Sulphur	.024	.028	.058	.036
Silica	31.91	33.13	35.06	37.11

SECONDARY CONCENTRATION OF THE ANIMIKIE ORES.

Structural conditions.—The movement of waters here has obviously been controlled by the bedding, for the ores constitute merely enriched layers with irregular lateral extent. To some extent also the waters have been concentrated in the intersecting faults. The formation is very thin and is subdivided by impervious igneous sills, making such movement of water as is possible in the formation essentially a horizontal one.

Original character of the iron-bearing formation.—As described on page 207, the lower part of the iron-bearing formation of the Animikie group was originally a greenalite rock with some carbonate and the upper part was originally an iron carbonate with some greenalite.

Nature of alterations.—The original greenalite and carbonate rocks have altered principally to ferruginous cherts in the manner described for other ranges. Local and for the most part subsequent alteration of the ferruginous cherts by leaching of silica has developed the ore. Coarsely crystalline secondary iron carbonate is abundant.

SEQUENCE OF ORE CONCENTRATION.

The alteration of the iron-bearing formation has occurred both before and since Keweenawan time. Evidence of the pre-Keweenawan alteration lies in the abundant fragments of ferruginous chert and iron ore which occur in the Keweenawan conglomerates. Evidence of later alteration is the fact that the deformation which produced fracturing and brecciation of the iron-bearing formation, and which in part determined the localization of the ore concentration, was later than Keweenawan time, as is shown by the similar phenomena of deformation in superjacent Keweenawan beds.

CHAPTER IX. THE CUYUNA IRON DISTRICT OF MINNESOTA AND ITS EXTENSIONS TO CARLTON AND CLOQUET, AND THE MINNESOTA RIVER VALLEY OF SOUTHWESTERN MINNESOTA.

CUYUNA IRON DISTRICT AND EXTENSIONS TO CARLTON AND CLOQUET.

GEOGRAPHY AND TOPOGRAPHY.

The Cuyuna iron district is the most recently discovered range in the Lake Superior region and as such is receiving a large share of attention. It trends N. 50° E. along the line of the Northern Pacific Railway, near Mississippi River, in the vicinity of the towns of Brainerd and Deerwood, Crow Wing County; Aitkin, Aitkin County; and Randall, Morrison County, in north-central Minnesota. (See Pls. XIV and XV.) Its boundaries are still being extended and limits can not yet be drawn with certainty in any direction. The area of present greatest activity lies south and east of Mississippi River in Tps. 43 to 48 N., Rs. 28 to 32 W. The length is more than 60 miles and the area for exploration amounts approximately to 32,000 acres.

The general geologic and geographic relations of the Cuyuna district to the adjacent territory appear on Plate XIV. A larger-scale map of the Cuyuna district itself, showing magnetic belts, is Plate XV. This map is not colored geologically for the reason that the district is heavily drift covered and the distribution of the underlying rocks is known only incompletely from drill holes. Any map attempting to show geologic boundaries would be sadly out of date by the time of publication. However, the magnetic lines follow approximately the distribution of the iron-bearing rocks.

The country is flat, being not less than 1,150 feet nor more than 1,300 feet above sea level. It is covered with a heavy mantle of glacial drift and dotted with many glacial hills, lakes, and swamps.

The rock surface beneath the drift shows slight local variations in elevation, and between widely separated points, because of the general slope of the surface, may show a difference of elevation of as much as 250 feet. Frequently the soft slates are found to be at lower elevations, because of erosion, than the harder iron-bearing formation adjacent—as, for instance, near Pickands, Mather & Co.'s shaft in sec. 8, T. 45 N., R. 29 W. Notwithstanding these local irregularities of the rock surface, it is generally flat. At many places in the district and in adjacent parts of Minnesota Cretaceous deposits are found just above the rock surface and beneath the drift, suggesting that this flat surface may be part of a pre-Cretaceous base-level or peneplain.

The Cuyuna district has almost none of the external aspects commonly associated with a Lake Superior iron range. The conspicuous topographic ranges are lacking, as well as the numerous rock exposures.

SUCCESSION OF ROCKS.

From the information so far available, consisting largely of drill samples, the succession of rocks for the Cuyuna district is as follows:

Quaternary system:
  Pleistocene series.......Glacial drift of late Wisconsin age, 35 to 400 feet thick.
Cretaceous system...........Sediments, thin and in small areas.

Algonkian system:
- Keweenawan (?) series... Igneous rocks, extrusive and intrusive, basic and acidic.
- Huronian series:
  - Upper Huronian (Animikie group).
    - Virginia ("St. Louis") slate: Chloritic and carbonaceous slates, with small amounts of interbedded graywacke, quartzite and limestone. Thickness unknown but great. Where intruded by Keweenawan (?) igneous rocks, this formation consists of garnetiferous and staurolitiferous biotite schists and hornblende schists.
    - Deerwood iron-bearing member of Virginia slate, consisting principally of iron carbonate where unaltered, but largely altered to amphibole-magnetite rocks, ferruginous slate and chert, and iron ore. Found in lenses in the Virginia slate, presumably near the base.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

UPPER HURONIAN (ANIMIKIE GROUP).

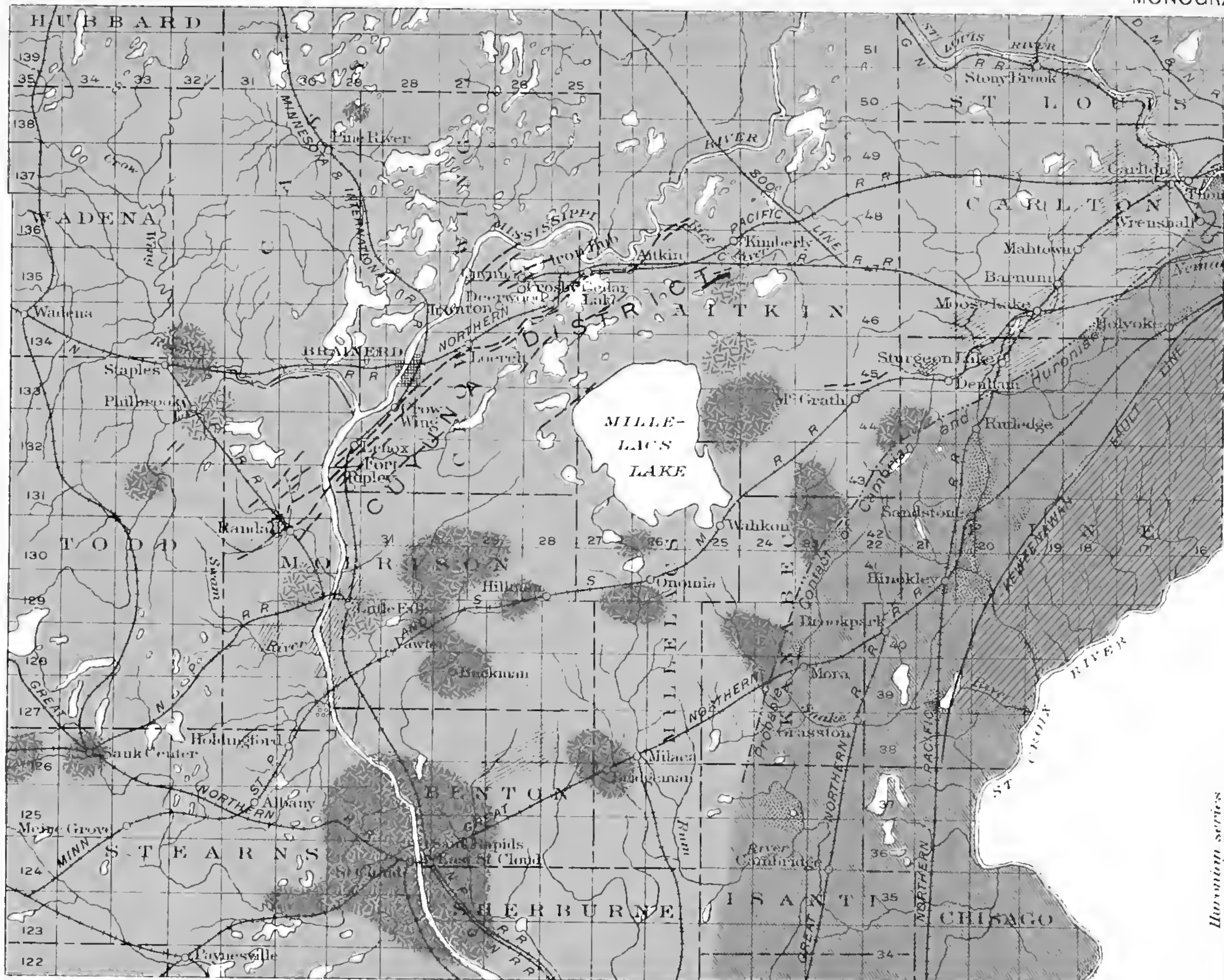
GENERAL STATEMENT.

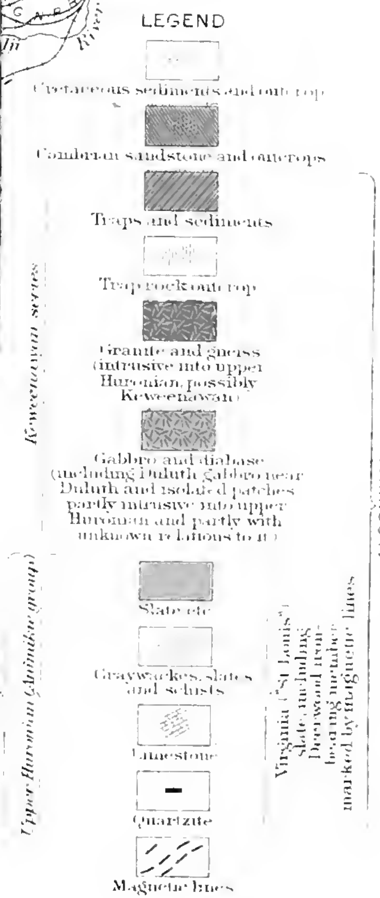
The upper Huronian rocks of this district, comprising the Virginia ("St. Louis") slate and its Deerwood iron-bearing member, are not separated for much of the district, but are interbedded and have similar structure. They are accordingly described together. The slate, hitherto known as the "St. Louis" slate, has been correlated with the Virginia slate of the Mesabi district. The name "St. Louis" as applied to this slate has priority over Virginia slate, but it is preoccupied by the well-known Carboniferous formation of the Mississippi Valley. The formation will therefore be called Virginia slate in this monograph. The iron-bearing rocks in this district have not been satisfactorily correlated with the Biwabik formation of the Mesabi district, and for them the new name Deerwood iron-bearing member is here introduced, from their typical development at and near Deerwood, in this district. The iron-bearing beds, being interbedded in the Virginia ("St. Louis") slate, properly constitute a member of the slate and are so treated in this report.

DISTRIBUTION AND STRUCTURE.

Sediments of upper Huronian age occupy practically all of the rock surface beneath the drift. They have been bent into repeated folds, as shown by drilling and magnetic work. In the southern part of the district the folding has been so close that the beds generally stand at angles of about 80° with the horizon, though locally varying at the ends of pitching folds. Toward the north the folding is less close and flatter dips are common. The folding has been accompanied by the development of cleavage in the softer layers, especially in the softer slates. Where the cleavage can be definitely distinguished from the bedding, there is usually a slight angle between them and the cleavage has the steeper dip. The iron-bearing member itself is less affected by the cleavage than the slate. The axial lines of folds and cleavage strike east-northeast—that is, about parallel with the axis of the Lake Superior syncline.

The iron-bearing member thus far found seems to be in the form of lenses whose longer dimensions are parallel to the highly tilted bedding of the series. The wall rocks are various phases of the Virginia ("St. Louis") slate. Intrusive rocks locally complicate these relations. Along the strike these lenses pinch out or widen and are locally buckled by the drag type of fold (fig. 12, p. 123). It is difficult to tell from the present state of exploration just how far the parallel lenses are independent lenses at different horizons in the Virginia slate and how far they may be the result of duplication by folding. The broader features of distribution are undoubtedly to be explained by folding. There is a narrow zone of iron-bearing rocks known locally as the "south range," extending from a point east of Aitkin southwest past Deerwood and Brainerd and west of Mississippi River, as shown by magnetic attractions and by drilling. This is made up of a large number of short parallel and overlapping belts. Whether these minor belts are repeated by folding or whether they are parallel independent lenses at different





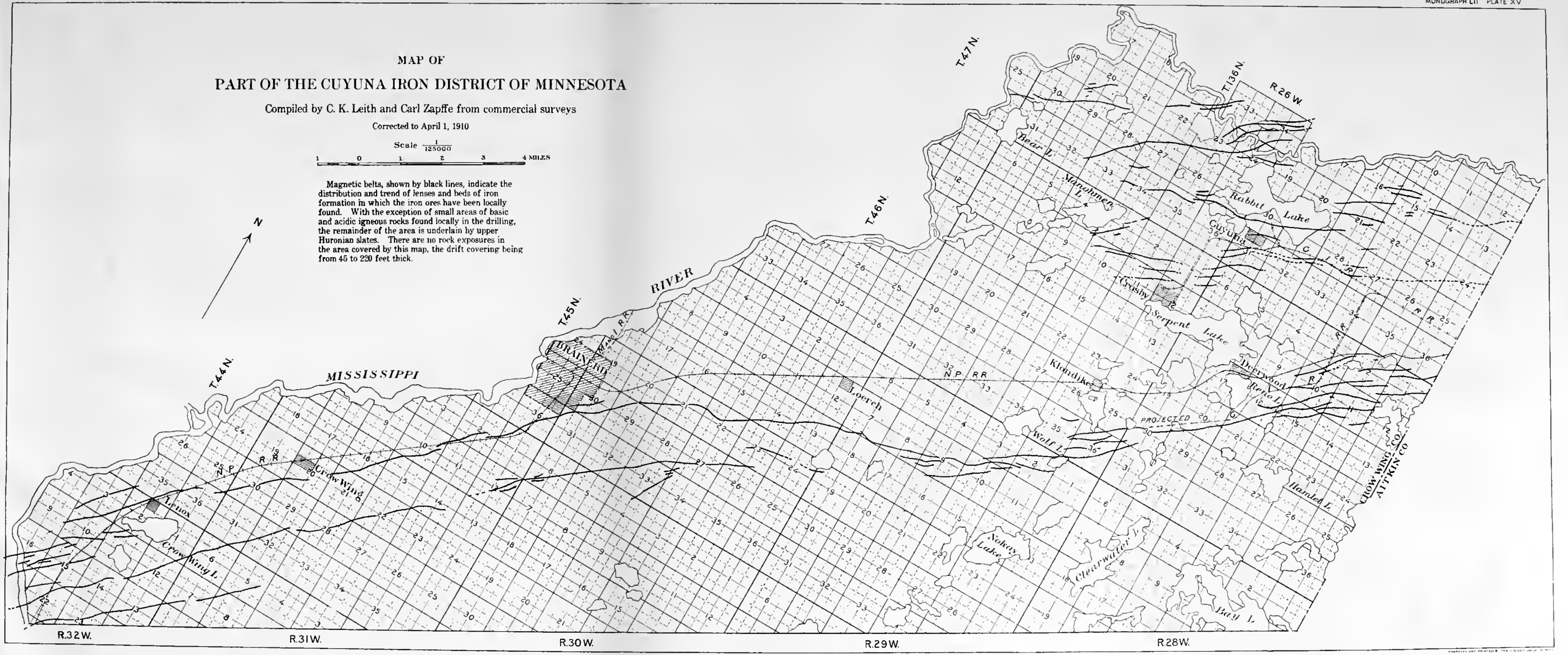
Compiled by C K Leith from map by C W Hall and commercial surveys of the Cuyuna district by Carl Zappfe and others

MAP OF CENTRAL MINNESOTA, INCLUDING CUYUNA DISTRICT

Scale 1:1250000

10 0 10 20 30 Miles

1910


MAP OF
PART OF THE CUYUNA IRON DISTRICT OF MINNESOTA
Compiled by C. K. Leith and Carl Zapffe from commercial surveys
Corrected to April 1, 1910
Scale 1/125000
1 0 1 2 3 4 MILES
Magnetic belts, shown by black lines, indicate the distribution and trend of lenses and beds of iron formation in which the iron ores have been locally found. With the exception of small areas of basic and acidic igneous rocks found locally in the drilling, the remainder of the area is underlain by upper Huronian slates. There are no rock exposures in the area covered by this map, the drift covering being from 45 to 220 feet thick.
N
MISSISSIPPI
RIVER
T.44 N.
T.45 N.
T.46 N.
T.47 N.
T.136 N.
R.26 W.
R.32 W.
R.31 W.
R.30 W.
R.29 W.
R.28 W.
BRAINERD
Lenox
Crow Wing
Crow Wing L.
Loerch
Klondike
Wolf L.
Nokay Lake
Clearwater L.
Bay L.
Hamlet L.
Deerwood
Reno L.
Serpent Lake
Crosby
Cuyuna
Rabbit Lake
Bear L.
Manohmen L.
N. P. R. R.
PROJECTED
CROW WING CO.
AITKIN CO.

horizons in the slate is not known. Six miles to the north, however, in the vicinity of Rabbit Lake, there is another belt of iron-bearing rocks, known locally as the "north range," which is undoubtedly brought up here by folding, for if it were an independent belt in a monoclinal succession it would imply too great a thickness of intervening strata between the north and south ranges. Still farther to the northwest, between Rabbit Lake and Mississippi River, are at least two more belts of iron-bearing rocks repeated by folding. Whether the folds reappear elsewhere prospectors are now trying to determine. Inspection of the map (Pl. XV) discloses a westward divergence of the south range and the north range belts of iron-bearing rocks. The best ores of the district are found in the angle between them. Divergence of strike to the west is also to be noted between certain pairs of the minor belts, though not in all. These facts may indicate either a general anticlinorium with eastward-pitching axis or a synclinorium with westward-pitching axis. The former is regarded as the more probable.

LITHOLOGY AND METAMORPHISM.

So far as the sedimentary rocks go, the emphasis in description should be placed on the altered phases, for they have all been much metamorphosed. Failure to recognize the schists as parts of the sedimentary series has caused confusion in the local interpretation of drill records. The changes in the quartzite and slate to schists are the typical anamorphic changes of the zone of rock flowage and igneous contacts.

Hall has shown how these slates, toward the south and west, where intrusive rocks are abundant, become garnetiferous and staurolitiferous biotite schists and hornblende schists.[a]

When subsequently exposed at the surface, there has been a leaching out of all the basic constituents, leaving light-colored, soft kaolinic and quartzose schists. This action is most conspicuous in their upper 15 or 20 feet. It is especially confined to the areas near the iron-bearing lenses. Farther south, where anamorphism was more intense, the rocks were made so hard and resistant that they have been affected but slightly by weathering where exposed at the surface.

The iron-bearing member, originally mainly iron carbonate, has also undergone anamorphism, resulting in the development of amphibole-magnetite rocks essentially similar to amphibole-magnetite rocks wherever they are found in other parts of the Lake Superior region. This action, however, was not sufficiently effective to destroy a large part of the iron carbonate constituting the original mass of the member. Where exposed to weathering the amphibole-magnetite rocks have been more resistant than the iron carbonates, but even they have become softer, owing to leaching of silica, which has resulted practically in the concentration of the iron, which remains substantially as magnetite. The iron carbonate has been altered to limonite at the surface. The result is a mixture of hematite, limonite, and magnetite in the iron-bearing member, soft and granular above and becoming harder and more siliceous below and showing more of the unaltered carbonate phases with depth. The gradation phases between the iron-bearing member and the slate have become ferruginous slates.

The anamorphism of the rocks of the Cuyuna district is probably to be explained in large part by the existence of intrusives in the area itself and west and south of it.

CORRELATION.

The sedimentary rocks of the Cuyuna district probably belong in the same series with the slates and schists of the Carlton, Cloquet, and Little Falls areas. They show many similarities in lithology, structure, and metamorphism and are geographically contiguous. Drilling in numerous places in Crow Wing and Aitkin counties shows the same pyritic and carbonaceous phases of slate as have been explored for coal in the vicinity of Mahtowa.

Succession and lithology are in accord with distribution and general structural relations in pointing to the identity of the rocks of the Cuyuna-Carlton-Little Falls area with the upper Huronian (Animikie group) of the Lake Superior region. The Animikie group as a whole,

[a] Hall, C. W., Keewatin area of eastern and central Minnesota: Bull. Geol. Soc. America, vol. 12, 1901, pp. 343-376.

where best known in the Mesabi and Animikie and Gogebic districts, consists of a great slate formation 2 miles or more thick, underlain by and interbedded in its lower portions with an iron-bearing formation of varying thickness, but averaging perhaps 1,000 feet, and this in turn underlain by quartzite varying from 1 to 200 feet in thickness. Exploration has not yet gone far enough to warrant a satisfactory estimate of the thickness of the formations in the Cuyuna district, but the information so far developed is in accord with the figures given for the Animikie group as a whole, except for the iron-bearing member, which thus far has not been found to be as thick as the average for the Lake Superior region. The Cuyuna range is separated from the Mesabi range on the northeast by a flat swamp and lake area about 50 miles wide, which completely lacks rock exposures. The Animikie group in the Mesabi district dips to the south under this low, flat area at an angle varying from 4° to 20°. It has long been obvious that the group here disappearing under the surface might somewhere be brought up to the south by folding.

In the Gogebic range, on the south side of Lake Superior, a similar group dips at an average of 60° toward the northwest beneath the Lake Superior basin, and it has long been thought that this group represents the Animikie group as it comes up again on the south side of the lake. An examination of the general structure of the west end of the Lake Superior basin, however, shows that the structure of the area between these two districts is not that of a simple syncline but of a syncline in which there are subordinate anticlines—that is, a synclinorium. One of these subordinate anticlines runs west and southwest from Duluth toward Little Falls and vicinity on Mississippi River. If the Animikie group comes to the surface anywhere between the Mesabi range on the north and the Gogebic range on the south, it should therefore appear in this subordinate anticlinal fold in the western part of the general synclinorium connecting these two regions, and it was on this hypothesis that the extension of the iron-bearing formation of the Mesabi and Gogebic districts was drawn by geologists, prior to its discovery, through the present Cuyuna district, which lies near the north side of this subordinate anticlinal fold. The existence of a quartzite exposure at Dam Lake, near Kimberly, and near Rabbit Lake, as shown by drill records, points to the fact that here erosion has cut down to the lower part of the Animikie group as it would in truncating an anticline. The course of Mississippi River itself suggests the existence of the anticline in the vicinity of the Cuyuna range, for after crossing the Mesabi range it flows south until it reaches the Cuyuna district and then turns suddenly westward as though deflected along the anticline toward a lower point of escape. Where it does break across, as at Little Falls, rocks are exposed.

The slates of the Carlton and Cloquet districts were early assigned by Irving and other geologists to the upper Huronian, but they were later referred by Spurr to the lower Huronian because of their greater metamorphism and folding than that of the upper Huronian slates in the Mesabi district to the north and because they are intruded by granites supposed to be of lower Huronian age. It is now known that the upper Huronian (Animikie group) of the Mesabi district is also intruded by granite. The facts developed in the Cuyuna district seem to confirm Irving's view of the correlation.

In view of the probable equivalence of the rocks of the Cuyuna and Carlton areas and the occurrence of small iron carbonate bands and nodules in the slates about Carlton and Cloquet and to the southwest similar to the broader bands in the Cuyuna area, the question naturally arises why erosion should not somewhere in this great area of exposed slate between Carlton, Cloquet, and Little Falls uncover the lower part of the Animikie group—in other words, the iron-bearing member. It may be that the crest of the anticline runs parallel with the Cuyuna district itself, allowing erosion to cut down here only into the main iron-bearing member, while to the south and southeast the thick capping of slates has not been removed, or it may be that the existence of great masses of intrusive granite and diabase and the intense metamorphism which they have accomplished have prevented erosion of the surface or have made the conditions unfavorable for the direct oxidation of the iron-bearing rocks under surface katamorphic conditions. Certainly enough facts are not yet available to warrant the assertion that the iron-bearing member may not yet be found in this area.

KEWEENAWAN SERIES (?).

Igneous rocks are abundant in the area of the upper Huronian (Animikie group). These include granites and basic rocks, many of the latter characterized by ophitic structure. Part are schistose; others are not. The granites outcrop conspicuously (thereby contrasting with the adjacent upper Huronian sediments) in the southern part of the district in a general belt extending from Carlton and Cloquet southwest beyond Mississippi River. Other exposures are known northwest of the district, in the vicinity of Randall and Motley. Basic igneous rocks of diabase and gabbro types also outcrop, though less abundantly, over the same area. Dikes of the basic rocks, up to 50 feet in width, are conspicuous in the Carlton area. The intrusive character of these igneous rocks as a whole admits of no doubt. Their metamorphic effect on adjacent sediments has already been described. Within and adjacent to the Deerwood iron-bearing member drilling has disclosed much igneous rock, both basic and acidic, of yet unknown extent and with unknown relations. The contacts are sharp, the adjacent members of the upper Huronian have been locally metamorphosed, and no basal conglomerates have been found in the sediments adjacent to the igneous rocks. From these facts it is concluded that the igneous rocks cut in drill holes are probably intrusive into the upper Huronian sediments, just as are the granites to the south. The textures and structural relations of some of the basic igneous rocks suggest the possibility that they may be extrusives contemporaneous with the upper Huronian rather than with later intrusives, but until mining operations disclose more underground sections this can not be determined. In only three localities are extrusives known. An acidic extrusive rock with amygdaloidal texture, in beds 15 to 25 feet thick, has been found by drilling to rest across the edges of the Virginia slate and Deerwood iron-bearing member, in sec. 2, T. 44 N., R. 31 W.; sec. 6, T. 44 N., R. 30 W.; and sec. 7, T. 45 N., R. 29 W.

The igneous rocks intrusive into the upper Huronian and the extrusives resting on the upper Huronian are provisionally classed as Keweenawan, because the Keweenawan is the next period of igneous activity, because abundant igneous rocks of Keweenawan age are known elsewhere in the region to cut the upper Huronian sediments, and because they are especially abundant in that part of the Cuyuna district which lies approximately along the central axis of the Lake Superior syncline, largely developed during Keweenawan time. (See pp. 421–422, 622–623.)

CRETACEOUS ROCKS.

Immediately below the surface, in widely scattered parts of the district in Crow Wing County, remnants of a conglomerate have been found. Some consist of small pebbles of the iron-bearing member in a slaty matrix; others of small pebbles of an extrusive rock. Generally the pebbles are about an eighth of an inch or less in diameter, but on two widely separated properties the oval pebbles measure as much as an inch in their longest dimension. This conglomerate is found resting unconformably, apparently in small depressions, on a rather level erosion surface of the upper Huronian. It does not contain fossil remains to identify it, but it is similar to the Cretaceous of the Mesabi range. An excellent opportunity to examine it was offered when an exploration shaft was sunk in the SW. ¼ SE. ¼ sec. 8, T. 45 N., R. 29 W.

More Cretaceous sediments have not been identified, probably because, being poorly cemented, they are chopped and brought to the surface in drilling as churnings. Drillers frequently report unbroken shells in the lower portion of that which is reported as "surface," and clay immediately above bed rock and below the surface, and frequently the top drill samples are light-colored, unconsolidated, and calcareous material, all of which might well be of Cretaceous origin. None of this has been very carefully examined. The common occurrence of large amounts of lignitic material in the glacial drift indicates a once wide distribution of Cretaceous deposits, possibly with remnants here and there such as are found in the Mesabi range to the north. Cretaceous beds continuously cover the pre-Cambrian rocks of western Minnesota. Those of the Cuyuna district may be regarded as outliers of the main Cretaceous area.

QUATERNARY SYSTEM.

PLEISTOCENE GLACIAL DEPOSITS.

The glacial deposits in the eastern part of the district belong, according to Upham,[a] to the eighth moraine and those in the western part of the district belong to the ninth moraine, counted back from the outermost moraine of the late Wisconsin glaciation. They vary from 35 to 400 feet in thickness. The heavy mantle of weathered material upon the rock surface is a remnant of the product of preglacial weathering, which in the other districts has been removed by glacial erosion. Obviously in the Cuyuna district glacial deposition has predominated over glacial erosion.

THE IRON ORES OF THE CUYUNA DISTRICT.

By the authors and CARL ZAPFFE.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The Cuyuna ores are scattered through a considerable area beginning a little east of Aitkin, Aitkin County, Minn., and extending southwestward past Brainerd into Morrison County. (See Pl. XIV.) The limits of the ore-bearing district are not yet known. The district lacks the distinct range or ridge characteristic of the other iron-producing districts, though in general it follows a drainage divide. The area is flat, heavily drift covered, and without exposures.

The development of the Cuyuna district is still in its exploratory stage. At this writing no shipments have been made. In the absence of exposures, information is available from about 2,000 drill holes and two shafts and from magnetic readings. The information is still inadequate to warrant any extended discussion. In the following general outline emphasis is placed on the facts thus far developed. No attempt at proportional treatment is made. This may be possible later.

The Deerwood iron-bearing member is magnetic as a whole, and hence its distribution is roughly shown by the magnetic belts outlined on Plate XV and by minor belts which do not appear on this plat. Parts of the member, however, are very weakly magnetic; they are found beneath very weak belts of attraction and extend laterally some distance away from the maximum magnetic line. The ore deposits may be more or less magnetic, usually less magnetic, than the associated iron-bearing member, and hence are not ordinarily situated under the belts of maximum variation, though they are not far from them.

Ore deposits of sufficient size and grade to be commercially available have been found in both the north and south ranges, so called. The south-range ores occur at intervals along the magnetic belts from a place a mile east of Deerwood more or less intermittently to the northeastern part of T. 43 N., R. 32 W., near Mississippi River southwest of Brainerd, a distance of about 30 miles. The north-range ores are in intermittent deposits, in a shorter but wider belt, extending from Rabbit Lake southwestward nearly to Mississippi River. The tonnage of the deposits thus far found is about equal in the two ranges, but on the north range the ores are more largely confined to a few large deposits of good grade, while on the south range the number of deposits is larger and their individual size smaller.

The ores are in nearly vertical lenses and layers from a few inches to 125 feet or more wide on the south range and up to 400 or 500 feet on the north range. The depths on the two ranges are variable as the widths. On the north range the greatest depth known is 850 feet and it is quite likely that this figure may be exceeded, but up to the present time the average depth is about 300 feet. On the south range the greatest depth known is about 250 feet, and it does not seem likely that this will be greatly exceeded. The average depth on the south range is about 150 feet, but the higher-grade ores invariably occupy only the upper 100 feet. The strike is east-northeast for distances varying from a few feet to half a mile and to an unknown greater distance.

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[a] Minnesota Geol. Survey, vols. 2 and 4.

Whether these lenses pitch in the direction of strike, following the axes of drag folds, is not yet disclosed by the drilling. (See fig. 49, p. 350.) From analogy with other districts the ore bodies are likely to have a pitch, and this pitch is likely to be more or less uniform in direction and degree, affording a guide for exploration. The drilling has not shown the pitch, because where they are vertical the holes are stopped as soon as they run out of ore, and if they go into lean rocks rather than ore they are ordinarily not carried far enough to locate any possible extensions of the pitches. Where the holes are put to one side of the ore body and inclined they are stopped as soon as they have penetrated the ore lens. These pitches are, as a matter of fact, extremely difficult to locate by drilling. Closely associated with the ore on one or both walls, or in layers within the ore, is amphibole-magnetite rock. At varying depths, but usually within 125 feet on the south range, the ores tend to grade vertically into cherty iron carbonate rocks, and at these depths also the amphibole-magnetite rocks contain much more iron carbonate than at the surface. It may be found that down the pitch the depth of gradation to iron carbonate is much deeper. The ores, with the associated amphibole-magnetite rocks and cherty iron carbonates, constitute the iron-bearing member of this district.

The Deerwood iron-bearing member as a whole constitutes lenses or layers in the great Virginia ("St. Louis") slate formation, lying parallel, overlapping, or end to end. Each major lens may be divided into minor lenses by intercalated slate layers.

The wall rocks of the ore may therefore be any of the phases of the Deerwood iron-bearing member or any of the phases of the Virginia ("St. Louis") slate. Characteristically one wall may be chloritic or black graphitic slate of the Virginia formation and the other wall amphibole-magnetite rock of the Deerwood iron-bearing member. The association of ore with carbonaceous slates finds its counterpart in the Iron River, Crystal Falls, and other districts of Michigan.

Dikes and irregular masses of basic intrusive rocks appear in all parts of this series and are associated with almost every ore deposit yet known. These may constitute one wall of the ore body or may be separated from the ore body on one wall by amphibole-magnetite rock.

A characteristic occurrence of the ores is shown in plan and cross section in figure 25. It is apparent from this figure that the information furnished from drill holes would depend largely on the angle at which the drill penetrates the iron-bearing member. In a vertical lens a vertical hole will tell nothing of the character of the material a few feet away across the strike. An inclined hole will indicate the proportions of iron ore, amphibole-magnetite rock, and slate layers, but may not show the greatest depth of the iron-ore lenses, or, on the other hand, it may pass through the carbonate phases of the beds beneath the ore.

The ore, where associated with magnetite rocks, is in many places also magnetic. The amphibole-magnetite rocks are somewhat more magnetic than the ores themselves, so that drilling on the maximum magnetic attraction is likely to show amphibole-magnetite rocks with the ores a few feet to one side or the other. A not uncommon relation is amphibole-magnetite rock on the maximum attraction, intrusive material on one side of the maximum, and ore on the other. The greatest distance from the maximum attraction at which ore has yet been found is one-half mile. It will be shown elsewhere (pp. 552–553) that the magnetic character of the member is not favorable to its richest concentration; this suggests that the best parts of the Cuyuna ore may yet be found farther away from the magnetic belt.

The fact that the foot and hanging walls of the ore deposits of most of the Lake Superior ranges are uniformly different in their lithology has led to the assumption that the foot and hanging walls of the Cuyuna ore deposits are uniformly different. Beginning in slate a few hundred feet either side of the magnetic belt, an inclined drill hole penetrates the iron-bearing member as the magnetic maximum is approached. The slate is ordinarily spoken of as "hanging wall." The drill is then likely to penetrate ore more or less interbedded with slate and amphibole rock. As the magnetic maximum is approached the amphibole-magnetite rock is likely to be more abundant. The drill may go beyond the maximum attraction into intrusive, which would be spoken of as "intrusive foot wall." (See fig. 25.) The terms "hanging-wall slate" and "magnetic foot wall" or "intrusive foot wall" therefore signify a certain tendency toward uniformity of relations which it is well to identify by such terms. But the assumption of uniformity implied by the use of these terms may lead to misapprehension of the facts. Slate similar to that of the hanging wall may be on either side of the iron-bearing member. If the drills go far enough, they are likely to find slate in both walls. Slate layers within the iron-bearing member itself, if first penetrated by the drill, would be likely to be called "hanging wall." In short, the nature of the foot and hanging walls will depend on the particular layers in which the drill happens to start and where it stops in the interlaminations of slate and iron-bearing member. The relations of the intrusive rocks to the ore deposits are still obscure, but it seems not unlikely that these may be found to constitute a definite foot wall for some of the ore bodies.

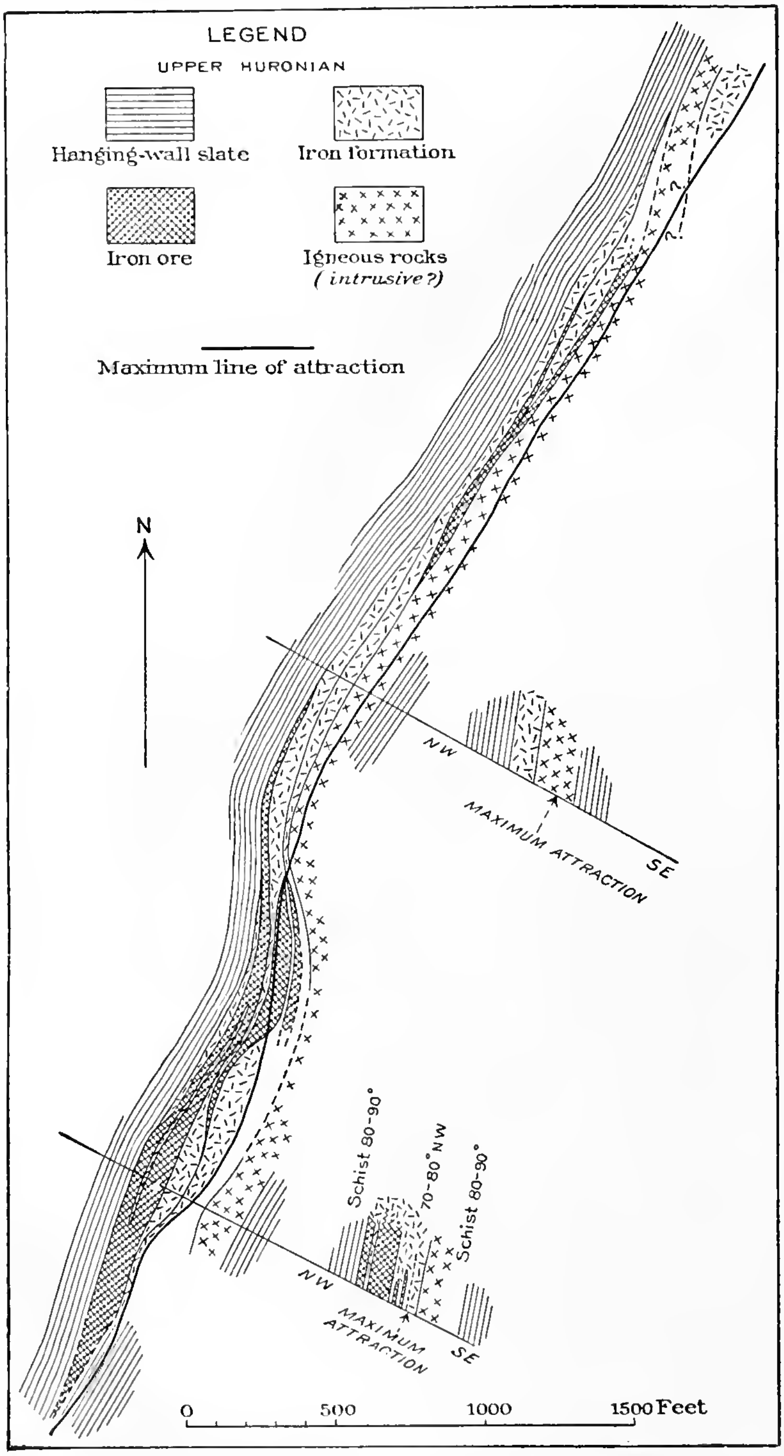

FIGURE 25.—Plan and cross section of the iron-ore deposit in sec. 12, T. 43 N., R. 32 W., Crow Wing County, Minn. By Carl Zapffe.

The facts just given are disclosed by drilling, but the drilling yet done gives a very incomplete view of the structure, and for the larger structural features we must rely principally on interpretations of the magnetic field. The existence of five magnetic belts in a zone 7 miles wide north and south suggests that the iron-bearing member is repeated by folding. If the dips were monoclinal and the several magnetic belts represented separate iron-bearing zones in the slate, the thickness of the series to be inferred would be greater than is reasonable. On the other hand, the drill cores show variations in the dip of the bedding indicative of folding. The cleavage of the slates is inclined to the bedding, and this relation is itself evidence of folding. These folds have a strike east-northeast parallel to the Lake Superior axis, to judge from the magnetic belts. Moreover, the discontinuity of these belts, their distribution en échelon, and the varying intensity of the magnetic field along a single belt all accord with the distribution required by pitching folds, which repeat the iron-bearing beds, the number of times differing with the locality. If the crests and troughs of the folds were horizontal, the beds would appear as parallel lines upon the horizontal erosion plane, but the actual crest and trough lines of the folds usually have a pitch; in other words, they are cross folded, so that on the erosion plane the beds appear to converge in the direction of the pitch. With folding of this type it is apparent that the beds may strike with a considerable variety on the erosion plane, according to the section this plane happens to make through the folds.

The magnetic belts fail to give all the information desired as to structure, for two reasons: (1) It is not certain that the iron-bearing lenses in all parts of the district are at the same horizons in the slate; indeed, it is known that within a few hundred yards there may be several iron-bearing bands, so that the question is raised whether iron-bearing layers in other parts of the district belong below, with, or above them stratigraphically. (2) It is difficult to tell whether two nearly parallel belts close together represent truncated iron-bearing layers on the two limbs of a single fold or the axes of two independent folds. The main belts of attraction several miles apart doubtless represent separate folds, but the closely associated minor belts making up each of the main belts may represent either the two limbs of a single fold or two horizons on one limb of a fold.

It is concluded, in general, that the iron-bearing member constitutes closely associated lenses and layers along a single general horizon in the slate. The finding of quartzite in a few places near the iron-bearing member suggests that this horizon is near the bottom of the slate formation, but this is not proved. The folding of the slates carrying the iron-bearing zones, followed by erosion, has developed the present distribution at the surface.

CHARACTER OF THE ORES.[a]

GENERAL APPEARANCE.

The Cuyuna ores fall into two main groups, hard and soft ores.

The soft ores are black, brown, and reddish hydrated hematites, soft and earthy and much like the soft ores of the Penokee-Gogebic district. They have large pore space. These soft ores are of two types—a high-grade ore containing 55 to 63 per cent iron, soft and powdery and of a brown to very dark color, and a lean reddish-purple ore containing 45 to 50 per cent iron. The latter ore is not so soft as the former. It is easily broken down with a pick but retains its stratified form and hangs together in fairly large chunks. In this type cherty layers are scattered through the mass at short intervals, the cherty impurity probably accounting for its low grade. This ore also has a large pore space.

The hard ores are also of two types. The bulk of the hard ore is a black to very dark brown hydrated hematite. It is closely stratified and has suffered close brecciation as a result of slumping caused by the leaching out of silica. This ore varies in iron content, but is mainly high grade, running from 50 to 60 per cent iron. Although this ore is brecciated it holds together in large masses, owing to the partial cementing of the brecciated pieces by the secondary introduction of iron. Much of the ore of this type has been classed as soft ore by the drillers because it is fairly easily penetrated by a churn drill and comes to the top broken up in very fine angular pieces. It can be distinguished, however, from the true soft ore, which is washed to the surface of the hole as a fine, even-grained, powdery mass. The Cuyuna hard ore described above must not be compared to Vermilion dense blue hematite of that range. It is much softer and more limonitic.

The other type of Cuyuna hard ore, small in amount as compared with that described above, is a hard blue hematite running about 58 to 63 per cent iron. It is massive and unbrecciated. This is a true hard ore and can only be drilled with diamonds. This ore occurs in layers in the softer ores and is found more frequently close to the intrusives.

[a] In the description of the ores the writers have drawn on quantitative data assembled by F. S. Adams (Econ. Geology, vol. 5, 1910, pp. 729-740; vol. 6, 1911, pp. 60-70, 156-180).

It is impossible to state at this incomplete stage of exploration the proportion of hard to soft ore on the Cuyuna range. The soft ores probably form the larger proportion, but the hard ore must be counted as a large factor and may occur in a much larger percentage than has previously been supposed.

Locally on the north or Rabbit Lake range black, highly manganiferous ores have been developed near the surface. These are unimportant in amount as compared with the other ores.

CHEMICAL COMPOSITION.

Because of the minute interbanding of the ore with lean, magnetic, and slaty phases, the chemical composition shows rapid alternation across the strike. The percentage of iron of the iron-bearing member ranges from less than 30 per cent in the lean siderite and amphibole phases to 60 per cent and more in certain of the iron ores. In certain estimates of tonnage which have been made it has been calculated that of the ores running above 40 per cent metallic iron 44.5 run above 50 per cent in iron and 21.3 per cent above 55 per cent in iron. These figures are based on a sufficient number of drill holes to warrant the belief that this proportion may have some general significance for the range. The average iron content of all ores above 50 per cent in iron on the north range, found by drilling to the time of writing, is about 1 per cent higher than that for such ores on the south range. The chemical character of the iron ore and interlayered masses as they stand in the ground may best be shown by the following analyses from a drill hole cutting the formation at an angle of 60°:

Analyses of iron ore and interlayered masses from the Cuyuna district, Minnesota.

Depth.	Fe.	P.	Mn.	SiO_2.	Al_2O_3.	CaO.	MgO.	Loss by ignition.
Feet.								
175–180	58.70	0.519	0.24	4.86	0.68	0.11	0.08	7.34
180–185	59.73	.547	.22	3.23	1.13	.15	.14	....
185–190	59.02	.425	.20	3.78	1.35	.10	.11	....
190–195	59.11	.404	.20	4.10	1.25	.17	.10	7.83
195–200	60.32	.414	.40	6.35	.63	.10	.09	....
200–205	59.60	.385	.51	7.22	.66	.08	.08	....
205–210	59.44	.353	.36	7.34	.62	.11	.10	5.35
210–215	60.93	.264	.40	6.68	.49	.18	.07	....
215–220	61.10	.229	.47	7.16	.44	.20	.05	3.36
220–225	57.82	.287	.44	13.00	.47	.10	.04	....
225–230	57.93	.284	.40	12.96	.48	.17	.08	....
230–235	55.52	.337	.43	15.19	.49	.16	.07	2.75
235–240	40.66	....	.94	9.79	2.00	.14	.06	....
240–245	49.07	....						
245–250	45.67	....	.48	29.30	.35	.13	.09	2.18
250–255	46.82	....						
255–260	47.95	....	.40	26.04	.59	.10	.10	....
260–265	48.74	....						
265–270	48.28	....	.50	26.00	.52	.16	.06	2.62
270–275	41.47	....						
275–280	41.80	....	.39	36.74	.54	.17	.08	....
280–285	40.36	....						
285–290	36.80	....	1.12	32.56	.73	.42	.36	....
290–295	37.19	....						
295–300	37.85	....	1.05	31.71	.74	.41	.37	7.11

It will be noted that the principal variants here, as in other districts, are iron and silica. Phosphorus is usually high, averaging about 0.34 per cent, which brings the ore into the class of the Iron River and Crystal Falls ores. The north range shows less phosphorus than the south range. Locally on the north range there are streaks of Bessemer ore.

Loss by ignition is high. This consists principally of water combined in the hydrated iron minerals but includes some carbon.

Manganese is usually in small amounts, but locally and near the surface may run up to 10 or 12 per cent or even up to 28 per cent. One drill hole on the north range averaged 13 per cent for the upper 35 feet. Another had an average of 11.33 per cent for the upper 30 feet.

The percentage of free water in the ore as mined can not be determined through drilling, and the ore has thus far been opened up by shafts to such a slight extent that the average free moisture for the ores can not yet be given. Three determinations from the Rogers, Brown Ore Co. shaft give moisture of 6.80 per cent, 10.40 per cent, and 14.20 per cent, with an average of

10.46 per cent, not far from the average of the Lake Superior region. Another determination by Pickands, Mather & Co. for the ore from their shaft in sec. 8, T. 45 N., R. 29 W., gives 12 per cent of free moisture. In analyses of ore from drill holes the iron content is usually calculated for the dried ore. If the moisture is included the iron content is lower. An average moisture of 10 per cent indicates that an ore appearing as a 55 per cent ore in the drill hole will mine as about 50 per cent. As prices are based on standard ores with moisture, this correction is an important consideration.

The slate layers interlayered with the iron-bearing member and intermediate phases between the iron-bearing member and the slate would run higher in alumina. The above analyses are confined to the iron member itself.

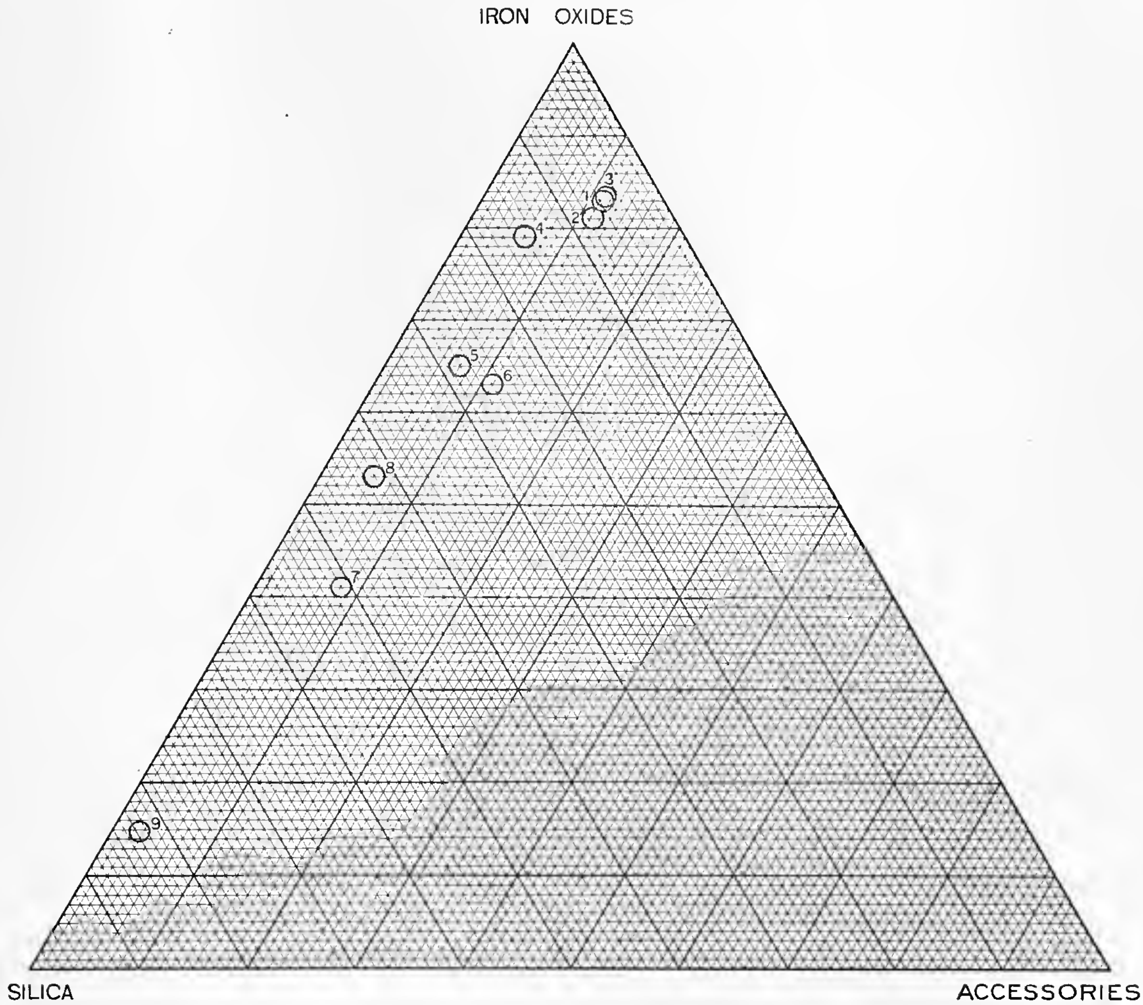

FIGURE 26.—Triangular diagram showing mineralogical composition of various phases of iron ores and ferruginous cherts of the Cuyuna district, Minnesota. After F. S. Adams. For description of method of platting and interpretation of diagram, see p. 182. 1, Hard blue ore from the Rabbit Lake section; 2, brecciated, hydrated hard ore (Rabbit Lake); 3, hard blue ore (sec. 21, T. 46 N., R. 28 W.); 4, soft ore (sec. 21, T. 46 N., R. 28 W.); 5, lean soft ore (Rabbit Lake); 6, dense, black, highly ferruginous chert; 7, 8, average ferruginous chert; 9, weathered highly siliceous chert.

MINERALOGICAL COMPOSITION.

The Cuyuna ores are more or less magnetic hydrated hematite with some limonite. The principal impurity is chert in layers. A less common impurity is clay in layers. In still smaller amount are iron carbonate and amphibole, which also show a tendency toward concentration in layers. The color varies from a light yellow through various brown and reddish tones to black, according to the hydration of the iron and the amount of magnetite in it. The highly manganiferous ores contain both the carbonates and oxides of manganese. They are most abundant near the surface. The mineral carrying the phosphorus is not known.

The mineralogical composition, figured from the foregoing analyses in which loss by ignition was determined, is as follows:

Mineral composition of Deerwood iron-bearing member.

Depth.	Hematite.	Limonite.	Quartz.	Kaolin.
Feet.				
175–180	42.10	48.80	4.06	1.72
190–195	40.90	50.90	2.63	3.16
205–210	54.60	35.35	6.61	1.57
215–220	68.20	22.10	7.65	1.11
230–235	64.10	17.80	14.62	1.24
245–250	53.10	14.20	28.89	.89
265–270	54.80	16.65	25.35	1.49
295–300	13.85	47.25	30.84	1.87

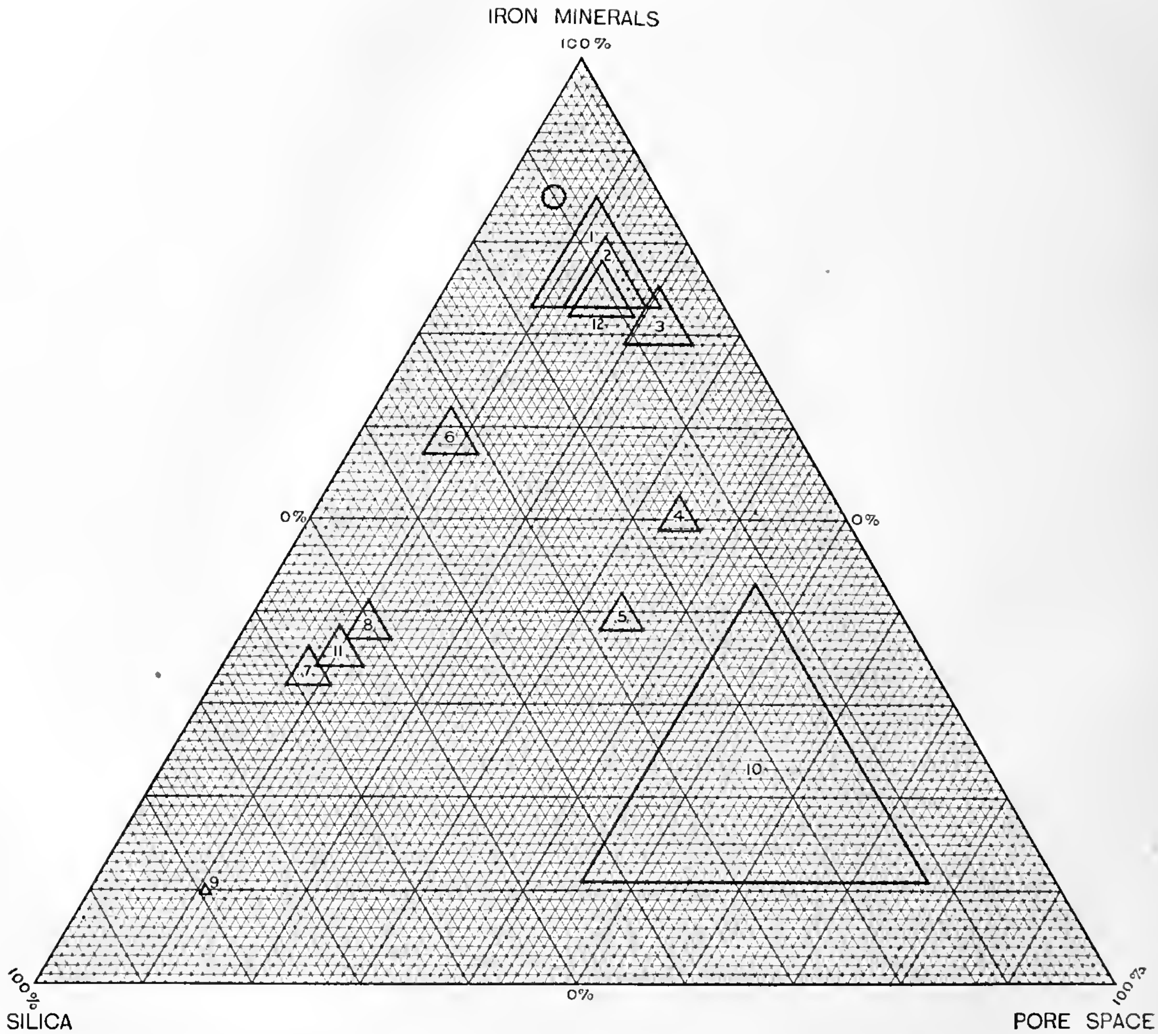

FIGURE 27.—Triangular diagram representing volume composition of various phases of iron ores and ferruginous cherts of the Cuyuna district, Minnesota. After F. S. Adams. For description of method of platting and interpretation of diagram, see p. 189. 1, Massive hard blue hematite; 2, brecciated limonitic hard ore; 3, hard ore from sec. 21, T. 46 N., R. 28 W.; 4, soft ore from sec. 21, T. 46 N., R. 28 W.; 5, lean soft ore, (Rabbit Lake); 6, dense, black, highly ferruginous chert; 7, 8, banded ferruginous chert; 9, weathered chert; 10, typical paint rock; 11, average ferruginous chert; 12, 13, average soft ore; 14, average cherty iron carbonate.

The ore really consists of hematite, limonite, hydrates intermediate between hematite and limonite, and magnetite. As it is almost impossible to determine what degree of hydration some of the minerals may have, the analyses are expressed in terms of hematite and limonite.

This is merely a conventional means of showing the degree of hydration for these ores. The amount of magnetite is so small that its calculation as hematite does not materially affect the result.

TEXTURE.

The density of the hard ores of standard grade averages 4.09. This includes both types of hard ore. The low figure is due to the hydrated character of the Cuyuna hard ore. The density of the soft ores averages 4.19. The lean soft ore shows an average density of 3.73. The hard blue unbroken type of hematite has an average density of 4.26. The limonitic brecciated hard ore shows a density of 3.95.

The pore space of the hard ores averages 13.13 per cent by volume. This includes both types. The soft ore has an average pore space of 36 per cent. The lean soft ore shows 33.3 per cent pore space. The hard ores show a range in porosity varying from 9 to 20 per cent by volume.

The hard ores of both types average 10 cubic feet per ton. The hard blue hematite varies between 9 and 10.5 cubic feet per ton. The hydrated brecciated hard ore ranges from 10 to 10.8 cubic feet per ton. The soft ores average 11.5 cubic feet per ton. The lean soft ore runs 12.6 cubic feet per ton.

An average figure to use in computing tonnage for a large deposit where various ores are represented and a tonnage estimate of each type is out of the question would be about 11 cubic feet per ton.

Notwithstanding the fineness of much of the ores, the texture is not disadvantageous, for there is probably less of it that will act as flue dust in the furnace than there is of the Mesabi ore, for the reason that it is as a whole less crystalline and more earthy and takes on a more coherent texture when compressed.

SECONDARY CONCENTRATION OF CUYUNA ORES.

Structural conditions.—The structural relations of the Cuyuna ores are still so imperfectly known that any statement concerning them must be made with much qualification. It is nevertheless obvious here that the concentration has been greatest at the surface and less with depth, and that at least in many places it has been very active next to the intrusives rocks which cut the member or along foot-wall slates or amphibole schist. Also it seems to have followed axes of minor drag folds. All the rocks have been weathered to a considerable extent. At present glacial drift covers them at depths of 35 to 400 feet, so that water stands much above the rock surface. The present condition is obviously quite different from that under which the ores were concentrated. It may be supposed that when the rock surface was exposed waters penetrated into the iron-bearing member as it was exposed on the anticlinal areas between the impervious hanging wall and the impervious foot wall and that where the member was cut by impervious igneous rocks they served further to control the circulation. The depth of circulation is not yet known, nor is it clear what topographic features may have been present in the past to control the depth of circulation.

Original character of the Deerwood iron-bearing member.—The member was originally cherty iron carbonate interbedded with slate.

Mineralogical and chemical changes.—The alteration of the original carbonate rocks was in different sequence from that in most of the Lake Superior ranges, because before it was exposed to weathering it underwent folding and intrusion, which partly altered the cherty iron carbonate to amphibole-magnetite rock. Subsequently, when erosion had exposed the member, the surface agents of alteration therefore had two phases of the member to work upon—unaltered iron carbonate and amphibole-magnetite rocks. The former went through the ordinary cycle of changes to ferruginous cherts and ore. The latter lost some of its silica and amphibole but as a whole was much more resistant than the carbonate. The net result of the alteration is a soft, hydrated ore containing much magnetite along certain bands, both containing silica as impurity and in increased amount with depth.

PHOSPHORUS IN CUYUNA ORES.

Phosphorus has been concentrated with the iron during the secondary concentration of the ores. It is probable, for reasons similar to those discussed on pages 192–196 for the Mesabi district, that phosphorus, leached from the overlying Cretaceous rocks, has been added to the ore during its secondary concentration. In general there is not sufficient lime in the ore to combine with all the phosphorus as apatite, hence some phosphorus is probably combined with the hydrous aluminum and iron minerals.

MINNESOTA RIVER VALLEY OF SOUTHWESTERN MINNESOTA.[a]

Pre-Cambrian crystalline rocks of the Minnesota River valley of southwestern Minnesota appear in numerous exposures along the river, protruding from the drift, from a point southeast of New Ulm to Ortonville on the northwest. The great bulk of the crystalline rocks are granites and gneisses. These appear for the most part in the river bottoms but stand also in a few isolated knobs on the higher ground south and west of the river. There are many varieties of granites and gneisses and all gradations between them. They are taken as a whole to represent the Archean or basement complex.

Associated with the granites and gneisses are a much smaller number of exposures of gabbros and gabbro schists. These present many varieties, all of which are believed to have resulted from the alteration of two original forms and their intergradations—a hypersthene-bearing gabbro and a hypersthene-free gabbro.

Peridotite is found in one exposure only in this valley, 3 miles southeast of Morton. The relations to the other rocks of the area could not be determined. Cutting the gneisses and gabbro schists throughout the area are numerous dikes of diabase. They vary in width from a fraction of an inch to 175 feet. Their age is probably Keweenawan.

Southeast of Redstone and near New Ulm are exposures of quartzite associated with coarse quartzite conglomerate. Near Redstone the strike of the quartzites is N. 60–70° W. and their dip varies from 5° to 27° N. In New Ulm the strike is N. 15° E. and the dip varies from 10° to 15° SE. The quartzite is believed to be the same as the quartzite found in a deep well at Minneopa Falls, near Mankato, Minn., which is covered by a quartzite conglomerate of Middle Cambrian age. The quartzite of Redstone and New Ulm is above the Archean granite and gneiss. It is believed to be of Huronian age, but whether upper or lower is unknown. The crystalline rocks of the Minnesota River valley are separated from the Virginia slate series of the Cuyuna and St. Louis River areas by a drift-covered area at least partly underlain by granite but partly unknown.

Overlying the crystalline rocks are Cretaceous shales and sandstones, which appear in rare exposures in the valley, and glacial drift.

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[a] For further detailed description see Hall, C. W., The gneisses, gabbro schists, and associated rocks of southwestern Minnesota: Bull. U. S. Geol. Survey No. 157, 1899, 160 pp., with geologic maps.

CHAPTER X. THE PENOKEE-GOGEBIC IRON DISTRICT OF MICHIGAN AND WISCONSIN.[a]

LOCATION, SUCCESSION OF ROCKS, AND TOPOGRAPHY.

The Penokee-Gogebic district lies south of the west half of Lake Superior, in the States of Michigan and Wisconsin. It extends from Lake Numakagon in Wisconsin about N. 30° E. to Lake Gogebic in Michigan, a distance of about 80 miles.

In the accompanying geologic map of the Gogebic range (Pl. XVI) the only essential change noted from earlier maps is in the vicinity of Sunday Lake, where faulting and perhaps folds have caused a marked effect in the iron-bearing formation.

The succession of formations in the district is as follows:

Cambrian system	Lake Superior sandstone.
Unconformity.	
Algonkian system:	
Keweenawan series	Gabbros, diabases, conglomerates, etc.
Unconformity.	
Huronian series:	
Upper Huronian (Animikie group)	Greenstone intrusives and extrusives. Tyler slate. Ironwood formation (iron-bearing). Palms formation.
Unconformity.	
Lower Huronian	Bad River limestone. Sunday quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granite and granitoid gneiss.
Eruptive unconformity.	
Keewatin series	Greenstones and green schists.

This chapter mainly deals with the Huronian series and especially with the upper Huronian (Animikie group). The Huronian series for most of the district has a breadth varying from less than half a mile to 2 or 3 miles.

The Huronian series has a simple structure. It consists of water-deposited sediments, the origin of which has been for the most part determined. The rocks have simply been tilted to the north at an angle which is convenient for determination of the succession of belts. They are without folding so marked that the belts do not follow in regular order from south to north. The series is terminated on the east by the unconformably overlying horizontal Cambrian sandstone and on the west by areas in which it has been entirely swept away by erosion, the Keweenawan series coming directly against the southern complex. It is marked off from the underlying granitic and gneissic rocks on the south and the Keweenawan series on the north by great unconformities.

The major features of the topography of the district are dependent upon the relative resistance of the formations. The strike of the harder formations largely controls the direction of the ridges. Extending along the southern border of the Huronian rocks is a prominent ridge, the crest of which in the western and eastern parts of the district is formed by the iron-bearing formation and in the central part of the district by the granitic rocks of the Archean. The Keweenawan igneous rocks north of the Huronian mark a second distinct ridge, the so-called Trap Range. Between these ridges, in the central two-thirds of the district, the soft Tyler

[a] For further detailed description of the geology of this district see Mon. U. S. Geol. Survey, vol. 19, and references there given.

slate constitutes level tracts and swampy areas between the more resistant rocks to the south and north.

The major lines of drainage are almost directly transverse to the ridges. All the important streams of the district rise in the basement complex, traverse the entire Huronian series, and break through the Keweenawan Trap Range to the north on their way to Lake Superior. Thus there are many notches in the east-west ridges. The elevation of the major portion of the district is between 1,400 and 1,600 feet, but a few points reach an altitude of 1,700 or 1,800 feet.

ARCHEAN SYSTEM.

GENERAL STATEMENT.

The Archean rocks comprise the Keewatin series (greenstones and green schists) and the Laurentian series (granites and gneisses), the latter being intrusive in the former. When the relations were first appreciated for the Gogebic district the term "Mareniscan" was applied to the greenstones and green schist series.[a] At that time it was not known that the rocks named "Mareniscan" are equivalent to the Keewatin series of the Lake of the Woods district. Inasmuch as the relations between the Keewatin and the Laurentian were worked out by Lawson for the two series of the Lake of the Woods before the term "Mareniscan" was proposed, Keewatin has precedence over "Mareniscan" as a general term.

KEEWATIN SERIES.

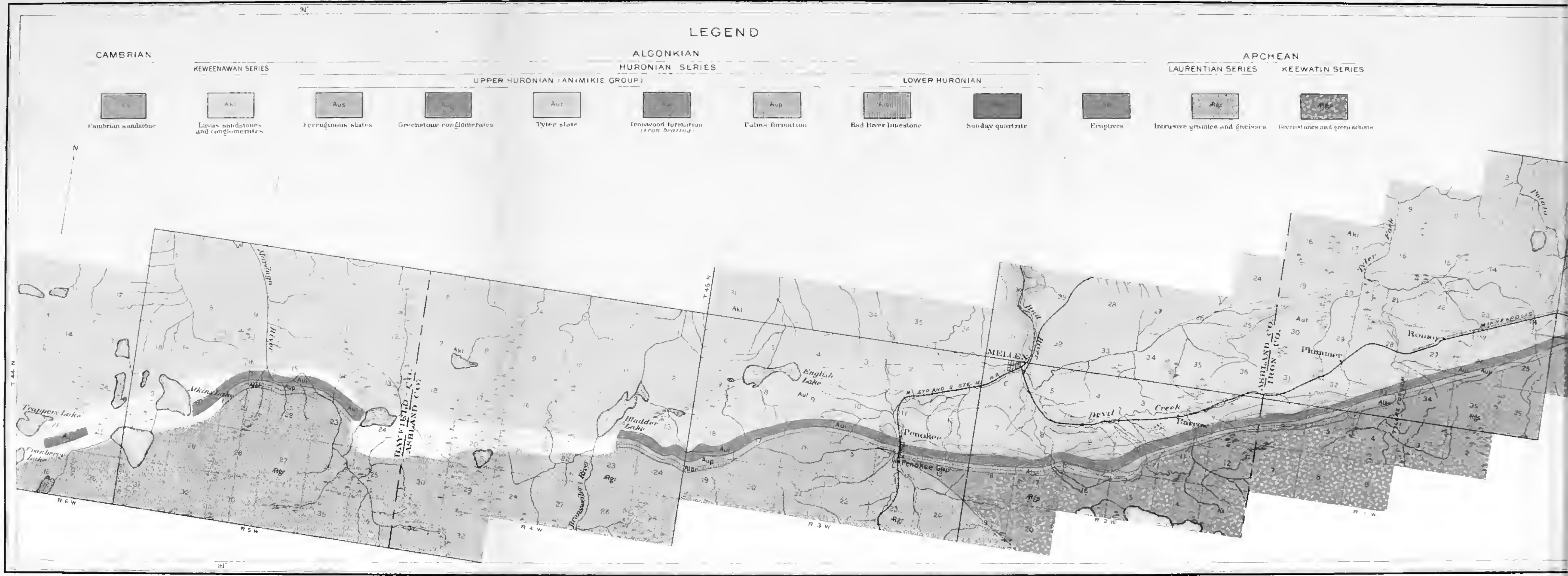
The Keewatin rocks are found in two principal areas, one in the central and the other in the eastern part of the district. They are mainly schistose basalts, for the most part fine grained and compact. The strikes and dips of the schistosity vary greatly, in this respect contrasting strongly with the strikes and dips of the beds of the Huronian sediments. The chief mineral constituents of the Keewatin are quartz, a variety of feldspar, hornblende, and biotite, with chlorite, magnetite, sericite, and epidote as subordinate constituents, although locally any one of these latter minerals may be very abundant. In places the schists have a banded appearance and are true gneisses. For the most part the Keewatin schists are completely crystalline and are allied to igneous rather than sedimentary rocks. Indeed, when the Gogebic district was mapped no material was anywhere found which could be asserted to be sedimentary, although patiently searched for. However, west of Sunday Lake a biotite schist was found which was stated to present in thin section a "strong fragmental appearance." Later work has shown that south and east of this lake some of the material is banded, weathers white, and appears to be true slate. It seems clear that here there is sedimentary material, but it is difficult to draw a line between the sediments and the greenstones. It is to be noted that the area in which the sediments are found is 2 miles from the Laurentian granite.

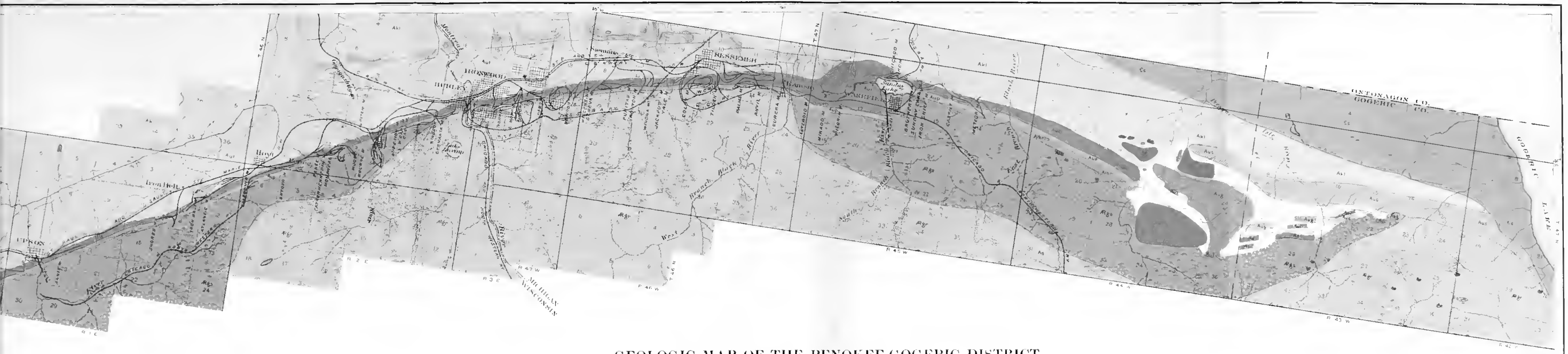
The existence of iron formation is reported in the Keewatin area near Marenisco. This, presumably, is analogous to the iron formation belts so common in the Keewatin in other parts of the Lake Superior region. It has not been examined by the authors.

LAURENTIAN SERIES.

The Laurentian granite occurs in three large areas—in the western, central, and eastern parts of the district. The granites of these areas, like all the other granites of the Laurentian of the Lake Superior region, vary greatly in chemical composition, mineral content, and structure. In general, in the district under discussion the granites are of a somewhat acidic type. However, in the central area, besides the granites there are syenites and even gabbros, and the three rocks seem to grade into one another. Structurally the granites range from rocks which have comparatively little schistosity to those which in general are strongly gneissoid. Aside

[a] Bull. U. S. Geol. Survey No. 86, 1892, p. 490.


LEGEND
CAMBRIAN
ALGONKIAN
ARCHEAN
KEWEENAWAN SERIES
HURONIAN SERIES
UPPER HURONIAN (ANIMIKIE GROUP)
LOWER HURONIAN
LAURENTIAN SERIES
KEEWATIN SERIES
Cambrian sandstone
Lavas, sandstones and conglomerates
Ferruginous slates
Greenstone conglomerates
Tyler slate
Ironwood formation (iron bearing)
Palms formation
Bad River limestone
Sunday quartzite
Eruptives
Intrusive granites and gneisses
Greenstones and green schists
Trappers Lake
Cranberry Lake
Atkins Lake
English Lake
Bladder Lake
MELLEN
Penokee
Penokee Gap
Devil Creek
Plummer
BAYFIELD CO.
ASHLAND CO.
IRON CO.
R 6 W
R 5 W
R 4 W
R 3 W
R 2 W
T 44 N
T 45 N



GEOLOGIC MAP OF THE PENOKEE-GOGEBIC DISTRICT

WISCONSIN-MICHIGAN

By C. R. Van Hise and R. D. Irving

(Revised to January 1, 1909)

Scale approximately

Contour interval 20 feet

1909

from the various feldspars and quartz, the most abundant minerals are the micas and hornblende. There are other subordinate minerals, of which magnetite and chlorite are important. In the dominant, more acidic phases of the rocks the alkaline feldspars, comprising orthoclase, microcline, and acidic plagioclase, are invariably the chief constituents and in many places compose as much as three-fourths of the rock. The gneissoid varieties of the Laurentian may be in part metamorphosed forms of granite. Correlative with the structural changes are important mineralogical changes. The most interesting is that by which the feldspars alter into biotite and quartz. Where this process has gone far little or no feldspar remains, this mineral being replaced by a finely crystalline interlocking mass of quartz and biotite. This results in a somewhat coarsely crystalline feldspathic rock (normal granite), changing into a finely crystalline gneissoid biotite-quartz rock. It is interesting to note that identical changes of a feldspathic fragmental rock in the Tyler slate have formed a mica schist.

RELATIONS OF KEEWATIN AND LAURENTIAN SERIES.

The fact has already been mentioned that the Laurentian granites intrude the Keewatin schists. It is characteristic for the district that with approach from the Keewatin rocks to the contact of the Keewatin with the Laurentian granite the former rocks become coarser and finally grade into coarse gneisses, not very different from granitoid gneisses. In many places the granites are found to cut through the schists in dikes and stocks. Indeed, there is between the two series usually a zone of considerable breadth in which the two rocks are in approximately equal proportions. In placing the boundary line between the series on the maps the plan has been to include in the Keewatin all those rocks the hand specimens of which do not have a strong granitic appearance. The relations between the two are plainly those which so characteristically obtain between the Laurentian and Keewatin. The former rocks are batholithic intrusions in the latter and have cut them intricately. Along the border the granites have profoundly metamorphosed the Keewatin, producing marked exomorphic effects, so that the most altered varieties of schists approximate the character of the granite.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER HURONIAN.

The lower Huronian in the Penokee-Gogebic district is represented only by the Sunday quartzite and the Bad River limestone.

SUNDAY QUARTZITE.

Lithology and distribution.—The Sunday quartzite is so named because of its exposures east of Sunday Lake. It may prove to be the same as the Mesnard quartzite of the Marquette district, but in the absence of definite proof that it is the same formation the new name Sunday is here introduced for it. The only known exposures of the formation are those a short distance east of Little Presque Isle River and those near the Newport mine. The former are rather extensive and the latter are small. Probably this quartzite is coextensive with the Bad River limestone, although it is not usually exposed. Wherever the Bad River limestone occurs there is room between it and the underlying Archean for the Sunday quartzite to be present. East of Presque Isle River the formation is mainly quartzite, with a thickness of at least 150 feet. Below the quartzite is a basal conglomerate, the fragments of which are largely derived from the immediately underlying Keewatin schists. This conglomerate for the most part is but a few inches thick, but in places it has a thickness of 10 feet. The dip of the quartzite is about 30° N. Near the Newport mine the Sunday quartzite is represented by a thin belt of conglomerate clinging to the face of the granite. This conglomerate contains different kinds of granite, porphyry, and various basic rocks. From the relations of this conglomerate to the Palms formation it is believed to be the equivalent of the conglomerate east of Presque Isle River.

Relations to adjacent formations.—The relations of the Sunday quartzite to the underlying formations, and especially to the Keewatin east of Presque Isle River, show that there is a great unconformity between them. The actual contact between the two is beautifully exposed for some distance. The schistosity of the Keewatin abuts against the bedding of the quartzite at various angles up to perpendicular. The Keewatin had been formed, metamorphosed, and denuded before the deposition of the conglomerate. The Sunday quartzite grades upward into the Bad River limestone.

BAD RIVER LIMESTONE.

Distribution.—The Bad River limestone is so named because of its occurrence at Bad River in the Penokee Gap section. The formation is present at several localities in the western part of the district, at one place in the central part, and in one area in the eastern part. The eastern area shows the most extensive exposures of the district, the formation here being continuous for several miles. Wherever the formation is found it strikes approximately parallel to the formations of the upper Huronian, and the dip is always to the north, being as high as 70° or 80° in the western part of the district and as low as 30° in the eastern part.

Lithology.—The formation is called a limestone because that is the predominant rock. The limestone is heavily magnesian and in places approaches a dolomite. It commonly bears silicates, of which tremolite is the most abundant, but chlorite and sericite are not uncommon. The rock is very siliceous. The coarsest varieties of the silica are quartz, but chert is more common. In many places the silica is closely intermingled with the dolomite. In other places it occurs in bands varying from a fraction of an inch to a much greater width, and in one place a band of siliceous material 45 or 50 feet wide was observed. Thus the chert and limestone are intermingled and interstratified. The cherty limestone is a water-deposited sediment. Whether the original carbonate was of chemical or organic origin we have no definite evidence, but there is no more reason to suppose that life was not concerned in the deposition of this cherty limestone than of those of later age.

Metamorphism.—The Bad River limestone has been much metamorphosed since its deposition. During its metamorphism the silica recrystallized. It was concentrated into bands. It was rearranged into veinlike forms. During these changes a part of the silica may have been introduced from an extraneous source or at least from parts of the formation now removed by erosion. The abundant tremolite is evidence that the metamorphism took place under deep-seated conditions when the silica united with the calcium and magnesium to form silicates, the carbon dioxide being released at the same time. This is an anamorphic change which took place with decrease of volume.

Relations to adjacent formations.—The relations of the Bad River limestone to the Sunday quartzite have already been considered. It is probable that everywhere it grades down into this formation, but whether it does so or not the distribution of the limestone at various places along the southern border of the Huronian, with a strike parallel to the upper Huronian, thus contrasting strongly with the varying strikes and dips of the green schist and gneisses, leaves no doubt that between the Archean and the Bad River limestone there is a great unconformity. Indeed, as chemical sedimentation at several points for a distance of 60 or 70 miles followed so promptly after the burial of the southern complex below the sea, it appears probable that when the limestone was laid down the Archean was reduced to an approximate plane. The lack of continuity of the limestone formation is due to the erosion which took place after its deposition before the lowest member of the upper Huronian was laid down. Evidences of this erosion are given under the description of the relations of the Palms formation to adjacent formations. If formations later than the Bad River limestone belonging to the lower Huronian were deposited, they were removed by erosion before the deposition of the upper Huronian, as was the larger part of the Bad River limestone itself. The limestone above the quartzite in the western area has a thickness of at least 200 feet, and to the west the thickness is not less than 300 feet.

UPPER HURONIAN (ANIMIKIE GROUP).

GENERAL STATEMENT.

The upper Huronian comprises the Palms, Ironwood, and Tyler formations. These formations extend continuously from Presque Isle River, east of Sunday Lake, several miles west of Bad River. They constitute a northward-dipping monocline. This monocline has various minor plications which give local variations to the strikes and dips, but they are neither abrupt nor large, the extreme variations in strike usually being between N. 60° W. and N. 60° E. At various places there are cross faults, the most notable of which are those at Penokee Gap, with a throw of at least 900 feet, at Potato River, with a throw of 280 feet, and west of Sunday Lake. Detailed studies of the iron-bearing formation, made in connection with the exploitation of the iron ore, show the presence of very numerous small transverse faults as well as numerous longitudinal faults, with hades parallel to the bedding, or nearly so. The latter were detected by the displaced dikes. Part of the faulting was prior to Keweenawan extrusions because it does not displace the Keweenawan. A notable instance of this appears in the great transverse fault just west of Sunday Lake. Other faults are clearly post-Keweenawan, for they affect both Huronian and Keweenawan beds.

PALMS FORMATION.

Distribution.—The Palms formation is given this name because it occurs in typical development south of the Palms mine. It comprises the lowest of the upper Huronian rocks of the Penokee-Gogebic district.

It constitutes a well-marked zone traceable through its entire extent, except in the volcanic area at the east end. It strikes on the average about N. 70° E. Its dip is everywhere north, varying from about 40° to 75°, the usual dips being between 55° and 65°. For the larger portion of the district the formation is 400 to 500 feet thick, but east of Sunday Lake it is thicker, the maximum being 800 feet.

Lithology.—The Palms formation consists of three members, of which the lowest is a thin layer of conglomerate, the central and dominant mass of the formation is a clayey slate, and the uppermost is a quartzite. The conglomerate is generally less than 10 feet thick and in many places is not more than 1 to 3 feet. The quartzite layer at the top is about 50 feet thick. The conglomerate varies with the character of the rock with which the Palms formation is in contact. Where it is next to the Bad River limestone, as would be expected, there are in it very abundant fragments of chert and limestone, but with these are also granite, gneiss, and schist from the Archean. Where the contacts are with the Keewatin, as at Potato River and the west branch of Montreal River, the dominant fragments of the conglomerate are derived from the schist. Where the formation is in contact with the granite, as in the central part of the area, the dominant fragments are from this formation, but in places—as, for instance, south of the Palms mine—with these fragments there are also pebbles of jasper, chert, and quartz.

The central part of the formation is a pelite. It has many facies, varying from fine-grained clayey slates through novaculites to graywackes. For the most part the alterations through which the pelite has gone are mainly metasomatic ones, such as quartz enlargement and the alteration of the feldspar to other minerals, especially biotite, chlorite, and quartz. In the western part of the district the feldspathic alteration and recrystallization are sufficiently important so that in places the rocks have become chloritic and biotitic slates. This greater metamorphism is doubtless connected with the intrusions so characteristic of this part of the district. For the most part there seems to be lithologic correspondence of the main mass of the slate with the immediately underlying Archean rocks, the slate being substantially the same whether north of the Keewatin schists or north of the Laurentian granite.

The upper part of the formation is a psammite which has been indurated by the process of cementation to a clean, typical, vitreous quartzite. As this quartzite approaches the overlying iron-bearing formation it becomes stained with oxide of iron and at the contact it is commonly of a deep brownish-red color.

Relations to adjacent formations.—In giving the relations of the Palms to the inferior formations it is necessary to consider separately its relations with the Bad River limestone of the lower Huronian and with the Archean.

The fact that where the belt of conglomerate at the base of the Palms formation lies above the Bad River limestone it bears much detritus from that limestone shows that the limestone after deposition became indurated and was eroded before Palms time. In general, the strikes and the dips of the two formations are approximately parallel, as are those of correlated formations in the Menominee district, but it is plain that the erosion was sufficient to remove the major portion of the Bad River limestone and also any later formations that may have been deposited in the lower Huronian. The lack of marked discordance in the bedding of the Bad River limestone and the Palms formation is no evidence that the time gap between the two was not long enough to have produced a pronounced discordance elsewhere, for the Penokee district at this time may have been distant from areas of important folding and thrusting which elsewhere may have occurred.

Between the Palms formation and the Archean there is a great unconformity. The proofs of this unconformity may be summarized as follows: First, the Palms formation and the other sedimentary formations of the upper Huronian strike with considerable uniformity across the country, being here in contact with one variety of the Archean, there with another, everywhere keeping their course, nowhere being penetrated or interfered with by any of the Keewatin or Laurentian rocks, whether schists, gneisses, or granites. Second, the Archean rocks are either massive ones which are presumably igneous or schists and gneisses in which the extreme of foliation and crystalline character is found, whereas the overlying upper Huronian rocks are plainly water-deposited sediments. Third, in a dozen places or more above the Archean are basal conglomerates or recomposed rocks which show the unconformable contacts. The detritus in each place is dominantly the same in character as the rock on which it rests. Where the inferior rock is granite it must be inferred that deep erosion must have exposed it at the surface prior to the deposition of the conglomerate. Where the basement rocks are Keewatin green schists their foliation had been developed and has been truncated before Palms time. This is well illustrated at Potato River, where the conglomerate contains large, flat fragments of green schists which have their schistosity lying parallel to the bedding of the Palms, which is at right angles to the schistosity of the Keewatin below. Fourth, the horizons of the upper Huronian with which the Archean is in contact are within a zone not more than 300 or 400 feet thick at most. This is the clearest sort of evidence that the underlying rocks were reduced to a peneplain before the beginning of the deposition of the Palms formation. From the foregoing fact it is clear that the break between the Palms formation and the Archean is profound. It included the time represented by the unconformity between the lower Huronian and the Archean, the time required for the deposition of the lower Huronian, and the time between the lower Huronian and the Palms formation.

IRONWOOD FORMATION.

Distribution.—The Ironwood formation was given this name from the fact that near the town of Ironwood it is well developed, and in this vicinity occur the more important mines. The formation is coextensive in its distribution with the underlying Palms formation. Its strike and dip are conformable with those of the Palms. The belt for the greater part of the district has a breadth of 800 to 1,000 feet. West of Sunday Lake the surface width of the formation is greater[a] and north and east of Sunday Lake the belt is narrower. Faults cross and follow the beds. These affect the distribution of the ores and the iron-bearing formation, as described on page 237. The average thickness of the formation is about 850 feet. In the extreme eastern part of the district, where volcanic action prevailed through much or all of upper Huronian time, the Ironwood formation is broken into thin and impure belts. West of Sunday Lake it is divided into two or more belts by intercalated quartzite and quartz slate beds. In other parts of the district, notably near Upson, the formation is divided by slate layers. In the main, in the western part of the district, except for the gaps where the streams

[a] Recent work seems to show this widening to be due to pre-Keweenawan overthrust folding and faulting from the west.

break through it, the Ironwood formation is a continuous ridge, and it was this range which first attracted the attention of explorers at Penokee Gap and vicinity. In the central part of the district the formation is softer and the prominent features are made by the Archean rocks to the south. Still farther east, beyond Sunday Lake, the Ironwood formation again constitutes prominent bluffs.

Lithology.—The Ironwood is the iron-bearing formation of the district. In the memoir on the Penokee iron-bearing series (Monograph XIX) it was simply called the iron-bearing formation, without a geographic name. The greater portion of the formation contains more than 25 per cent metallic iron and there are considerable thicknesses in which the amount of iron averages 37 per cent. (See p. 238.) The ore bodies contain a higher percentage of iron.

The Ironwood formation consists of four main varieties of rock—(1) slaty and commonly cherty iron carbonate and ferrodolomite, (2) ferruginous slates and ferruginous cherts, (3) actinolitic and magnetitic slates, and (4) black slates.

The iron-bearing carbonates are usually found only near the upper part of the formation, where they have been protected by the Tyler slate. The ferruginous slates and ferruginous cherts are characteristic of the central iron-producing part of the district, and the actinolitic and magnetitic slates are characteristic of the western and eastern parts of the district. The latter also form a belt 20 to 300 feet wide bordering the Keweenawan rocks on the north. In the intermediate areas there are of course gradations between the ferruginous slates and ferruginous cherts and the actinolitic and magnetitic slates, as there are also gradations between the cherty iron carbonates and the ferruginous slates and ferruginous cherts. Black slates form thin intercalated layers in the iron-bearing formation. Quartzite is also found in layers up to 100 feet thick well up from the base of the formation near Sunday Lake.

The slaty and cherty iron-bearing carbonates are composed largely of iron carbonate and chert, but with these materials are various amounts of calcium carbonate and magnesium carbonate. Recent reexamination has shown that in these rocks there are also subordinate amounts of greenalite. With these important constituents are other minor constituents, largely secondary, such as limonite, magnetite, carbonaceous and graphitic matter, iron pyrites, and rarely fragmental quartz. The carbonate is both fine and coarse grained and both original and secondary. Coarse-grained recrystallized carbonate is especially abundant near the contact of the Keweenawan in the Sunday Lake area.

The cherty iron-bearing carbonate was the original rock of the iron formation. The origin of this class of rock is fully discussed in another place (pp. 499 et seq.) and therefore the subject will not be considered here. From it the ferruginous cherts and actinolitic cherts have been produced. The actinolitic and magnetitic cherts were formed under deep-seated conditions largely through the influence of the Keweenawan intrusive rocks, and especially of the great western laccolith. These changes are anamorphic ones, which mainly took place in Keweenawan time. The ferruginous slates and ferruginous cherts formed from the cherty iron carbonates by katamorphic changes largely in the belt of weathering and also in part in the belt of cementation. These changes were mainly post-Keweenawan, after erosion brought the iron-bearing formation to the surface, and they have continued to the present day. Previously formed actinolitic and magnetitic rocks were in a much more refractory condition than the unaltered cherty iron carbonates and have been little affected by the alterations of the zone of katamorphism.

The ferruginous slates and ferruginous cherts have silica as their predominant constituent in various forms of crystallization, from amorphous through partly crystalline and chalcedonic material to finely crystalline quartz. With the silica are the various oxides of iron. Hematite and brown hydrated hematite are especially prevalent. Limonite is common and some magnetite occurs. Where the hematite is in large quantity, to the exclusion of the hydrous oxides, the rocks are genuine jaspers; but this variety is rather unusual in the district. The rocks vary in their stratification from the regular lamination of a slate to irregularity. In many places the laminæ have the appearance of having been disrupted and recemented.

The actinolitic, grüneritic, and magnetitic cherts and slates, like the rocks of the second variety, have quartz as their dominant constituent. This quartz is crystalline throughout and clearly nonclastic. The actinolite varies in amount from a very little to a constituent of great prominence. The iron oxides are mainly in the form of hematite and magnetite.

The black slates are carbonaceous fragmental slates in layers in the iron-bearing formation. These exceptionally form the foot wall of the ore deposits. (See p. 242.)

Relations to adjacent formations.—The Ironwood formation rests conformably upon the Palms formation. The change from the clastic quartzite to the nonclastic iron-bearing formation is astonishingly abrupt. Generally it can not be said that there is any evidence of the transition between them. Locally a thin conglomerate marks the contact. For some reason the clastic deposits of the quartzite ceased and the nonclastic deposits of the Ironwood formation began. Above, the Ironwood formation passes gradually into the Tyler slate.

TYLER SLATE.

Distribution.—The Tyler slate was given its name from the typical occurrence of the formation along Tylers Fork. It extends from a point about 6 miles west of Bad River nearly to Sunday Lake—that is, it is confined to the central two-thirds of the district. In breadth the formation varies up to 2½ miles at Tylers Fork. The strike of the formation is parallel to that of the iron-bearing formation below. Its dip is also similar to that of the iron formation. At this wider part its dip is from 70° to 75°. It apparently follows, therefore, that for the central part of the district—that is, from Bad River to Montreal River—this formation has a thickness ranging from 7,000 to 11,000 feet. It is plainly the great formation of the district. It is probable that minor plications partly explain this apparent thickness.

Lithology.—Study of the formation as a whole shows that it is dominantly a pelite but locally it is a psammite, including both arkoses and feldspathic sandstones. There is a general connection between the character of the rocks to the south and those of the slate belt adjacent. The greater part of the belt has received its material in part from the granitic and in part from the schistose areas; the part of the belt west of Penokee Gap has received nearly all its material from the syenitic granite to the south and west. The different varieties of rocks of the Tyler slate may be grouped under three heads—(1) mica schists and mica slates; (2) graywackes and graywacke slates; (3) clay slates or phyllites. Each of these main types has the various phases shown by the following tabulation:

Mica schist and mica slate:	
Micaceous	Muscovitic. Biotitic. Muscovitic and biotitic.
Micaceous and chloritic	Chloritic and biotitic. Chloritic and sericitic or muscovitic.
Graywacke and graywacke slate:	
Micaceous	Biotitic. Biotitic and muscovitic.
Micaceous and chloritic	Chloritic and biotitic.
Chloritic	Chloritic. Magnetitic and chloritic. Ferruginous and chloritic.
Clay slate	Chloritic. Chloritic and magnetitic.

It is not necessary to describe in detail the different varieties of these rocks, except as to their alterations.

Metamorphism.—In the monograph on the Penokee iron-bearing series the alterations of this slate are discussed.[a] It is there shown that each of the varieties of rocks mentioned above has developed from pelites and psammites almost wholly by metasomatic changes within the formation itself, without the addition or subtraction of material from an extraneous source.

[a] Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 332–345.

In general, the eastern part of the formation is less altered than the western part. Here the prevailing rocks are clay slates, graywackes, and graywacke slates. From the central to the western part of the district the rocks become more crystalline, and at the extreme west end, especially west of Penokee Gap, only mica slates and mica schists are found. Where the rocks are much metamorphosed cordierite is sparingly developed.

The parts of the Tyler slate which contain large fragmental particles of quartz are those in which the clastic character is easiest to recognize, for the grains of quartz everywhere remain in their entirety. It may be and indeed it is usually true that they have undergone a second growth and have thus become angular; but generally the original cores are easily discovered. In the nearly pure feldspar sediments, on the other hand, where the feldspar has changed to other minerals, it is more difficult and in specimens of the most crystalline mica schist impossible to make out the original fragmental character of the rock.

On the whole, the major modifications of the formation are those of the zone of anamorphism rather than the zone of katamorphism. This is what would naturally be expected, for at the time these alterations took place the rocks were buried to an unknown depth below the overlying Keweenawan rocks.

As the processes by which a clastic rock alters into a fine-grained crystalline mica schist were first described in detail with regard to the Penokee-Gogebic district,[a] the principles involved in the development of this particular rock will be summarized here. As already indicated, the sediments from which the mica schists were derived were very feldspathic. Without going into details, the process which has resulted in the development of mica schists has been the alteration of the feldspar into mica, both muscovite and biotite, with the simultaneous separation of quartz. For the change into muscovite the feldspar itself contains all the necessary constituents. For the change into biotite a certain amount of iron and magnesium are necessary. For the iron it is not so difficult to account, as the sediments are ferruginous. In some places also the sediments contain more or less carbonate, and doubtless from this source has been derived at least a part of the necessary magnesium. At the time of the recrystallization the newly forming mica flakes developed with a parallel arrangement. At the same time the quartz recrystallized. The total result was to produce from a somewhat coarsely crystalline arkose a finely laminated mica slate or mica schist.

The Penokee-Gogebic district is an exceptionally good one in which to work out the changes from the little-altered pelite to a mica schist, because of the very gradual change in the amount of alteration in passing from the central to the western part of the district.

At the time the Penokee-Gogebic monograph was written no reason was assigned for the crystalline character of the rocks at the west end of the district. Later studies on metamorphism have led us to connect this alteration with the great laccolith of the Keweenawan gabbro, which, in the western part of the district, occurs in contact with and cutting the Huronian rocks. The intrusion of this rock essentially parallel to the bedding would result in great pressure, as well as in raising the temperature, and it was under these conditions that the recrystallization took place. The absence of similar alterations in the central and eastern parts of the district is explained by the fact that there immediately overlying the slate are the surface Keweenawan lavas, which are locally interstratified with sandstones. It is plain that the alterations of the pelites to mica slates and mica schists took place in Keweenawan time.

Relations to adjacent formations.—The Tyler slate rests conformably on the iron-bearing Ironwood formation. It is overlain unconformably by the rocks of the Keweenawan series.

UPPER HURONIAN (ANIMIKIE GROUP) OF THE EASTERN AREA.

In the eastern part of the district—that is, from about 6 miles east of Sunday Lake to Gogebic Lake—the upper Huronian rocks have an exceptional character. In the larger part of the district the conditions were those of quiet sedimentation, but in this eastern area

[a] Van Hise, C. R., Upon the origin of the mica schists and black mica slates of the Penokee-Gogebic iron-bearing series: Am. Jour. Sci., 3d ser., vol. 31, 1886, pp. 453–459.

throughout the greater part of the upper Huronian there was continuous volcanic action. In consequence the rocks are lava flows, volcanic tuffs, conglomerates, agglomerates, and slates, with all sorts of gradations, just such as one would expect if a volcano arose in a sea and volcanic action continued for a great period. Naturally in this area it is not possible to map any continuous sedimentary belts. The dominant rocks are greenstone conglomerates and lavas and massive eruptives. The uppermost formation for the extreme eastern part of the area is a ferruginous slate. This ferruginous slate, though dominantly clastic, contains narrow bands of nonclastic sediments, such as chert, cherty ferrodolomite, ferrodolomitic chert. It is believed that the ferruginous slate is probably at the same horizons as the Ironwood formation to the west and that its dominant fragmental character is due to the presence in this area of one or more volcanic mountains which rose above the water and upon which the waves were at work after the close of the period of active volcanic outbreaks.

KEWEENAWAN SERIES.

GENERAL DESCRIPTION.

Rocks of the Keweenawan series lie north of and are coextensive with the upper Huronian rocks; indeed, to the west they extend far beyond the westernmost known outcrop of the Huronian. It is not the purpose here to describe this series more than is sufficient to show its relations to the Huronian. It has already been indicated that for most of the district the appearance of the Keweenawan is marked by a distinct range known as the Trap Range. For the eastern part the Keweenawan rocks first encountered in traveling north are ordinary basic, amygdaloidal lava flows characteristic of that series. One bed follows upon another and it is easy to ascertain their strike and dip. These bedded lava flows may be very conveniently seen adjacent to Sunday Lake. Their strike and dip are easily determinable as almost exactly parallel to the beds of the underlying Huronian.

In the central part of the district the Keweenawan rocks immediately above the Tyler slate are sandstones and conglomerates. These are seen in Michigan north of Bessemer and in Wisconsin a few miles west of the State boundary. Above the sedimentary beds of the lower Keweenawan follow lavas similar to those which occur farther east.

In the western part of the district the sediments and bedded lavas of the Keweenawan are replaced by the great plutonic basal gabbro laccolith of Wisconsin, analogous to the laccolith of the north shore of Lake Superior.

RELATIONS TO ADJACENT SERIES.

The Keweenawan series reposes upon the upper Huronian (Animikie group) unconformably. As the two series are nearly conformable in strike and dip, this fact was only slowly appreciated. The proof of the unconformity rests entirely upon broad field relations. In the central part of the district the Keweenawan is upon a great slate formation (the Tyler slate) which has a maximum thickness of at least several thousand feet. At the east and west ends of the district the Keweenawan cuts diagonally across these slates and comes into contact with the iron-bearing Ironwood formation. In the west end of the district this relation might be supposed to be explained by the intrusion of the Keweenawan laccolith, but this can not apply to the eastern part of the district, for there the lower beds of the Keweenawan are the surface lava flows. The time gap between the Huronian series and the Keweenawan series must have been sufficient for a widespread orographic movement and deep denudation.

As the Keweenawan series is largely composed of igneous rocks and rests upon the Huronian series, naturally the latter has been extensively intruded by the former. The intrusives in the Huronian series, so far as known, are mainly dolerites. Considerable masses of them in the eastern and western ends of the district appear to follow roughly parallel to the range and seem to be intruded sheets or laccoliths. Some of them may be surface flows contemporaneous in origin with adjacent Huronian sediments. In addition to these intercalated masses, numerous dikes cut the Huronian formations. These dikes are found in all formations, but they have an especial significance and importance in connection with the iron ore. (See pp. 235–238.) In that part of the district which has been the seat of mining operations a large number of these dikes cut the containing formations perpendicularly to the bedding. That these dolerite dikes are the avenues through which have passed from deep within the earth the vast amount of material which formed the overlying basic volcanic flows of the Keweenawan series of the Trap Range to the north can hardly be doubted, for in chemical composition the lavas of this range are practically identical with the dikes. (See pp. 404–405.) In general, the dolerite dikes are very fresh, except in the lower parts of the Ironwood formation, where they have been subject for a long time to the action of percolating waters. Analyses of the latter rocks show that they have undergone extensive changes, which have been referred to in connection with the origin of the iron ores.

By far the greatest of the intrusive masses is the great gabbro laccolith at the west of Bad River. This was at first supposed to be a great basal flow, but all their later studies lead the writers to believe that it is a plutonic intrusive introduced comparatively late in Keweenawan time, the major dimensions of the intrusion being nearly parallel to the beds of the Huronian and the lava flows of the Keweenawan, which were separated by the inwelling mass of gabbro.

CAMBRIAN SANDSTONE.

The Cambrian sandstone is found only in the northeastern part of the district, near Gogebic Lake. It is there found as a flat-lying reddish sandstone, known as the Lake Superior sandstone. It rests in horizontal position against the Keweenawan, the Huronian, and the basement complex. In one place a basal conglomerate bears detritus from all the lower formations. It is plain that during and after Keweenawan time the Huronian and Keweenawan series were turned up steeply. Lofty ranges, which must have been formed then, were removed by denudation, and the Cambrian sandstone was deposited. Therefore a great unconformity separates the Cambrian sandstone and all the earlier series.

THE IRON ORES OF THE PENOKEE-GOGEBIC DISTRICT.

By the authors and W. J. Mead.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The iron-ore deposits occupy part of the district, extending from a point about 2 miles east of Sunday Lake in Michigan to within 4 miles of Potato River in Wisconsin, a distance of about 26 miles. Ore has recently been developed in sections 15 and 21, T. 47 N., R. 43 W., near Gogebic Lake, far to the east of the previously known deposits.

The iron-ore deposits constitute about 1 per cent of the area of the iron formation. This percentage is less than that in the Mesabi, which is 8 per cent. However, the vertical dimensions are much greater than in the Mesabi district. Ores have already been found to extend to a depth of 2,500 feet, one of the largest ore bodies in the district now being known at that depth.

In both the east and west ends of the Gogebic district the character of the formation has been influenced by intrusives, with the result that the iron oxides are largely magnetite disseminated through the formation and not concentrated to a commercial extent.

The ore deposits come to the surface most largely along the north-middle slopes, locally on the lower slopes, of the topographic feature known as the Gogebic Range.

In the Gogebic district the iron-bearing Ironwood formation dips with the other formations of the upper Huronian toward the north at angles averaging about 65°. The underlying rock is the quartzite, at the top of the Palms formation, and it thus forms the foot wall of the iron-bearing formation; the overlying formation is the Tyler slate. Slate and quartzite also form interbedded layers in the iron-bearing formation. Numerous greenstone dikes of Keweenawan age cut the entire series in such a manner that the intersection of the dikes with the bedding usually pitches to the east. The intersections of the dikes with impervious layers, principally quartzite of the foot wall, but also slate layers within the iron-bearing formation, constitute eastward-pitching troughs at angles from 15° to 30°, in which most of the deposits are found (fig. 28).

Westward-pitching dikes intersecting with eastward-pitching dikes or continuous with them, and both intersecting foot-wall quartzite, form canoe-shaped basins for the ore, as illustrated by the Aurora, Pabst, and Newport deposits. East of the Bessemer the main dike in the Tilden mine has an eastward pitch and the main dike in the Palms mine has a westward pitch.

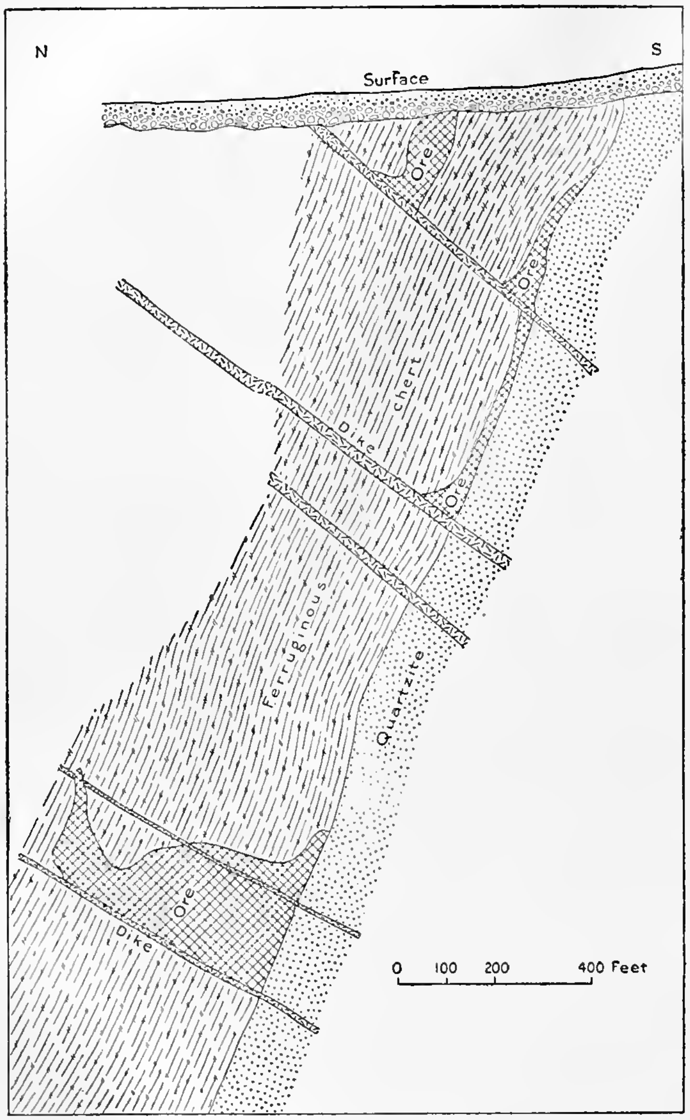


FIGURE 28.—Cross section showing the occurrence of ore in pitching troughs formed by dikes and quartzite foot wall, in the Gogebic district. Made up from mine plats and slightly generalized.

On the south the foot wall of the ore is therefore generally quartzite, locally slate, and on the north the ore rests against greenstone dikes. Slate foot walls are seen at the Iron Belt, Mikado, Brotherton, and Sunday Lake mines, from 250 to 2,000 feet north of the quartzite foot wall.

The ore deposits are generally sharply defined along the foot walls and the dike rocks, but in many places vary upward by imperceptible stages into the ferruginous cherts of the iron-bearing Ironwood formation. Where there are a number of parallel dikes, one below the other, there may be several ore bodies one below another—as, for instance, at the Ashland and Norrie mines. (See fig. 29, *a* and *b*.) After many years of mining on upper dikes in the Newport mine one of the largest deposits of the district has been found on a lower dike. The main Norrie dike is over 30 feet thick. The main Aurora-Pabst-Newport dike is from 20 to 25 feet thick. The main Colby dike is over 90 feet thick. Where a strong dike breaks into many stringers at a depth, as in the Colby mine, the ore body is also likely to be broken up and become small and perhaps worthless. The dike rocks are altered to soapstone or paint rock along their contacts with the ore by the leaching of the bases.

An ore deposit is likely to have its maximum depth in the apex of a trough, and from this apex a belt of ore may extend to the north along the dike and to the south along the foot wall. In many instances the ore bodies follow the foot walls almost exclusively, as at the Norrie mine. (See fig. 29, *c*.) Usually where the deposits follow both the quartzite and dikes the former is larger and more continuous than the latter. Where an ore deposit follows both it may divide before reaching the surface into two parts separated by rock, called the south and north veins of the mines, but where such deposits are traced below the surface they unite into a single body. The ore grades above or laterally into the ferruginous chert or ferruginous slate.

The conspicuous association of the ores with pitching troughs formed by the intersection of dikes and foot-wall quartzite for a considerable time obscured the importance of fracturing in localizing the ore deposits. From evidence now available it seems likely that this factor also is of great consequence. An examination of mine sections taken almost at random in the district shows ore cutting through the ferruginous cherts and dikes in a most irregular way and quite independent of the pitching troughs. Much of it may be directly connected with brecciation, fissuring, or faulting to be seen in the ore and adjacent rocks. It is altogether likely that more fractures exist than are known, because the concentration of the ores is of a nature to obscure evidences of them. There are fault planes both parallel with and intersecting the bedding. The displacements have both horizontal and vertical components. The faults intersecting the bedding were first recognized because of the ease of detecting the displacements in the bedding. Those parallel to the bedding were for a long time not observed, and probably there are still many to be detected because of the difficulty of distinguishing the evidence. They may be determined only from the displacements of the dikes, and as the dikes are numerous and of varying thickness a considerable amount of ground must be opened up before the various fractured dikes may be correlated. The ore in many places lies between the displaced edges of the dike. At the Pabst mine the ore follows down over the broken and displaced ends of the faulted dike toward another dike below, where it again develops into a large body.

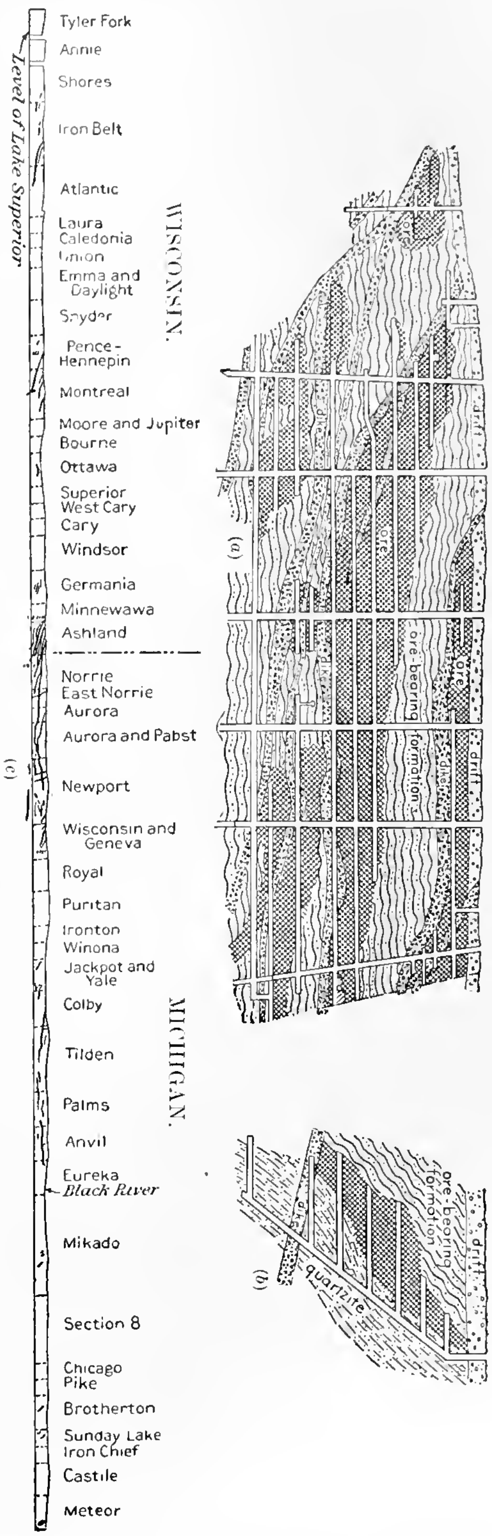


FIGURE 29.—Ore deposits of the Penokee-Gogebic district. Both ore exploited and ore now in mine are represented as ore, as the purpose of this figure is to show the manner of the development of the ore rather than the present stage of exploitation.

a. Vertical east-west longitudinal section of Ashland mine, showing relation of ore deposit to eastward-pitching dikes and manner in which ore and a lower dike may make their way under a higher dike, there being rock capping between. As shown by the figure, the ore extends to the drift upon the upper dikes, but does not on the lower dikes. The bodies of ore resting upon the upper dikes are comparatively thin. The main body of ore is on a lower dike. Below the main mass of the deposit ore is found on still lower dikes. It is highly probable that the quantity of ore upon the upper dikes was far greater in preglacial time than at present and that a large amount has been lost through glacial erosion. Between the outcrops of the successive dikes are feeding areas. The water entering at one of these areas formed an ore deposit upon the dike below. This to the east passes below a higher dike. Scale: 1 inch=200 feet. From plat furnished by W. J. Olcott.

b. Vertical north-south cross section of Norrie mine at No. 7 shaft, showing relations of ore to adjacent rocks. This ore deposit is one of the greatest in the Gogebic district. As shown by the figure, the quartzite is the foot wall, a strong dike is at its base, and the ore-bearing formation constitutes the hanging wall. The figure shows that the ore extends to the drift. Scale: 1 inch=400 feet. From Newett's Mines and mineral statistics of Michigan, Lansing, 1896, page 78.

c. Vertical longitudinal east-west section parallel with the Gogebic range, showing the intersections of the principal dikes with the foot wall. Note the prevalence of eastward pitch. Vertical dotted lines are property boundaries. Scale: 1 inch=15,500 feet, approximately. Compiled from map of L. E. Paddack, 1904.

Another important factor governing the location of the ore deposits has only recently been clearly recognized. Certain of the iron formation layers were originally richer in iron than others, and the ores show a distinct tendency to follow these rich original beds. In some deposits, like those of the Mikado, Brotherton, and Sunday Lake mines, this seems to be a controlling factor, though the ores of the Brotherton and Sunday Lake mines and less certainly of the Mikado mine have suffered more or less secondary concentration along intersections of dike and foot wall and along fissures.

CHEMICAL COMPOSITION OF THE FERRUGINOUS CHERTS AND ORES.

The following analyses represent two complete sections through the iron-bearing formation. In the Norrie mine a crosscut, extending from foot-wall quartzite to the hanging-wall slate, entirely in ferruginous chert, was sampled in five samples, each sample representing approximately 120 feet of crosscut. In the Atlantic mine a crosscut in ferruginous chert extending for several hundred feet across the formation was sampled. Anaylses are by Lerch Brothers, Hibbing, Minn.

Partial analysis of ferruginous chert, Gogebic range.

[Samples dried at 212° F.]

	Fe.	SiO_2.	P.	Al_2O_3.	Volatile matter.
Norrie mine No. 1	35.33	43.78	0.143	1.54	1.42
Norrie mine No. 2	23.39	61.22	.034	.71	.85
Norrie mine No. 3	30.03	51.80	.037	1.09	1.48
Norrie mine No. 4	27.62	54.57	.046	1.78	1.67
Norrie mine No. 5	26.81	54.62	.074	1.94	1.64
Atlantic mine	29.26	52.67	.037	.88	2.89
Average	28.74	53.11	.062	1.32	1.66

It is believed that this average represents closely the true average composition of the unaltered ferruginous cherts.

A large part of the ferruginous cherts shows partial alterations to ore. An average of 490 analyses, representing 5,890 feet of drilling in this phase of the formation, which is probably nearer to the true average of the formation, is 36.65 per cent.

The average composition of the Gogebic ores for the years 1906 and 1909, calculated from average cargo analyses for each grade, each analysis being weighted in proportion for the tonnage represented, is given in the following table:

Average composition of ore mined on the Gogebic range in 1906 and 1909.

	1906	1909
Moisture (loss on drying at 212° F.)	11.21	11.30
Analysis of dried ore:		
Iron	60.35	59.62
Phosphorus	.051	.060
Silica	6.58	8.16
Alumina	1.93	1.92
Manganese	.76	.77
Lime	.40	.37
Magnesia	.233	.28
Sulphur	....	.034
Loss by ignition	2.81	2.82

Range in percentage of each constituent in Gogebic ores mined in 1909, as shown by average cargo analyses.

Moisture (loss on drying at 212° F.)	4.51 to 15.75
Analysis of dried ore:	
Iron	43.70 to 63.40
Phosphorus	.027 to .206
Silica	4.07 to 23.52
Alumina	.58 to 3.29
Manganese	.20 to 7.20
Lime	0 to .87
Magnesia	.01 to .79
Sulphur	.006 to .022
Loss on ignition	.56 to 5.80

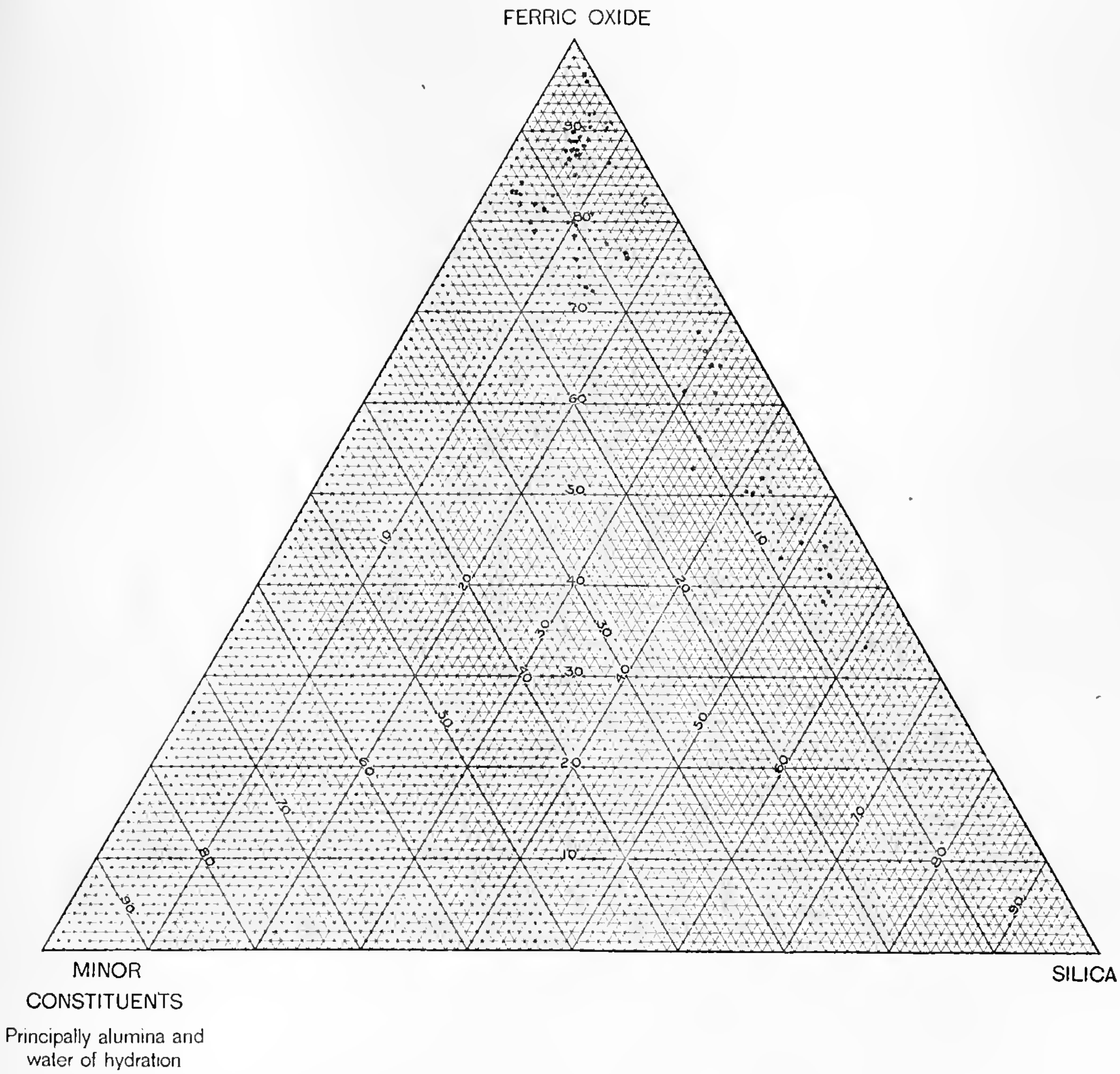


FIGURE 30.—Triangular diagram showing chemical composition of various phases of Gogebic ores and ferruginous cherts in terms of ferric oxide, silica, and minor constituents (essentially alumina and combined water). These analyses include all of the ores and cherts shown in figure 32 and also a number of additional analyses.

In figure 30 the triangular method of platting is employed to show the chemical composition of the various phases of the chert and ore studied. (See p. 182 for explanation of diagram.)

MINERALOGICAL COMPOSITION OF THE FERRUGINOUS CHERTS AND ORES.

The approximate mineral composition of the ores and cherts was calculated from the chemical analyses, as follows:

Approximate mineral composition of average ferruginous chert and average ore of the Gogebic range.

	Average chert.	Average ore.	
		1906	1909
Hematite (including a small amount of magnetite)	34.00	73.50	77.25
Limonite (other hydrated iron oxides calculated as limonite)	8.20	14.70	9.30
Quartz	51.63	4.31	5.81
Kaolin	3.35	4.89	4.70
Other minerals	2.82	2.60	2.94
	100.00	100.00	100.00

PHYSICAL CHARACTERISTICS.

GENERAL APPEARANCE.

The iron ore of the Gogebic district is a soft red, somewhat hydrated hematite. Much of it is so friable that it can be broken down with a pick, although as taken from the mines a large portion of it is compact enough to hold together in moderately large lumps. These lumps are porous, many of them more or less nodular, and many also roughly stratiform. The strata conform in a general way to the strike and dip of the iron formation. Mingled with this soft hematite in a few mines is a small quantity of aphanitic hard steel-blue hematite, which breaks with conchoidal fracture and is of remarkable purity. In general, this exceptionally hard material is found in contact with or close to the diorite dikes of the mines.

DENSITY.

The specific gravities of the ores and cherts were determined by the two general methods already discussed (see p. 184)—(*a*) calculated specific gravity obtained by properly combining the specific gravities of constituent minerals; (*b*) actual determinations by gravity methods. The specific gravities of the minerals as used in determining the mineral specific gravity of the ore or chert are as follows: Hematite, 4.5 for earthy ores and chert, 5.1 for crystalline and hard ores; limonite, 3.6; kaolin, 2.62; quartz, 2.65.

The average mineral density of all ore mined in 1906, calculated from the above mineral analysis, is 4.33.

Following are six analyses of ferruginous cherts and ores with specific gravities determined by both methods, as a check on the accuracy of determination:

Density of individual cherts and ores determined by calculation and by measurement.

Chemical composition.							Mineral composition.				Specific gravity.	
Fe.	SiO_2.	P.	Al_2O_3.	Volatile matter.	Mn.	Moisture of saturation.	Hematite.	Limonite.	Quartz.	Kaolin.	Calculated from analyses.	Determined by pycnometer.
3.30	87.91	0.007	6.81	0.41	0.15	3.70	4.71	....	79.91	17.25	2.73	2.68
30.30	48.34	.027	6.30	1.53	.50	9.30	43.30	....	43.24	10.95	3.38	3.38
43.20	32.88	.022	4.40	1.55	.45	3.35	61.70	....	27.70	11.13	3.80	3.805
46.80	29.83	.015	1.32	1.08	.85	10.50	63.30	4.21	28.28	3.34	3.83	3.89
52.00	12.59	.029	7.40	5.43	.25	7.15	57.70	19.38	3.89	18.72	3.89	3.90
63.40	4.00	.078	2.94	1.78	.70	10.50	86.20	5.24	.54	7.45	4.79	4.74

POROSITY.

Porosity was determined on hand specimens by the usual method of saturation in water described on page 185. An average of ten determinations on typical specimens of ferruginous chert gave 4.1 per cent pore space. The average of the porosity of all the ores examined was approximately 34 per cent.

CUBIC CONTENTS.

The ores vary in cubic content from 7.5 cubic feet to the ton in the small masses of pure steel ore to 14 cubic feet in the softest yellow ores. The average calculated for the 1906 output is approximately 10.75 cubic feet to the ton.

TEXTURE.

The average texture of the Gogebic ores is shown by the following table of screening tests. These were made by the Oliver Iron Mining Company and represent all of the ores mined by that company in the Gogebic district in 1909. Samples of the different ores were taken twice a week, quartered down each month according to the tonnage shipped, and at the end of the shipping season quartered to 100 pounds of dry ore, on which the tests were made. The following table represents 10 grades of ore, totaling 1,256,557 tons. The texture of the ore is seen to be similar to that of the ores of the Marquette district. A comparison of the textures of the ores of the several Lake Superior districts is shown in figure 72, page 481.

Textures of Gogebic ores as shown by screening tests.

	Per cent.
Held on ½-inch sieve	28.97
¼-inch sieve	32.30
No. 20 sieve	16.08
No. 40 sieve	8.32
No. 60 sieve	4.03
No. 80 sieve	2.56
No. 100 sieve	1.89
Passed through No. 100 sieve	5.92

MAGNETITIC ORES.

At the extreme east and west ends of the Gogebic range the iron-bearing formation consists of dark-gray, green, or black dense crystalline banded rocks, consisting of magnetite, quartz, amphiboles, and other silicates in varying proportions in different bands and different localities. Ore deposits are rare or altogether lacking. For a discussion of reasons for this condition see pages 552–553. The average chemical composition of these rocks is as follows:

Analyses of magnetitic rocks.[a]

Fe_2O_3	44.606
FeO	13.811
SiO_2	34.616
Al_2O_3	.588
CaO	1.802
MgO	2.166
MnO	1.158
P_2O_5	.018
S	.083
H_2O	.997
	99.845
Metallic iron	41.95

[a] Mon. U. S. Geol. Survey, vol. 19, 1892, p. 197.

When this composition is compared with that of the ferruginous cherts of the Gogebic district it is apparent that there is but little difference between the two.

SECONDARY CONCENTRATION OF GOGEBIC ORES.

STRUCTURAL CONDITIONS.

The ores of this district are probably localized in bands of the iron formation which were originally rich in iron, but for most of the district secondary concentrations have so masked the primary distribution in bands that the evidence for it is not clear. Probably the clearest case is in the Mikado, Brotherton, and Sunday Lake mines, where the ores seem to follow certain originally rich horizons in the iron formation, the later concentration apparently not having seriously modified their distribution.

The secondary alterations of the iron-bearing beds are accomplished (1) by waters following the pitching trough formed by the intersection of the dikes with impervious quartzite or slate beds below the iron formation layers, and (2) by following fissures or bedding planes independent of the dikes. The control by the dikes is by far the most conspicuous one for the district as a whole. The movement of the concentrating waters is in general eastward toward lower levels, following the eastward pitch of the troughs formed by the intersection of the dikes with foot-wall quartzite or exceptionally foot-wall slate. The waters may thus be brought beneath other dikes. This explains the common occurrence of ores on several dikes one below the other. The movement of the water is controlled to an important degree by bedding planes, by faults, and by joints, and where so controlled the ores are more or less independent of the dikes and foot wall. The control by faults is especially well shown in one locality where faulting parallel to the bedding has displaced the ends of a dike and the ore follows over the broken end of the dike along the fault plane, obviously a zone followed by percolating waters. Faults and joints may give an eastward pitch of the ore bodies, for many of the fissures along which alteration takes place pitch in the same direction as the dikes; in fact, the dikes have been intruded along fissures of this kind. That some fissures were there before the intrusion of the dikes is shown further by the fact that the iron formation near Sunday Lake has been displaced by faulting, whereas the Keweenawan igneous beds to the north, with which the dikes are genetically connected, have not been displaced. These early fissures also preceded the Keweenawan folding. If fissures were present in the rocks before the dikes, there is no reason why some concentration should not have been prior to the intrusion of the dikes in the east and west ends of the district, where the cover of slate was not too great to prevent ingress of water; but evidence of this would be extremely difficult to detect because of later alterations since the dikes were intruded.

The greatest depth to which the waters, and therefore the ore concentration, may be carried by the eastward-pitching troughs or by the fault and joint planes is yet unknown. Large ore bodies have been found to a depth of more than 2,500 feet; one of the largest deposits thus far found in the district was recently developed at this depth. Theoretically the depth of concentration is a function of the head determined by the height of the erosion edge of the iron formation and the lowest point of escape; but the difficulty is to determine where the latter point is, for reasons stated above. Even if the head were known, there would be difficulty in calculating the effective depth of the circulation because the medium through which it is flowing is not homogeneous. Further, if the depth of the active circulation could be worked out within reasonable limits, this would give us only the maximum depth of the ore deposits, for it might well be that the waters do not carry oxygen abundantly to the maximum depth to which they penetrate.

Theoretically the concentration of the ore should be more effective on the middle slopes of the hills, because these would be places where descending waters are effective, whereas valleys are places where the waters are ascending unless prevented by other structural conditions, and not so effective for the purposes of ore concentration. It is unlikely that each of the cross valleys should have the same control of the circulation, and it is difficult to tell which of the valleys has been most effective. Also it is to be remembered that the pitch of the dikes to the east is greater than the surface slope and that therefore the underground waters, where passing under a valley, would be prevented from escaping by the overlying impervious dikes, except where faulting would allow the waters to come through. Mining operations actually disclose artesian flows through dikes, as at the Germania mine. Also, ascending waters are actually observed to follow faults across the dikes, as in the Newport mine. From anything that is now known to the contrary, the faults in the dikes may be sufficiently numerous to allow upward escape of the water somewhat freely along the cross valleys at the surface. This is especially likely in view of the fact that the cross valleys are observed to have developed along fault planes. These planes must cut the dikes, though some of them are not observed to do so. The cross valley under such conditions is simply the surface expression of the weak faulted zone. It is therefore not to be expected that there is a close relation to be observed between the topography and the distribution of the ores. The ore deposits extend below both elevations and minor valleys, but at some of the principal cross valleys ore deposits are small or lacking. For illustration, ores extend abundantly under Montreal River at Ironwood, but east of the Newport mine these ores seem to end at a pronounced cross depression northwest of Bessemer, through which Black River flows. It is thought by James R. Thompson, formerly manager of the Newport mine, that the drainage for the Ironwood-Newport group of mines is probably carried eastward and escapes through this channel.

ORIGINAL CHARACTER OF THE IRON-BEARING FORMATION.

Originally the iron-bearing formation consisted largely of cherty iron carbonate interlayered with sideritic slates and possibly also with banded chert and ferric hydrates. (See p. 231.) Some layers were probably richer than others. The alteration of the cherty iron carbonates to ore has been accomplished in the general manner already described as typical for the region—(1) oxidation and hydration of the iron minerals in place, (2) leaching of silica, and (3) introduction of secondary iron oxide and iron carbonate from other parts of the formation. These changes may start simultaneously, but change 1 is usually far advanced or complete before changes 2 and 3 are conspicuous. The early products of alteration, therefore, are ferruginous cherts—that is, rocks in which the iron is oxidized and hydrated and the silica is not removed. The later removal of silica is necessary to produce the ore.

ALTERATION OF CHERTY IRON CARBONATE TO FERRUGINOUS CHERT.

Chemical change.—The alteration of cherty iron carbonate to ferruginous chert involves the oxidation of iron according to the following reaction:

$$2FeCO_3 + nH_2O + O = Fe_2O_3.nH_2O + 2CO_2.$$

Mineral change.—The cherty iron carbonate is practically identical mineralogically with the sideritic cherts of the Mesabi range. The constituent minerals are segregated into alternate layers of siderite and chert. The oxidation of the siderite involves a change to a heavier mineral. Either introduction or removal of silica may accompany this change.

Volume change.—The volume involved in the alteration indicated in the above equation is a loss of 49.25 per cent, considering the resulting iron oxide to be anhydrous. If hydration of the iron oxide takes place, the volume reduction is smaller in proportion to the degree of hydration, being only 18.3 per cent when the product is limonite. Approximately 60 per cent of the volume of the cherty iron carbonate is silica; therefore the reduction in volume caused by the oxidation of the iron is effective on approximately only 40 per cent of the volume of the rock. The loss in volume, then, for the entire rock, taking into account both iron and silica, ranges from 17.2 per cent to 6.4 per cent, depending on the degree of hydration of the resulting iron oxide.

Development of porosity.—The decrease in volume, due to the alteration of the iron minerals, develops pore space in the resulting ferruginous chert. Determinations of porosity on several typical specimens of cherty iron carbonate showed an average of less than 1 per cent pore space.

A series of ten determinations on typical specimens of ferruginous chert gave a range of 0.9 to 8 per cent pore space, with an average of 4.1 per cent. Evidently the actual porosity is not sufficient to account for the theoretical volume change. This may be explained in the following ways: (*a*) Part of the iron oxide in the ferruginous chert may have been original and not altered from siderite. As the calculated pore space is based on the assumption that all of the iron oxide in the ferruginous chert is the result of the oxidation of siderite, original ferric oxide in the chert would decrease the resulting pore space. (*b*) Infiltration of iron oxide or silica subsequent to or accompanying the alteration may have closed part of the openings formed. This is certainly true to at least a small extent, as shown by microscopic examination of thin sections. (*c*) The difficulty of obtaining saturation and perfect drying in the determination of porosity in the specimens of ferruginous chert may have made the results too low. (*d*) In the rocks under discussion, both original and secondary, the iron minerals tend to be segregated in parallel layers separated by comparatively barren chert. The volume changes in the alteration of the iron minerals would then be largely confined to the ferruginous layers. If these are assumed to be practically pure iron mineral, the cubical shrinkage should vary between 49.25 per cent and 18.3 per cent (as previously calculated) for the different original and secondary minerals noted above, the linear shrinkage between 6.5 and 20.3 per cent. The shrinkage normal to the layers would probably not result in openings to any large extent, as slumping of the flat layers would close any cavities formed, and as a matter of fact such openings are not observed. On the other hand, shrinkage parallel to the beds is taken to explain the common intersecting sets of cracks confined to the ore layers and breaking them into small parallelepiped blocks when the ore has not suffered general deformation. These by actual measurement give a volume of openings ranging from 12½ to 36 per cent of the volume of the iron layers, which would be approximately 5 to 14½ per cent of the volume of the rock.

It is believed, then, that the increase in porosity and development of cracks in the ferruginous chert, together with the slump which has obliterated a part of these openings and the infiltration of iron salts, fully accounts for the change in volume which accompanies the production of these cherts from the cherty iron carbonate.

ALTERATION OF FERRUGINOUS CHERT TO ORE.

The alteration of ferruginous chert to ore is almost identical with the secondary concentration of the ores of the Mesabi district. As in the Mesabi concentration, the essential change is the leaching of silica. The several possibilities resulting in the leaching of silica are discussed on pages 537–538. It is seen that the space left by the removal of silica may remain as pore space and may be partly or entirely closed by slump or may be filled partly or entirely with infiltrated iron oxide. To determine the relative importance of these possibilities, quantitative methods similar to those employed in investigation of the Mesabi ore were used.

In order to include the factor of porosity in a comparison of ores and cherts, it is necessary to consider their composition in terms of volume rather than of weight. The volume composition of any chert or ore is readily calculated from the mineral composition and the porosity.

The volume composition of the average ores and ferruginous cherts is as follows:

Average volume composition of ores and cherts of Gogebic range.

	Ores.	Ferruginous cherts.
Hematite	37.30	19.60
Limonite	14.98	7.23
Quartz	10.43	65.00
Kaolin	3.25	4.03
Pore space	34.00	4.10
	99.96	99.96

The above volume composition is expressed diagrammatically in figure 31. The most important factor in forming ore from the cherts, as shown by the diagram, is the removal of silica.

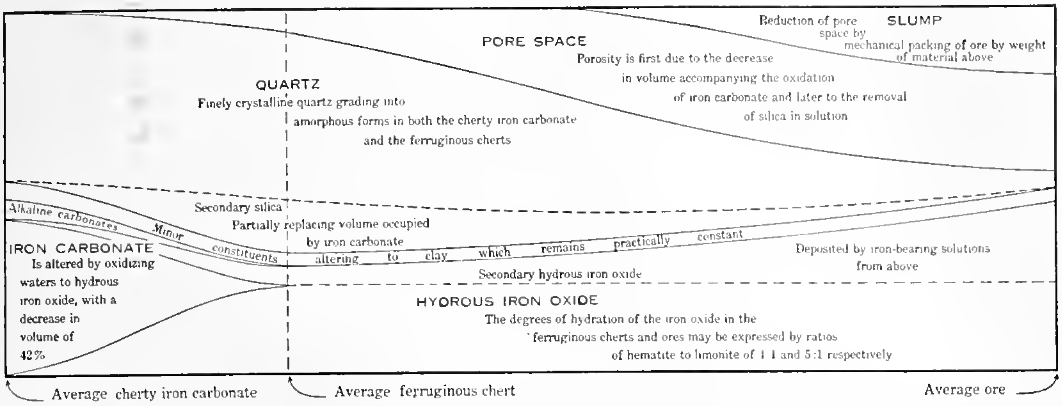


FIGURE 31.—Diagrammatic representation of the changes involved in the alteration of cherty iron carbonate to ferruginous chert and ore, Gogebic district. The mineral compositions of the various phases are indicated in terms of volume by vertical distances. The compositions of the cherty iron carbonate, ferruginous chert, and ore represented are averages of a large number of analyses.

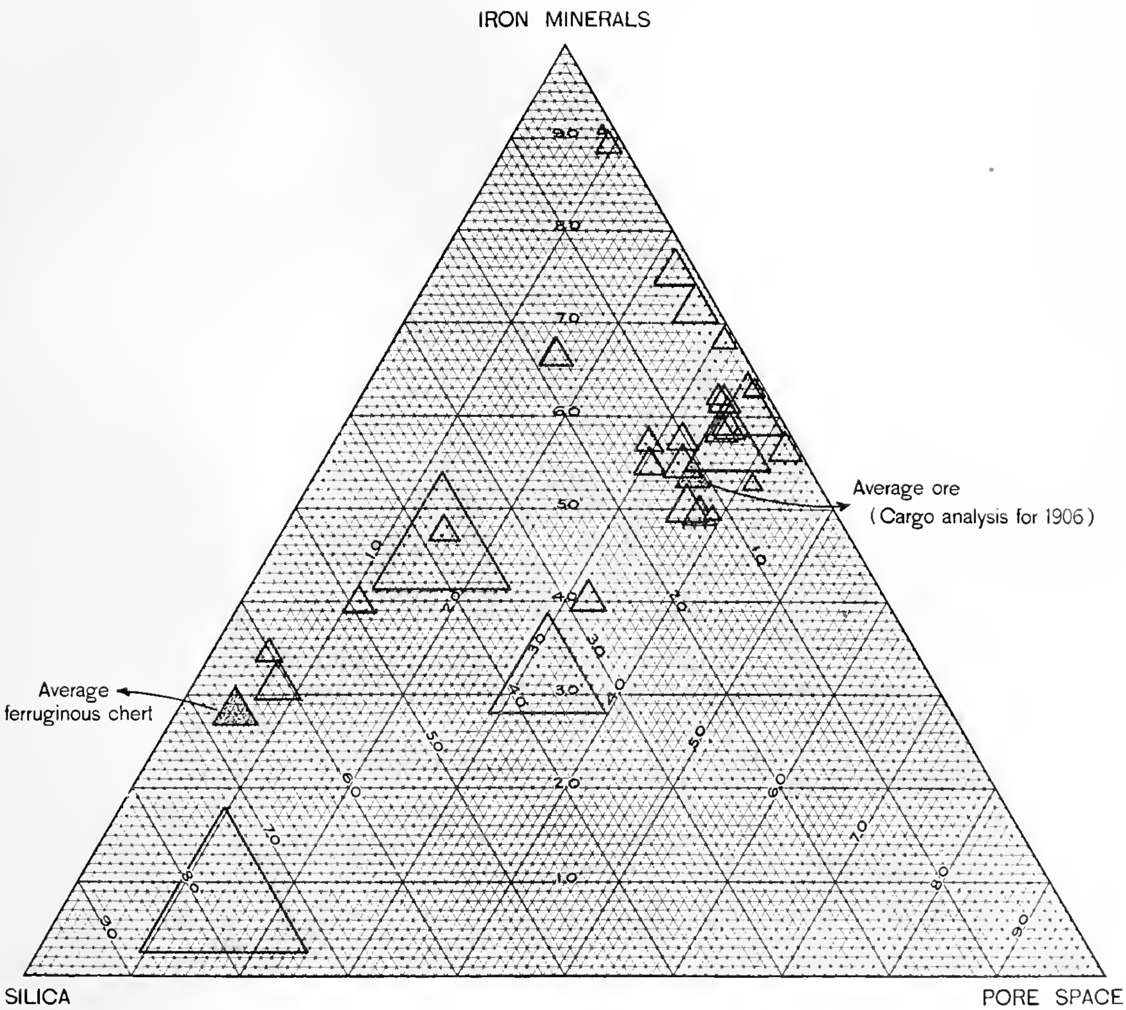


FIGURE 32.—Triangular diagram showing volume composition in terms of pore space, iron minerals, silica, and minor constituents (clay, etc.) of the ferruginous cherts and iron ores of the Gogebic range. See page 189 for discussion of method of plotting.

TRIANGULAR DIAGRAM ILLUSTRATING SECONDARY CONCENTRATION OF GOGEBIC ORES.

In figure 32 the triangular method (described on p. 189) of representing the volume relation of ferruginous cherts and ores and intermediate phases is applied to the Gogebic ores. As already explained, each small triangle within the large one represents an individual specimen and by its size and position indicates composition in terms of the volume of pore space, silica, iron minerals, and minor constituents. The average ferruginous chert, as indicated, is represented by a small triangle in the lower left-hand side of the diagram, with low pore space and a large content of silica. The average ore is represented in the upper right-hand part of the diagram, and has more pore space, less silica, and more iron than the average ferruginous chert. Scattered about in the area between these two points are intermediate phases between ferruginous chert and ore.

In the alteration of ferruginous chert to ore, as represented in the triangle, the following changes have evidently taken place: (*a*) Decrease in silica, (*b*) increase in pore space, and (*c*) increase in iron. Obviously the dominant process has been the removal of silica, as this is necessary to an increase of pore space and iron. Removal of silica alone without introduction of iron or mechanical slump would increase the porosity in proportion to the amount of silica removed. Such a process would be represented on the triangle by a series of small triangles in a line parallel to the base, as the relative volume of iron would remain constant. In the actual case known the relative volume of the iron mineral increases from 26.83 per cent in the cherts to 52.18 per cent in the ores. This could be accomplished in two ways—by mechanical slumping or packing of the material, weakened by too great a porosity, or by infiltration of iron. From the diagram it is impossible to tell which of these processes, slumping or infiltration, is more important. Observation shows, however, that slumping has been important, but that introduction of iron has taken place to a much greater extent than it did in the concentration of the Mesabi ores.

ALTERATION OF ROCKS ASSOCIATED WITH ORES DURING THEIR SECONDARY CONCENTRATION.

The various conditions and agencies which were effective in the concentration of the ore from the cherty iron carbonates and ferruginous cherts caused alterations of a similar nature in the various rocks associated with the iron-bearing formation—namely, the interbedded slates, the basic intrusive rocks, and the slates immediately overlying the iron-bearing formation. The alteration of the slates produced paint rock or ferruginous slate similar to that of the Mesabi range. The alteration of the basic dikes by oxidation of the iron, breaking down of feldspars, and leaching of soluble constituents formed a soft kaolinic product, locally termed soap rock or, if iron stained, paint rock. The following analyses of fresh and altered dike rock are typical of this alteration:

Analyses of fresh and altered dikes associated with ore.

	1 (fresh).	2 (altered).	Assuming Al_2O_3 constant.
SiO_2	47.90	46.85	32.20
Al_2O_3	15.40	22.62	15.40
Fe_2O_3	3.49	5.12	3.53
FeO	8.41	.....	.....
MgO	8.11	2.01	1.39
CaO	9.99	1.25	.86
Na_2O	2.05	.80	.55
K_2O	.23	2.66	1.83
H_2O-	.15	3.12	2.15
H_2O+	2.34	8.25	5.68
TiO_2	.82	1.12	.77
P_2O_5	.13	.16	.11
CO_2	.38	1.89	1.30

1. Specimen 12880. Unaltered diabase dike rock in iron-bearing formation, from southeast part of sec. 13, T. 47 N., R. 46 W., Michigan.
2. Specimen 12878. Altered diabase dike. Same locality as No. 1.

A comparison of the two analyses on the assumption that alumina has remained constant (see third column in the table) shows a loss of silica, iron, magnesia, lime, soda, phosphorus, and titanium and a gain in potassa, water, and carbon dioxide. Except for the behavior of potassa, the alteration is typical of weathering under conditions of oxidation, carbonation, and hydration.

Specific gravity and porosity determinations on the specimens analyzed resulted as follows:

Specific gravity and porosity of unaltered and altered phases of diabase.

	Specific gravity.	Porosity.
Unaltered diabase	2.92	0.50
Altered phase of diabase	2.76	28.40

On the basis of the specific gravities and the assumption that alumina is constant, the calculated porosity due to leaching of soluble constituents is 27.1 per cent of the volume $\left(1.00-\frac{15.60}{22.62}\times\frac{2.92}{2.76}=0.271\right)$, which agrees very well with the actual determinations of porosity, and also denotes the approximate correctness of the assumption that alumina is constant.

The approximate mineral composition of the fresh and altered diabase, calculated from the analyses, is as follows:

Mineral composition of fresh and altered diabase.

	Unaltered diabase.	Altered phase of diabase.
Feldspars	51.00	6.82
Ferromagnesian minerals	40.00	....
Quartz	1.00	17.00
Calcium-magnesia carbonates	.90	4.00
Apatite	.31	.38
Magnetite	5.34	....
Ilmenite	1.50	2.13
Kaolin, chlorite, sericite, etc	....	63.00
Limonite	....	6.10
Specific gravity	2.92	2.76
Porosity	.50	28.40

OCCURRENCE OF PHOSPHORUS IN THE IRON-BEARING FORMATION.

PHOSPHORUS CONTENT.

The phosphorus content of the principal phases of the iron-bearing formation is as follows:

Phosphorus content of the iron-bearing Ironwood formation.

	Iron.	Phosphorus.	Ratio of phosphorus to iron.
	Per cent.	*Per cent.*	*Per cent.*
Cherty iron carbonate	24.51	0.026	0.001060
Ferruginous chert	28.76	.046	.001600
Iron ore	58.15	.062	.001067

The range in phosphorus content in the various commercial grades of ore produced in the district in 1906 was from 0.028 to 0.275 per cent. In the Mesabi ores the phosphorus content was found to depend to a large extent on the chemical composition of the ore, high phosphorus occurring as a rule in the more hydrous ore and in ore high in alumina. In the Gogebic ores the increase of phosphorus with the degree of hydration is not apparent, as is shown in figure 33, where the relation of phosphorus content to water of hydration is represented graphically.

The average degree of hydration of the Gogebic ores is considerably lower than that of the Mesabi ores, and the high phosphorus ores of the Mesabi range contain more water of hydration than the most hydrous of the Gogebic ores.

As in the Mesabi range, the phosphorus content of the altered slates or paint rocks and slaty ores of the Gogebic range is high. These phases are high in alumina and comprise a complete gradation from high-grade ore to ferruginous clay. The unaltered interbedded slates as a rule have a higher phosphorus content than the iron-bearing rocks proper and their alteration products are correspondingly high in phosphorus. Hence an examination of analyses shows, in a general way, an increase of phosphorus with an increase in the alumina content. The altered dikes, locally termed soap rock or paint rock, are characteristically high in phosphorus, evidently owing to the original phosphorus content of the diabase. (See analyses, p. 246.)

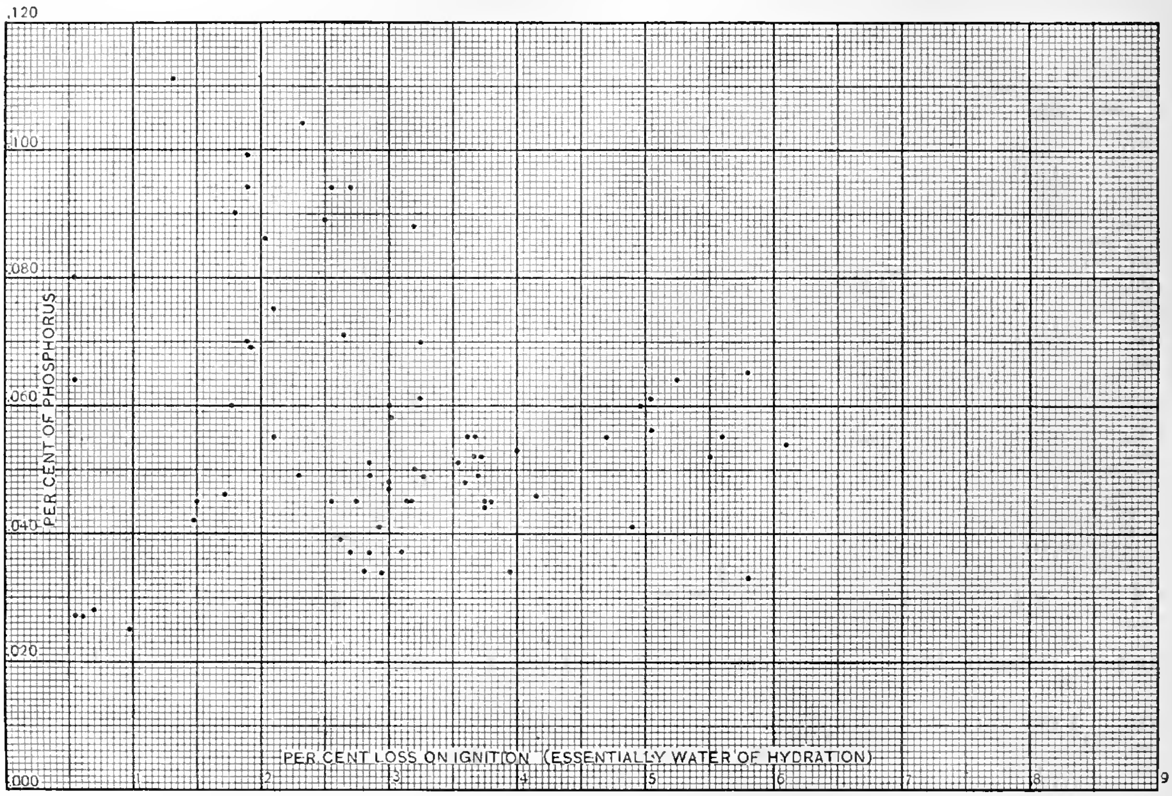


FIGURE 33.—Diagram showing relation of phosphorus to degree of hydration in Gogebic ores.

High-phosphorus ores are sometimes found immediately above the dikes and in the angle of the trough formed by a dike and the foot wall. It is not true, however, that all ore immediately overlying dikes is high in phosphorus, the opposite being true in many places.

MINERALS CONTAINING PHOSPHORUS.

The discussion of the occurrence of phosphorus on the Mesabi range (pp. 192–196) applies practically verbatim to the Gogebic range. No phosphorus-bearing minerals have been identified in the ores or cherts; hence possible occurrence of phosphorus must be inferred from chemical evidence. Figure 34 is similar to figure 23, showing the relation of phosphorus to lime and the possibility of phosphorus occurring as apatite (calcium phosphate). The diagonal dotted line indicates the ratio of the two elements in apatite. Points falling above the line indicate an excess of calcium and points below the line an excess of phosphorus. From the fact that a number of analyses show an excess of phosphorus it is to be inferred that phosphorus-bearing minerals other than apatite are present. It is highly probable that at least part of the phosphorus occurs in combination with the hydrates of iron and alumina. The extremely small percentages present make determination of these minerals practically impossible.

BEHAVIOR OF PHOSPHORUS DURING SECONDARY CONCENTRATION.

Examination of the average analyses of the cherty iron carbonates, ferruginous chert, and ore shows that the ratio of phosphorus to iron has remained practically constant during the concentration of the ores; in other words, both have been concentrated to essentially the same degree.

It was found that in the secondary concentration of the ores of the Mesabi district phosphorus was actually introduced into the ores from the overlying Cretaceous rocks known to be

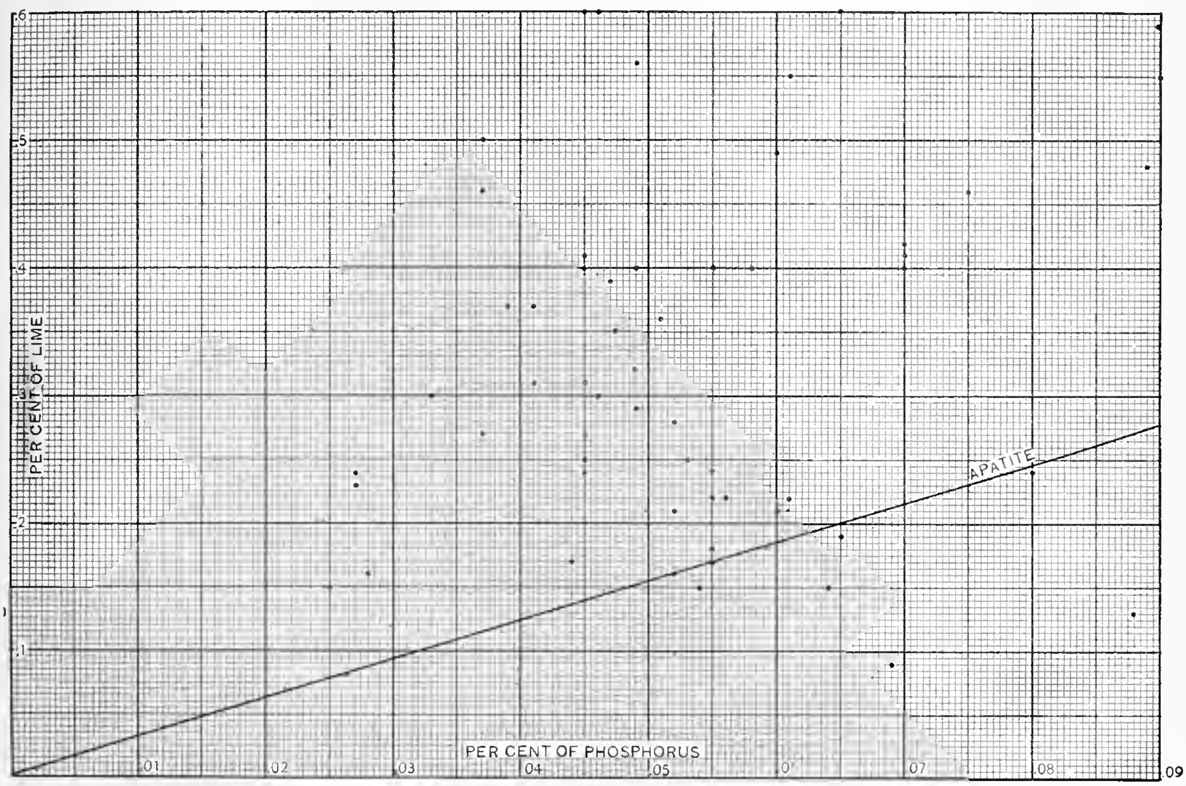


FIGURE 34.—Diagram showing relative amounts of phosphorus and lime in Gogebic ores.

high in phosphorus. The absence of a source of phosphorus such as the Cretaceous rocks of the Mesabi district may explain why phosphorus has not been concentrated to a greater degree in the iron in the Gogebic ores.

It was suggested that the hydrated portions of the Mesabi may have had some effect in causing this increase in phosphorus. The Gogebic ores are much less hydrous than the Mesabi ores, and this fact suggests a further possible explanation for the increase in phosphorus in one case and not in the other.

High-phosphorus ores commonly occur immediately above or below dikes. The dikes themselves are characteristically high in phosphorus, and, furthermore, the alteration of the dike is accompanied by a loss of phosphorus. (See analyses, p. 246.) It is possible that the high phosphorus in the neighboring ore may be directly contributed by the altering dike rock.

SEQUENCE OF ORE CONCENTRATION IN THE GOGEBIC DISTRICT.

Before the deposition of the Keweenawan series there had been a slight folding of the upper Huronian (Animikie group) containing the productive iron-bearing Ironwood formation. A gentle syncline was developed along the present productive area with its limbs at the two ends of the district. Erosion then exposed the iron-bearing formation only at the two ends of the district, leaving the central and nonproductive part still covered by a considerable thickness of slate, and soft ores and ferruginous cherts were developed along erosion surface and fissures at the east and west ends of the district to a minor extent. The Keweenawan igneous and sedimentary rocks, laid down upon this gently bowed surface, affected the underlying ferruginous cherts and soft ores at the east and west ends of the district, perhaps dehydrating them, and developed red jaspers and hard ores. The iron carbonates at these places were changed to amphibole-magnetite rocks by contact metamorphism. Igneous intrusives of Keweenawan age are more abundant at these localities than elsewhere in the district. They had no contact effect upon the iron-bearing formation in the central part of the district because it was covered by slate. Then came the great post-Keweenawan folding, resulting in the tilting of the upper Huronian iron-bearing formation (Ironwood) and Keweenawan beds in the Gogebic district to angles of 60° and 70° N. The iron-bearing formation underwent dynamic metamorphism at the east and west ends, where it constituted a comparatively thin layer between the hard rocks of its basement and those of the covering Keweenawan. The following erosion exposed not only amphibole-magnetite rocks, hard ores, and jaspers previously formed at the east and west ends of the district but exposed for the first time from beneath the Tyler slate the unaltered iron-bearing formation, consisting principally of carbonate, in the central and present productive portion of the region. The concentration of the ore for this district began at this time. It was well advanced before Cambrian time and has continued intermittently since. (See pp. 557–560.)

CHAPTER XI. THE MARQUETTE IRON DISTRICT OF MICHIGAN, INCLUDING THE SWANZY, DEAD RIVER, AND PERCH LAKE AREAS.

MARQUETTE DISTRICT.[a]

INTRODUCTION.

Although the following account of the geology of the Marquette district is based mainly on the work of the United States Geological Survey, we would express our indebtedness to Prof. A. E. Seaman, of the Michigan College of Mines, for important modifications in our ideas of the structure and distribution of the rocks. Prof. Seaman was the first to prove the existence of an unconformity between what is here called middle Huronian and the lower Huronian, both of which had been treated together as lower Huronian in the United States Geological Survey monograph on the district. He has also contributed a considerable number of corrections to the geologic map and a detailed plat of the extensive faulting near Teal Lake (Pl. XIX). The Cascade area shows considerable changes in mapping, due to the large amount of careful exploration work accompanied by geologic mapping that has been done by mining companies. We are especially indebted to Messrs. Oscar Rohn, O. B. Warren, and W. O. Hotchkiss and to the Oliver Iron Mining Company for changes in this area. Other important corrections on the Marquette map have been furnished by the work of the Cleveland-Cliffs Iron Company, Longyear & Hodge, and others.

LOCATION, SUCCESSION, AND GENERAL STRUCTURE.

The Marquette district extends from Marquette, on Lake Superior, in longitude 87° 20′, west to Lake Michigamme, in longitude 88°, a distance of somewhat less than 40 miles. The district roughly follows parallel 46° 30′. (See Pl. XVII, in pocket.) It lies wholly in Michigan and derives its name from the city of Marquette. The more important towns besides Marquette are Ishpeming, Negaunee, Champion, and Republic. The breadth of Algonkian rocks, which are the special subject of this chapter, varies from about 1 mile to more than 6 miles. From the western part of the main Algonkian area two arms project for several miles, one to the southeast, the Republic trough, and one to the south, the Western trough.

The succession of the formations for the district, from the top downward, is as follows:

Quaternary system:
- Pleistocene series.

Cambrian system:
- Upper Cambrian sandstone (Potsdam sandstone).

Unconformity.

Algonkian system:
- Keweenawan series.................... Not identified but probably represented by part of intrusives in upper Huronian.
- Huronian series:
  - Upper Huronian (Animikie group).. {Greenstone intrusives and extrusives. / Michigamme slate (slate and mica schist), locally largely replaced by volcanic Clarksburg formation. / Bijiki schist (iron bearing). / Goodrich quartzite.

[a] For further detailed description of the geology of this district see Mon. U. S. Geol. Survey, vol. 28, 1897, and references there given.

Algonkian system—Continued.	
Huronian series—Continued.	
Unconformity.	
Middle Huronian	Negaunee formation (chief productive iron-bearing formation). Siamo slate. Ajibik quartzite.
Unconformity.	
Lower Huronian	Wewe slate. Kona dolomite. Mesnard quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granite, syenite, peridotite. Palmer gneiss.
Keewatin series	Kitchi schist and Mona schist, the latter banded and in a few places containing narrow bands of nonproductive iron-bearing formation.

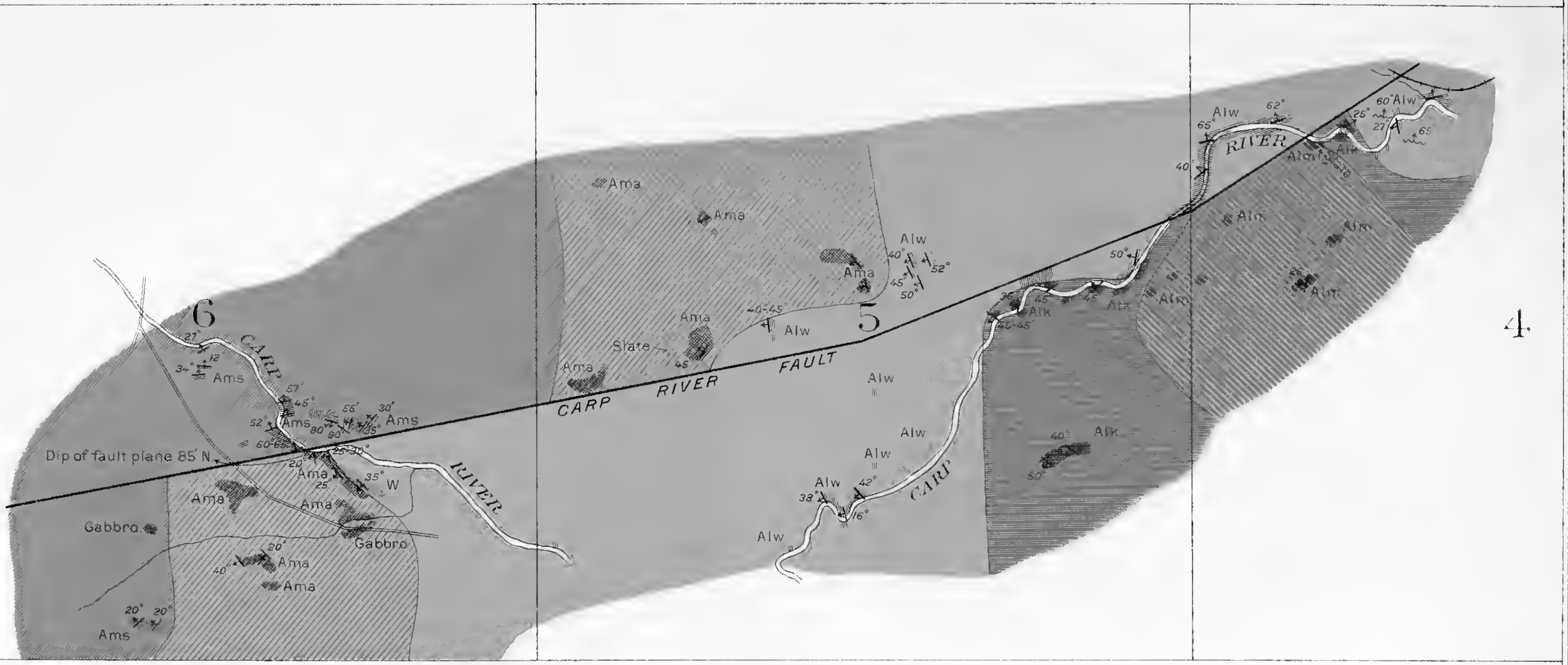
In addition to the rocks tabulated above, basic igneous rocks in many dikes and bosses, large and small, intrude all the Archean and Huronian formations.

The central and western parts of the district are bounded on the north and south by more or less continuous east-west linear ridges of Algonkian rocks. The area between these ridges is relatively low lying, with minor elevations. Also these ridges on the whole stand above the country north and south of the district. The major portion of the district is a bluffy plateau, for the most part lying between altitudes of 1,400 and 1,600 feet, but it has points that rise higher and a few points that reach an altitude of 1,800 feet. The eastern part of the plateau slopes rather steeply toward Lake Superior, and for this part of the area the altitudes of the higher points are between 800 feet and 1,000 feet. Each of the formations is locally resistant, and where in this condition constitutes bluffs. One traversing the district from north to south is almost constantly either climbing or descending a steep slope.

The drainage is largely transverse to the longer dimension of the district. Branches of Escanaba River, in the Lake Michigan drainage basin, cross the central part of the range at two places. In the eastern part of the district Carp River flows to Lake Superior in a direction roughly parallel to the strike of the rocks. In the western part of the district Michigamme Lake, the one large lake in the district, and Michigamme River are purely structural in their locations, the main arm of the lake lying east and west parallel to the strike of the district and a north arm swinging toward the south with the cross fold, which appears at this locality. Michigamme River, the outlet of the lake, follows the axis of the Republic trough and connects with Lake Michigan waters.

The Archean rocks occur in two areas, one north and one south of the Huronian series. The northern one is called the northern complex and the southern one the southern complex. In a broad way the Huronian rocks constitute a great synclinorium between the two areas of Archean. Superimposed upon the larger folds are folds of lesser orders down to minute plications. Though it is therefore clear that the folding is extremely complex from Lake Superior to Michigamme Lake, it may be said that the Algonkian constitutes a great canoe-shaped basin, which comes to a point at the east end of the district but does not at Michigamme. As a result of this, in passing from Lake Superior to the west, one comes to higher and higher formations and only reaches the highest formation of the district west of Ishpeming.

This synclinorium is of peculiar and complicated character. For much of the district the rocks in the outer borders of the Algonkian belt are in a series of sharply overturned folds. The Algonkian rocks on either side of the trough have moved up and outward over the more rigid Archean granite, and as a consequence on each side of the Algonkian trough a series of overfolds, especially in the softer slates, plunge steeply toward its axis, producing a structure resembling in this respect the composed fan structure of the Alps. There is, however, this great difference between the structure of the Marquette district and that of the Alps—that newer



MAP OF CARP RIVER FAULT, MICHIGAN

By W. N. Smith

0 ½ 1 Mile

1909

LEGEND

HURONIAN SERIES

MIDDLE HURONIAN: Ams Siamo slate; Ama Ajibik quartzite

LOWER HURONIAN: Alw Wewe slate; Alk Kona dolomite; Alm Mesnard quartzite

Strike and dip

Symbols show outcrops

rocks appear near the axis of the trough rather than older ones, as if composed fan folds of Alpine type were sagged downward into a synclinorium. The structure also differs from the inverted intermont trough of Lapworth. It may be called an abnormal synclinorium.[a] (See fig. 35.) This structure prevails in the central part of the area from Ishpeming and Negaunee westward to Clarksburg, but it does not extend to Lake Superior on the east nor to Lake Michigamme on the west.

Although the more conspicuous folds of the district have in general an east-west axis, the rocks have also been under strong east–west compression, as a consequence of which the folds are buckled so that many of them show a steep pitch. In places the north-south folds become more prominent than the east-west folds and control the prevalent strikes and dips. This is illustrated by the western trough, at the west end of the district. In certain areas in the southeastern part of the district the compression has been about equally great in both directions, producing most irregular strikes and dips.

Minor fracturing in the district has been pervasive, as will be explained in succeeding pages, but only at a few localities are there faults so extensive that they have been detected in the mapping of the formations. Of these major faults, three at least are of very considerable displacement, all in the eastern part of the district, one of these being the Carp River fault (Pl. XVIII) and the other two in the Cascade area. A number of less important faults occur in the quartzite east of Teal Lake (Pl. XIX).

The lower Huronian, comprising the Mesnard quartzite, the Kona dolomite, and the Wewe slate, is confined to the eastern third of the district. At the time these rocks were deposited either the western part of the district was not submerged or else the erosion following this period removed the rocks before the deposition of the succeeding middle Huronian beds.

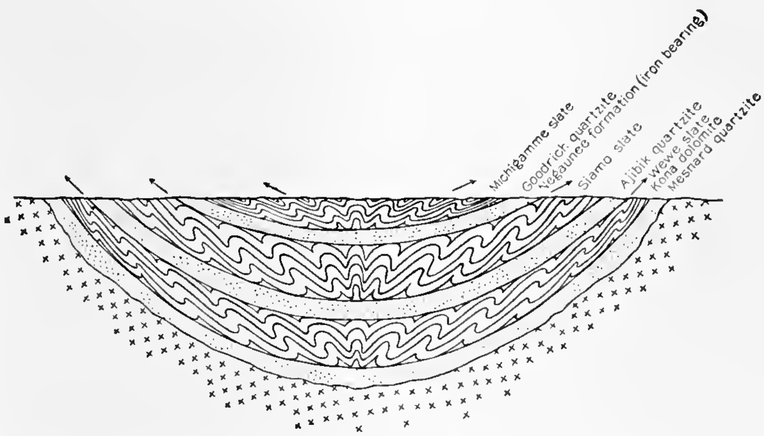


FIGURE 35.—Idealized north-south section through the Marquette district, showing abnormal type of synclinorium. The axial planes of the minor folds converge downward. The attitudes of the minor folds are determined by the differential movements in the more competent strata indicated by arrows. In general the soft slate layers of the district are the ones best illustrating the minor folds. The quartzite layers are more competent and therefore more simple in outline.

The middle and upper Huronian rocks west of the central part of the district are in linear belts, one following the other in regular order, but east of the central part of the district the distribution is less uniform and, because of the somewhat equal closeness of the north-south and east-west folds, some of the formations lose their linear character and cover considerable areas.

The Marquette district is the type district for the Lake Superior Huronian in that it is the only district in which the upper, middle, and lower Huronian are well represented. Moreover, the unconformable relations between the middle and lower Huronian and between the middle and upper Huronian are demonstrated by the clearest evidence, as is also the unconformity between the Huronian and the Archean.

ARCHEAN SYSTEM.

The rocks of the Archean system are so different in character from the Huronian sediments that there is really no difficulty in distinguishing between them. This discrimination was made by Brooks and Irving before it was known that an unconformity separated them. The

[a] Van Hise, C. R., Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1896, pp. 612, 615–621.

Archean rocks are all crystalline, comprising both massive and schistose varieties. The different phases have very intricate relations to one another as compared with the Huronian, and this led Irving to designate the whole mass as the "Basement Complex." The rocks of the Archean are divisible into two series, Keewatin and Laurentian. This was recognized before the International Committee had agreed on the definitions of these terms and to the two divisions were given the names "Mareniscan" and Laurentian, as in the Gogebic district.

The northern area and southern area of Archean will be separately described.

NORTHERN AREA.

KEEWATIN SERIES.

The Keewatin rocks of the northern area were described in the Marquette monograph under two divisions—the Mona schist and the Kitchi schist. The Mona schist comprises both basic and acidic varieties, the former being dominant. The basic schists comprise both dense and banded forms. In color all are various shades of green. They belong to the general class which has been described by G. H. Williams [a] as greenstone schists. The mineral constituents are mainly epidote, chlorite, hornblende, plagioclase (largely albite), leucoxene, quartz, and usually calcite. The chloritic and calcitic character of these schists is very widespread, persistent, and characteristic. In general the composition of the schists is very similar to that of basalts. The banded character of these rocks early led to the belief that they were water-arranged sediments, but the later studies have shown that while this is true in part they are largely, though not altogether, schistose basic flows and tuffs.

The basic Kitchi schist differs from the basic Mona schist mainly in that it clearly shows an agglomeratic and in some places a conglomeratic character. This appearance is typically shown at the old Deer Lake furnace. A close study of the rocks of this area shows beyond all question that, while they are largely volcanic conglomerates, some of the material of these conglomerates has been worked over by water into greenstone conglomerates. Where the material is comparatively fine they approach in appearance the banded Mona schist.

The change from Mona to Kitchi schist takes place by the appearance of conglomeratic and agglomeratic bands in the Mona. There is reason to believe that the main mass of basic schists composing the Kitchi and Mona schists is the same formation, the main difference being that the Mona schist is more metamorphosed and probably contained a larger proportion of finer material.

In the areas of both the Mona and Kitchi schists are subordinate areas of acidic rocks which are largely sericite schists. Whether these are contemporaneous with the basic schists or are later intrusives is not altogether clear.

In the area of Mona schist are small masses of ferruginous slate, ferruginous chert, and magnetite-grünerite schists which are identical in hand specimen and in microscopic character with similar rocks of the iron-bearing Negaunee formation. These appear in their best development within the banded Mona schist adjacent to Lighthouse Point, but are found also in other localities, especially north of the old Holyoke mine in sec. 2, T. 48 N., R. 27 W. If these rocks are supposed to be of the same origin as the similar rocks of the Negaunee formation, and there is no evidence that they are not, they indicate the presence locally of conditions of nonclastic subaqueous sedimentation, and if this is so it is probable that much of the banded Mona schist of this area has been extensively rearranged by water. Therefore, while these schists have the composition of an igneous rock, it is probable that they partly represent fine volcanic ash which has been deposited in water and arranged by it without much assorting.

Near Mud Lake a series of green schists, graywackes, and slates intervenes between the typical Mona schist on the north and the Huronian beds on the south. The intervening series is conglomeratic near its contact with the Mona schist and in turn is overlain unconformably by the Huronian series, with basal conglomerate. These green schists and slates look not

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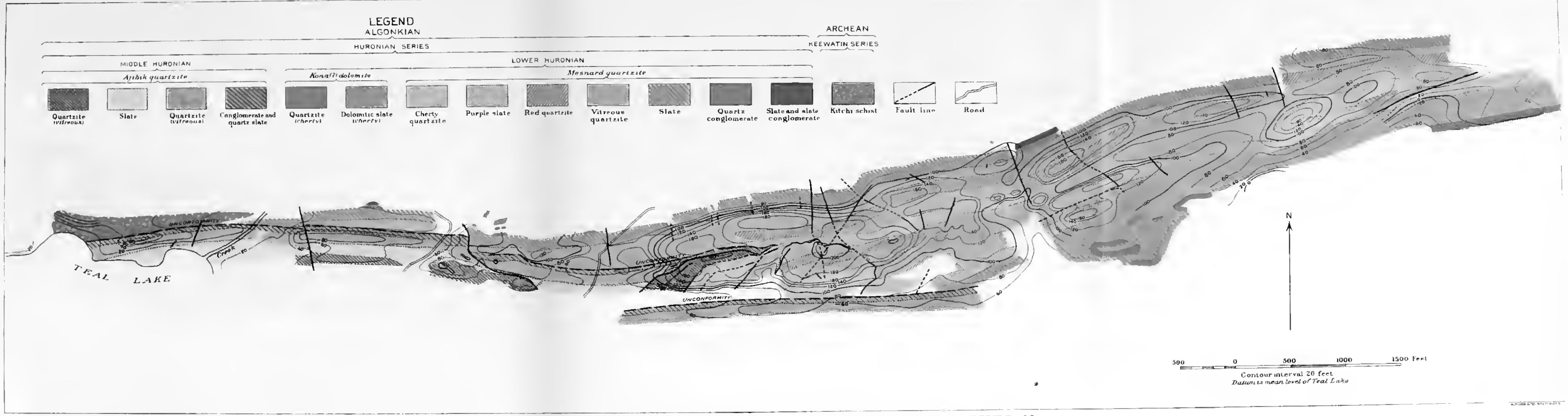
[a] Bull. U. S. Geol. Survey No. 62, 1890.



DETAILED MAP OF QUARTZITE RIDGES OF TEAL LAKE, MICHIGAN
SHOWING FAULTING AND UNCONFORMITY OF AJIBIK QUARTZITE AND MESNARD QUARTZITE
by A. E. Seaman
1909

unlike some of the phases of Kitchi schist farther west, suggesting the possibility that the Kitchi schist may be partly younger than the Mona schist and may be locally more largely sedimentary than is apparent in the typical Mona schist area. Indeed, if mapped independently of other parts of the district, the green schists and slates between the Mona schist and the Mesnard quartzite of the Mud Lake area would be mapped as sedimentary, probably lying unconformably below the Huronian and unconformably upon the Mona schist.

In conclusion it may be said that both the Mona and the Kitchi schists are dominantly igneous in origin, being mainly a set of lava flows and volcanic fragments which fell upon water and were more or less arranged by it; locally subordinate amounts of material from other sources have been contributed.

LAURENTIAN SERIES.

The Laurentian rocks of the northern area comprise principally granites and gneissoid granites which include both biotite and muscovite granites. In general these rocks show a considerable amount of dynamic action and alteration, the schistose phases passing into rocks which may be called granitoid gneiss. In the western part of the district the Laurentian rocks are adjacent to the Huronian; in the eastern part between them and the Huronian are interposed the Kitchi and Mona schists, into which the Laurentian rocks are batholithic intrusions. The boundary between the two sets of rocks is not sharp and defined. Numerous dikes and bosses of granite are found in the schists along the border, and schist masses are included in the granite.

Another important variety of Laurentian rock is hornblende syenite, which is found in the eastern part of the area. This rock has the same relations to the schists as the granite. It differs from the granite in the absence of quartz, the primary constituents being orthoclase, plagioclase, sphene, magnetite, and biotite. The secondary products, plagioclase, microcline, chlorite, quartz, epidote, muscovite, and leucoxene, have developed to some extent. The structure of the gneissoid syenites is the same as that of the gneissoid granites.

A third class of intrusive rocks in the Keewatin schists is peridotite. One well-known area of peridotite occurs at Presque Isle, but by far the largest area, between 4 and 5 miles in length, is in the central part of the district within the Kitchi schist. These peridotites are very much altered, the olivine and diallage both being extensively serpentinized and magnetite, dolomite, and other usual products developing; also uralite and chlorite have formed from the diallage. Indeed, in most of the specimens the olivine and diallage have entirely disappeared and secondary products have taken their place.

SOUTHERN AREA.

The southern area is composed dominantly of granites, granitoid gneiss, and gneissoid granites which are in most respects not different from the granites of the northern area. Schists are subordinate, but are found at several places. They include micaceous schists, chlorite schists, and amphibole schists similar to those of the northern area. The micaceous schists include muscovite schists, biotite schists, feldspathic biotite schists, and hornblende-biotite schists. They have nowhere sufficient extent to be mapped as formations separate from the granites. The origin of these schists is not clear. Their foliation is secondary, due to mashing and recrystallization. In places they have a clastic appearance and may be, in part at least, sedimentary in origin. Between the different varieties of schists there are of course gradations. There is every reason to suppose that the chlorite schists and hornblende schists are similar in origin to like rocks of the northern area.

In the eastern part of the district south of the Cascade range and bordering the Huronian is a narrow and distinct belt of Laurentian rocks which has been called the Palmer gneiss. It is a gneiss consisting dominantly of quartz with minor quantities of feldspar and mica, the origin of which is in doubt. Phases of it look like metamorphosed sediments; other parts seem to be the result of metamorphism of granitic and pegmatitic rocks. On the earlier map of the district[a] there were included in the west end of the Palmer gneiss belt certain metamorphic schists which have since been found to represent metamorphosed phases of the Siamo slate.

ISOLATED AREAS OF ARCHEAN ROCKS.

In the eastern part of the district, within the Algonkian, are small isolated areas of Archean rocks. These comprise granites, gneissoid granites, and greenstone schists in no respect differing from the corresponding rocks of the main northern and southern areas.

Intrusive in all the previously described rocks are dikes and bosses of diabase and diorite which are similar to those which intrude the Huronian rocks, and therefore are much later in age. They do not properly belong with the Archean.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

As already stated, the Huronian series in the Marquette district is divided into upper Huronian (Animikie group), middle Huronian, and lower Huronian.

LOWER HURONIAN.

The lower Huronian consists, from the base upward, of the Mesnard quartzite, the Kona dolomite, and the Wewe slate. It has been pointed out that these formations appear only in the northeastern part of the district.

MESNARD QUARTZITE.

Name and distribution.—The Mesnard quartzite is so named because it composes the larger part of the mass of Mount Mesnard, south of Marquette. The quartzite borders the Huronian rocks from a locality a short distance east of Teal Lake east to Lake Superior, thence south and west to a point 2 miles west of Goose Lake. Also patches of Mesnard are found on the north margin of the Huronian rocks as far west as 2 miles west of Teal Lake. In the eastern part of the district the Mesnard quartzite is repeated by the appearance of a central anticline, so that in making a section north and south just west of Mount Mesnard four belts of the formation are found. The nature of the structure at this locality is shown by the section on Plate XVII (in pocket).

Lithology.—The Mesnard quartzite has three distinct members—a lower conglomerate, a central quartzite, and an upper slate. These members are not separately mapped because exposures as a whole are not sufficient to make this possible.

The lower conglomerate member comprises conglomerates with subordinate amounts of graywacke, graywacke slate, and quartzites, with all gradations between the different phases. Naturally the finer-grained varieties are more prevalent near the top of this member, and locally a slate appears between the conglomerate and the quartzite.

The conglomerate adjacent to the southern granite has two different phases. The common phase is a coarse granite conglomerate, but locally the granite of the Archean seems to have been disintegrated so that it yielded individual grains of quartz, feldspar, and mica. Where this was the case the recomposed rock very closely resembles the original granite. This is especially true where the two together have been anamorphosed to schists. Indeed, at such places it is difficult to place the exact line between the two formations.

The conglomerates adjacent to the northern Archean bear detritus both from the granite and from the Mona schist and therefore carry pebbles and bowlders from both of these formations. The granite pebbles comprise coarse-grained muscovite granite and fine-grained granite. The pebbles from the Mona schist include various kinds of greenstone schists and chloritic schists identical with the phases of the Mona schist, so that there can be no doubt as to the source of the material.

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, atlas sheet IV.

The second member, constituting the great mass of the formation, is dominantly a pure vitreous quartzite, although locally there are feldspathic quartzites and fine-grained conglomerates. In this belt is one layer of conglomerate in which cherty jasper, quartz, and ferruginous schist pebbles are characteristic. For the most part the quartzite is indurated by cementation. Toward the top the quartzite member becomes slaty and finally passes into a graywacke slate. This rock is from less than 30 to about 100 feet thick and is in fact a transition pelite member between the quartzite and the Kona dolomite.

Metamorphism.—The Mesnard quartzite as a whole has been much mashed, and the result is that the conglomerates, quartzites, and graywackes include rocks varying from those which are indurated mainly by siliceous cementation to those which are crystalline schists. Some of the rocks have been much shattered, the shattering extending to the individual grains. The openings which have been formed by the shattering have been cemented mainly by quartz and by iron oxide. So pervasive have been the dynamic effects that not a single clastic grain has escaped. Where the pressure has been the least undulatory extinction is shown by the quartz grains. A large portion of the quartz grains have been sliced by parallel fractures, some in one direction, some in two directions at right angles to each other. Where the formation is feldspathic the feldspars have very extensively altered into sericite and quartz. In places where the metamorphism is extreme the formation is transformed into a sericite schist by granulation and recrystallization. The schistose varieties of the rocks are especially prevalent along the southern border of the southern conglomerate adjacent to the granite.

Partial analyses of the massive Mesnard quartzite and the schistose phase along its contact with underlying formations are given below:

Analyses of massive and schistose Mesnard quartzite.

[Analyst, R. D. Hall, University of Wisconsin.]

	Specimen 24096 (quartzite).	Specimen 24123 (sericite schist).
SiO_2	98.87	58.85
Al_2O_3	.41	26.22
Fe_2O_3	.08	3.01
FeO	.11	.17
MgO	.04	.63
Na_2O	.08	.05
K_2O	.15	8.44
H_2O- H_2O+	.17	2.31

Apparently the principal result of the development of schistose structure has been the loss of soda and silica and ferrous iron. Alumina, potassa, ferric iron, water, and magnesia have remained in nearly constant and mutual proportions. This change is similar in all respects to one shown by the Waterloo quartzite of southern Wisconsin. It is believed to be one due to metamorphism, but the possibility can not be excluded that the differences are partly those of original composition.

Relations to adjacent formations.—The conglomerates at the base of the Mesnard quartzite, here adjacent to the Laurentian granite, there next to the schists of the Keewatin, show that between the Archean and the Mesnard there is a very great unconformity. It is clear that the complex history of the Archean was practically complete before the Mesnard quartzite was deposited. The Keewatin schists had been intruded and metamorphosed by the granites and the two together had been deeply truncated before the Mesnard was laid down. One of the conglomerates at the base of the Mesnard is especially interesting, in that it was the first in which the clear evidence of unconformity was found. This contact is north of Mud Lake and along an old road known as the State road, and the conglomerate has sometimes been called the "State Road" conglomerate. Since the discovery of this contact other contacts have been found along the southern belt of Mesnard at a score of places. The conglomerates adjacent to them are splendid granite conglomerates, many of which contain great well-waterworn bowlders of granite.

On the knobs northeast of the southeast end of Goose Lake quartzite mapped as Mesnard is found to lie directly upon the Kona dolomite. The quartzite with this relation may be an interstratified layer in the Kona dolomite similar to quartzite layers seen in this formation in the Mount Chocolay section. The boundary between the quartzite overlying the Kona dolomite in this locality and the true Mesnard quartzite is not known.

Thickness.—As the Mesnard quartzite was the first formation of a transgressing sea, it naturally varies in thickness owing to the irregularities of the basement upon which it was deposited. The thickness ranges from 150 feet to nearly 700 feet.

KONA DOLOMITE.

Name and distribution.—The Kona dolomite is given the name Kona from the prominent hills of that name east of Goose Lake, where it is exposed.

This formation, like the Mesnard quartzite, is confined to the eastern part of the district. In distribution it constitutes a westward-facing U, the arms of which terminate a short distance east of Teal Lake on the north and at the east shore of Goose Lake on the south.

The exposures commonly constitute a set of sharp and abrupt cliffs cut by ravines or separated by drift-filled valleys. The formation very well illustrates the complex folding of the district. In some places the north-south folds are the more prominent, but more generally the east-west folds are dominant.

Lithology.—The Kona formation is dominantly a dolomite, but interstratified with this are layers of slate, graywacke, and quartzite with all gradations between the mechanical sediments and the pure dolomites. Thus there are finely crystalline dolomite, cherty dolomite, quartzose dolomite, argillaceous dolomite, dolomitic quartzites, dolomitic slates, dolomitic cherty quartzites, and dolomitic chert. The dolomite beds range in thickness from a few inches to many feet, but even the most dolomitic beds contain thin cherty layers, mingled with which in some places is clastic material. In color the rocks vary from pink and red to dark brown. Because of the impurities of the dolomite the weathered surface has very characteristically a jagged appearance, due to the solution of the dolomite and the consequent protrusion of siliceous phases.

Metamorphism.—The dolomite has usually yielded to the folding without prominent fractures or cleavage, but it has suffered a minute shattering and is cemented by finely crystalline quartz or coarsely crystalline dolomite, or the two combined. The slate layers usually have a slaty cleavage and many of the graywacke, quartz, and cherty quartz layers are brecciated. These breccias where schistose are difficult to distinguish from conglomerates. The completeness of this shattering and brecciation was appreciated only by a study of the thin sections, where every one of the numerous slides shows the phenomena mentioned to a greater or less extent. Not a half-inch cube has escaped.

Relations to adjacent formations.—The Kona dolomite grades into the Mesnard quartzite below. Above, by a lessening of the calcareous constituent, it gradually passes into the Wewe slate.

Thickness.—Because of the complicated folding of the Kona dolomite it is difficult to give an accurate estimate of its thickness, which probably varies greatly. In some places it seems to be a comparatively thin formation, not more than 200 to 250 feet thick. In other places where the whole formation is well exposed it appears to be 650 or 700 feet thick, and it may be thicker than this.

WEWE SLATE.

Distribution.—The Wewe slate, like the Mesnard quartzite and Kona dolomite, is confined to the east end of the district, making a westward-facing U. The slate, being a less resistant formation than the Kona dolomite below or the Ajibik quartzite above, is in general marked by valleys, and consequently the exposures are few.

Lithology.—The Wewe slate was a pelite formation evidently varying in its character from a fine mud to a coarse sandy mud with numerous alteration phases. As a result of the compacting and modification of these beds the formation is now a slate, shale, novaculite, and graywacke. The color of these rocks varies from red to black, depending on the quantity and conditions of the iron oxide.

Metamorphism.—In consequence of the folding and metamorphism the slates have developed a cleavage. The rock locally has been sufficiently metamorphosed to become a mica slate and even to approach a mica schist, but usually the alteration has not gone sufficiently far to obliterate the bedding.

The rocks have been commonly fractured parallel to the bedding or to the secondary structures which intersect the bedding. At some localities fracturing has been sufficiently powerful to shatter the rocks throughout, or even to produce friction breccias. Where further movements have rounded the fragments of the breccia the rock becomes a pseudoconglomerate. The openings which have been produced by the fracturing have been cemented by quartz, by hematite, and by a jaspery mixture of the two. In some places these varieties of material follow one another and locally the amount of hematite in the breccia is so great as to have led to prospecting of the formation for iron ore.

Relations to adjacent formations.—It has been pointed out that the Kona dolomite grades into the Wewe slate by a disappearance of the calcareous material. The Wewe slate is overlain unconformably by the Ajibik quartzite. The evidence of this unconformity will be given under the description of the latter formation.

Thickness.—In one place, where there is an almost continuous exposure of slate, the thickness is calculated at 1,050 feet, but it is entirely probable that there are here subordinate rolls. The real thickness of the slate is doubtless much less than this. At one place, indeed, the thickness of the formation does not appear to be more than 100 feet.

MIDDLE HURONIAN.

The middle Huronian of the Marquette district comprises the Ajibik quartzite, the Siamo slate, and the iron-bearing Negaunee formation.

AJIBIK QUARTZITE.

Name and distribution.—The Ajibik quartzite is so named because the predominant rock is quartzite and because typical exposures of it occur on the bold Ajibik Hills northeast of Palmer.

The distribution of the Ajibik quartzite is practically coextensive with the outlines of the Marquette district. For all of the area west of Negaunee it is the Huronian formation which rests against the Archean. For the area east of Negaunee it is separated from the Archean by the lower Huronian rocks already described. Along the south side of the district the formation is very thin, locally not more than a few feet. The Ajibik quartzite, being a resistant formation, is for the most part well exposed and at various places it constitutes prominent bluffs—as, for instance, east of Teal Lake.

Deformation.—In general the folding of the Ajibik is that of a great synclinorium, the dips being south from the great northern belt and north from the southern belt. The Cascade trough, the Republic trough, and southwestern arms at the west end of the district constitute subordinate synclinoria. In detail, as at Broken Bluffs, there is secondary infolding of the formation with isoclinal dips.

The formation is displaced by at least three great faults—that of Carp River, the east-west throw of which apparently amounts to as much as 3,000 feet; the fault along the south side of the Ajibik Hills, the throw of which is apparently several thousand feet; and the fault at the Volunteer mine, which again apparently has a horizontal throw of 2,000 feet or more. In addition to these there are a number of minor faults east of Teal Lake, the character of which is indicated by Plate XIX (p. 254).

Lithology.—Petrographically the Ajibik formation has two facies—conglomerate, which is in subordinate amount and is at the bottom of the formation, and quartzite, which constitutes the major portion of the formation. Associated with the conglomerates are interstratified slates and graywackes.

The conglomeratic phase has two main areas—a western one in which it rests directly upon the Archean and an eastern one in which it is underlain by lower Huronian rocks. Where the formation rests directly upon the Archean its basal part is a conglomerate or recomposed rock, the material of which is derived mainly from the rocks immediately subjacent. This conglomerate varies from place to place as the subjacent rock varies. In general it is a granite conglomerate. In the Cascade range such material is derived from the Palmer gneiss and other igneous formations, and near the Kitchi schist the material is mainly derived from that formation. In the eastern part of the district the Ajibik quartzite rests upon the Wewe slate, somewhat farther west upon the Kona dolomite, and still farther west upon the Mesnard quartzite—that is, it cuts diagonally across these three formations. This applies to both its northern and its southern arms. As would be expected from this relation, the conglomerate at the bottom of the formation in this area contains dominantly débris from the lower Huronian, but includes also material from the Archean.

The basal conglomerates, slates, and graywackes are usually of only moderate thickness, although the conglomeratic beds are persistent. These rocks grade up into quartzite.

Metamorphism.—The major portion of the formation was a quartz sand. By cementation, dynamic action, and recrystallization it has now been transformed to many varieties, of which normal quartzite, cherty quartzite, ferruginous quartzite, ferruginous cherty quartzite, quartz rocks, quartzite breccia, and quartz schists, in places sericitic, are the more prominent. The predominant phase is a typical rather pure vitreous quartzite, which locally is conglomeratic. This least-altered variety of the quartzite is composed almost wholly of rounded grains of quartz of somewhat uniform size, which are beautifully enlarged, the enlargements filling the interspaces. The grains uniformly show undulatory extinction, and some of them are distinctly fractured. From this variety there are all gradations to the other forms mentioned.

Locally interstratified with the quartzite were mud beds which now have become graywacke slate, mica slate, or mica schist. The micaceous varieties of the rock are especially abundant where the psammite was feldspathic, the feldspar altering into mica and quartz or into chlorite and quartz. At the west end of the district, especially in the Republic and Western tongues, the mashing has been so great as to transform the rock to a quartz schist, and where the psammite was impure there were developed typical biotite schists, muscovite schists, and chlorite schists, which are in places garnetiferous.

In their very general brecciation, with consequent abundance of pseudoconglomerates; in the secondary veining, both with coarsely and finely crystalline quartz; and in the large quantity of secondary hematite and magnetite, these quartzites differ from the Goodrich quartzite of the upper Huronian.

Relations to adjacent formations.—The Ajibik quartzite rests upon both the Archean and the lower Huronian unconformably. The unconformity between the Ajibik quartzite and the Archean is conspicuous and was early recognized, but the unconformable relation between the Ajibik and the lower Huronian was overlooked at the time the Marquette monograph was written. The careful mapping and studies of Seaman in the eastern part of the district showed the true relation.

It has already been pointed out that in going from the east end of the Ajibik westward it is found at first in contact with the Wewe slate, next with the Kona dolomite, next with the Mesnard quartzite, which thins westward to an edge. West of the last outcrops of Mesnard quartzite the Ajibik is in contact with the Keewatin, Kitchi schist, and with Laurentian rocks. Thus it cuts diagonally across the beveled edges of formations varying in age from Wewe to Keewatin. These relations, together with the presence of conglomerates at the base which bear débris from the lower Huronian, show that the lower Huronian was sufficiently indurated to yield fragments to the Ajibik before the deposition of that formation. The absence of the lower Huronian in the western part of the district is doubtless largely if not wholly due to its removal by erosion between the time of the Wewe slate and the deposition of the Ajibik quartzite.

Where mashing and metamorphism have been sufficient to transform the conglomerate into a schist the Archean has been similarly metamorphosed; consequently the Ajibik quartzite apparently grades down into the Archean.

The Ajibik quartzite in the northern belt and in the eastern part of the district grades upward into the Siamo slate. This change takes place by a gradual transition of the psammite into a pelite formation. In the southern belt the Siamo slate is absent and the Ajibik quartzite grades into the Negaunee formation. This gradation may be particularly well seen in the Cascade area.

Thickness.—The best opportunity to determine the thickness of the formation is at the east end of the U, where the apparently secondary folding is absent. Here the thickness appears to be about 700 to 750 feet. Along the south side of the district the formation thins to a few feet.

SIAMO SLATE.

Name and distribution.—The Siamo slate is so called because abundant and typical exposures occur on the Siamo Hills southwest of Teal Lake. The formation appears at the northwestern part of the district, north of the Michigamme mine, and extends in a continuous belt of varying width to a point northeast of Negaunee. Here, owing to the canoe shape of the eastern part of the district, it widens out to broad irregular areas with several arms between the Ajibik quartzite and the Negaunee formation. There is no southern belt of Siamo slate corresponding to the northern belt. The slate, being a soft formation, is not well exposed, but where it is metamorphosed into a mica slate or where it is a coarse graywacke ledges are numerous.

Deformation.—The folding of the formation as a whole corresponds to that of the district. In detail it is more complex than that of the associated quartzites. The northern belt, with southern dip, has superimposed upon it isoclinal folds of the second order. In the eastern part of the district, where the broad area of Siamo slate is situated, the formation is folded into a series of rolls, indicated by the sinuous contact between the Siamo and Negaunee formations. The westward-projecting salients of the Siamo constitute the crests of anticlines and the reentrants are the synclines.

Lithology.—The rocks of the Siamo formation are dark gray or greenish gray and some of the coarser are light gray. They vary from a coarse-grained graywacke, approaching a quartzite, through massive graywacke to a very fine grained slate. The slates and fine-grained graywackes are the predominant phases. The finer-grained varieties are in many places affected by slaty cleavage, which is rather uniform in direction for a given area and thus traverses the bedding. Locally movements later than the development of the cleavage have resulted in many partings along this secondary structure, giving the rock a fissility.

The less-altered Siamo rocks are composed mainly of well-rounded grains of quartz, a few of them finely complex and cherty looking, and of grains of feldspar, between which is a sparse matrix consisting of chlorite, biotite, muscovite, finely crystalline quartz, and more or less iron oxide. Usually the chlorite predominates over the muscovite and biotite, but in some of the rocks the micas are as abundant as the chlorite. Some of the quartz grains are distinctly enlarged. Most of them show pressure effects by undulatory extinction and fracturing, the fractures being locally arranged in a rectangular system. The feldspars comprise orthoclase, microcline, and plagioclase, in places changed into chlorite and quartz, biotite and quartz, or muscovite.

Metamorphism.—The mineral alterations have been noted. In proportion as there is dynamic action there is a tendency for secondary leaflets of the chlorite, biotite, and muscovite to have a parallel arrangement. Where this is well advanced there is also granulation of the larger quartz grains, and the secondary quartz may become as coarsely crystalline as the original quartz. Where all these changes have gone far the rock becomes a mica slate or a mica schist. The process of development thus briefly outlined is the same as for the Tyler slate of the Penokee-Gogebic district, described in another place. (See pp. 232–233.)

Other phases of the Siamo rocks exhibit very well a fracture or slip cleavage which may be in only a single direction parallel to the bedding, or in two directions intersecting at angles varying from nearly right angles where the pressure has been least to acute angles where it has been strong. In thin section the latter rock has an appearance like that of a drawn-out net.

The largest areas of mica schist, representing the most advanced phase of metamorphism of the formation, lie north of Michigamme. The greater metamorphism of this part of the formation is attributed to the large masses of intrusive greenstone which have been introduced roughly parallel to the contact of the Siamo slate and the Negaunee formation. Other considerable masses of greenstone are also found within the area of the Siamo. Evidence of the metamorphic effect of the greenstone is afforded by numerous large secondary crystals of hornblende in the slate adjacent to the larger masses of greenstone.

Relations to adjacent formations.—At the upper and lower horizons the slates tend to become ferruginous. In these phases there is present a considerable quantity of iron oxide, generally hematite but in many places magnetite. In the upper part of the formation especially these ferruginous slates have interlaminated layers of material similar to the ferruginous and sideritic slates and cherts and grünerite-magnetite schists of the Negaunee formation. The Ajibik quartzite grades up into the Siamo slate. It is apparent from the appearance of interlaminated layers of material like the Negaunee formation in the upper parts of the Siamo slate that the transition into the Negaunee is a gradation by interstratification. The fragmental sediments gradually die out and nonfragmental sediments become dominant; this change takes place irregularly, producing interstratification of the two forms of sediments.

Thickness.—The area perhaps most favorable for determining the thickness of the Siamo slate is that adjacent to Teal Lake. If the formation were there assumed to be monoclinal, the thickness would be from 1,250 feet to 1,300 feet, but as there are an unknown number of subordinate rolls at this locality, and slaty cleavage has developed, it is probable that the real thickness of the formation is not more than half of this amount.

NEGAUNEE FORMATION.

Name and distribution.—The principal iron-bearing formation of the Marquette district is named Negaunee because in the town of that name and to the south are typical exposures of the formation.

The Negaunee formation extends from the northwest end of the district along the north side of the Huronian to the north side of Michigamme Lake. From this place eastward for a distance of 5 miles the formation is cut out by the unconformity at the base of the Upper Huronian. Near Ishpeming it widens out into a broad area and occupies a large portion of the famous T. 47 N., R. 27 W., and also a considerable portion of T. 47 N., R. 26 W. From this broad area a short southern arm, known as the Cascade range, extends to the east and a long arm to the west along the south side of the Algonkian; the formation is found also on both sides of the Republic and southwestern arms. In the western part of the main southern belt and in the Republic and southwestern arms the formation is apparently absent for distances varying from a fraction of a mile to several miles. It is believed this lack of continuity is due to the fact that the Negaunee formation was completely removed by erosion before the deposition of the upper Huronian (Animikie group).

Deformation.—The two long arms of the iron-bearing formation of the main belt, as well as the two belts of iron-bearing formation in the Republic and southwestern belts, are the two sides of a synclinorium. The two main arms join in the large area of Negaunee at Ishpeming, showing that it also is in a broad way an east-west synclinorium. This trough pitches to the west. Thus the lower members of the Negaunee formation outcrop on the east adjacent to the Siamo slate and the higher members outcrop on the west adjacent to the Goodrich quartzite. The sinuous contacts between the Negaunee and the formations above and below express its folding.

The salients to the east into the Siamo slate represent synclines and the reentrants anticlines; the salients to the west into the Goodrich quartzite represent anticlines and the reentrants synclines. The Palmer belt of the Negaunee formation, extending from the main area as a southeastern arm, is also a synclinal fold, which ends to the east in a canoe with a westward pitch. The structure of this syncline is modified by a great fault along the south side of the Ajibik Hills and by faulting at the Volunteer mine.

Lithology, including metamorphism.—Petrographically the iron-bearing formation comprises sideritic slates, which may be grüneritic, magnetitic, hematitic, or limonitic; grünerite-magnetite schists; ferruginous slates; ferruginous cherts; jaspilite, and iron ores. The ferruginous cherts and jaspilite are commonly brecciated, the other kinds less commonly.

The sideritic slates are most abundant in the valleys between the greenstone masses in the large area south of Ishpeming and Negaunee. These rocks are regularly laminated, are fine grained, and when unaltered are of a dull-gray color. The purest phases of them are approximately cherty iron carbonate, as shown by two analyses made by George Steiger in the laboratory of the Survey. It is unusual to find exposures of the cherty siderite slates which have not been more or less affected by deep-seated alteration or by weathering processes. The iron carbonates pass by gradations, on the one hand into grünerite-magnetite schists and on the other into ferruginous slates, ferruginous chert, jasper, or iron ore.

The grünerite-magnetite schists consist of alternating bands composed of varying proportions of the minerals grünerite and magnetite and quartz. Where least modified they have a structure precisely like the sideritic slates from which they grade, the grünerite-magnetite belts having taken the place of the carbonate bands. In some places the grünerite-magnetite schists are minutely banded, the alternate bands consisting of dense green grünerite and white or gray chert, with but a small quantity of magnetite. Certain important kinds appear to be composed almost altogether of grünerite, with a little magnetite. In general the grünerite-magnetite schists are found at low horizons, below the ferruginous chert and jaspilite—that is, at or near the same horizon as the sideritic slates. In many places also they are below intrusive masses of greenstone.

By oxidation of the iron carbonate the sideritic slates pass into the ferruginous slates, the iron oxide being hematite or limonite, or both. These rocks, in regularity of lamination and in structure, are similar to the sideritic slates, differing from them mainly in the fact that the iron is present as oxide. In the different ledges may be seen every possible stage of change from the sideritic slates to the ferruginous slates. The only necessary change is a loss of carbon dioxide and oxidation of the iron. On weathered surfaces, along veins, and along some of the bedding planes the transformation may be complete, and between this material and the original rock there are numerous gradations.

From the oxidation of the less slaty phases of the sideritic rocks result the ferruginous cherts, consisting mainly of alternating layers of chert and iron oxide, although the iron oxide bands contain chert and the chert bands contain iron oxide (Pl. XXXIII, *B*, p. 466). This iron oxide is mainly hematite, but both limonite and magnetite are locally present. Rarely magnetite is the predominant oxide of iron. In such places the silica is usually coarsely crystalline. The rocks are folded in a complicated fashion, as a result of which the layers present an extremely contorted appearance. Many of the folded layers show minor faulting. On account of the exceedingly brittle character of these rocks, they are very commonly broken through and through, and some of them pass into friction breccias. In places the shearing of the fragments over one another has been so severe as to produce a conglomeratic aspect. The ferruginous cherts are particularly abundant in the middle and lower parts of the iron-bearing formation, just above or in contact with the greenstone masses. In a number of places they are between the grünerite-magnetite schists or sideritic slates below and the jaspilite above. The rocks here named ferruginous chert are called by the miners "soft-ore jasper" to discriminate them from the "hard-ore jasper," or jaspilite, because within or associated with them are found the soft ores of the district.

The jaspilites consist of alternate bands composed mainly of finely crystalline, iron-stained quartz and iron oxide (Pl. XXXII, p. 464). The exposures present a brilliant appearance, due to the interlamination of the bright-red jasper and the dark-red or black iron oxides. The iron oxide is mainly hematite and includes both red and specular varieties, but magnetite is commonly present. Many of the jasper bands have oval terminations or die out in an irregular manner. The folding, faulting, and brecciation of the jaspilites are precisely like those of the ferruginous chert, except that in the jaspilite they are more severe. The interstices produced by the dynamic action are largely cemented with crystalline hematite, but magnetite is present in subordinate quantity. In the folding of the rock the readjustment has occurred mainly in the iron oxide between the jasper bands. As a result of this the iron oxide has been sheared, and when a specimen is cleaved along a layer it presents a brilliant micaceous appearance; such ore has been called micaceous hematite. This sheared lustrous hematite, present as some form of iron oxide before the dynamic movement, is discriminated with the naked eye or with the lens from the later crystal-outlined hematite and magnetite which fill the cracks in the jasper bands and the spaces between the sheared laminæ of hematite. The jaspilite differs mainly from the ferruginous chert, with which it is closely associated, in that the siliceous bands of the jaspilite are stained a bright red by hematite, and the bands of ore between them are mainly specular hematite, whereas in the cherts the iron oxide is earthy hematite. The jaspilite in its typical form, whenever present, usually occupies one horizon—the present stratigraphic top of the iron-bearing formation, just below the Goodrich quartzite. In different parts of the district it has a varying thickness. With this jasper, or just above it, are the hard iron ores of the district; hence it has been called "hard-ore jasper" by the miners to discriminate it from the ferruginous chert, or "soft-ore jasper."

Relations to adjacent formations.—The iron-bearing formation rests conformably upon the Siamo slate or upon the Ajibik quartzite and grades downward into one or the other of these formations through the increase of clastic material and a lessening of the ferruginous constituents. The gradation may occur within a few feet or may require 100 feet or more. The transition is accomplished by interlaminations of material which are alternatively chiefly fragmental and chiefly nonfragmental.

The overlying formation, the Goodrich quartzite, rests unconformably upon the Negaunee formation. The amount of folding and erosion of the Negaunee formation accomplished before the Goodrich quartzite was deposited differs in different parts of the district. In some places the erosion has gone so far as to have removed the iron formation entirely. It therefore follows that the contact between the two formations is here at one horizon of the iron-bearing formation and there at another, ranging from the highest known horizon to the lowest.

Thickness.—It is evident from these relations that the thickness of the formation varies from practically nothing to its maximum. It is, however, difficult to estimate this maximum because of the pervasiveness of the intrusive rocks in the Negaunee. It is roughly estimated that in the broad area to the east of Ishpeming and Negaunee the thickness may be considerably above 1,000 feet, although it is entirely probable that the maximum thickness is less than this amount.

Intrusive and eruptive rocks.—Within the iron-bearing formation there are numerous intrusive masses of "greenstone," really diabase and its altered equivalents. These occur in the form of both dikes and bosses, and many of the latter are of large size, running up to masses 2 miles or more in extent. These rocks are especially prevalent in the broad area of the iron-bearing formation near Ishpeming, where they occupy between one-third and one-half of the area. In many places the greenstones intrude the sedimentary series in a roughly laccolithic fashion. In consequence of this, where the two have been folded together their relations are roughly similar to those of sedimentary formations, but when examined closely the greenstones are always found to cut the Negaunee formation to a lesser or greater degree.

Surface eruptive rocks also appear in the formation in the vicinity of Clarksburg. (See p. 268.)

UPPER HURONIAN (ANIMIKIE GROUP).

The upper Huronian is structurally divisible into a lower belt of conglomerate and quartzite, called the Goodrich quartzite, a belt of ferruginous rocks called the Bijiki schist, a belt of slate and schist known as the Michigamme slate, and, to the south, a mass of volcanic rocks called the Clarksburg formation. The Animikie group as a whole occupies the center of the main Algonkian synclinorium from Ishpeming to the west end of the district. In this part of the region it is the chief surface rock, occupying all the area between the belts of the Negaunee formation.

GOODRICH QUARTZITE.

Distribution and structure.—The belt of Goodrich quartzite forms a westward-opening U, bordered on the outside principally by the Negaunee formation, with its eastern margin near the city of Ishpeming. The folding is similar to that of the Negaunee formation, though somewhat less complex. The sinuous contact of the two formations in the vicinity of Ishpeming expresses the complexity of folding at this end of the synclinorium.

Lithology, including metamorphism.—Petrographically the Goodrich is dominantly a quartzite, although usually there is a conglomerate at the base. As the underlying rock is in most places the Negaunee formation this conglomerate is an ore, chert, jasper, and quartz conglomerate. Where the conglomerate is near the Archean this system may furnish material for it—as, for instance, at Palmer, where there are numerous granite, greenstone, and schist bowlders derived from the Archean.

Where the conglomerate is ore, chert, and jasper conglomerate immediately in contact with the Negaunee formation, the particles have been flattened and schistosity has developed in both the conglomerate and the original basement rock, making it difficult to place the exact line between the two formations. This is illustrated at Humboldt. At several localities the conglomerate resting upon the Negaunee formation has had quartz leached out and hematite and magnetite deposited, developing a material rich enough in iron to be an ore. This is illustrated at the Goodrich and Volunteer mines. The quartzite is mainly quartz but contains many particles of chert and jasper and usually considerable amounts of feldspar. Cementation by enlargement is an important process in the induration of the rock. In the eastern part of the district dynamic action has not usually been great enough to give the particles more than undulatory extinction, or at most fracturing. However, these effects are pervasive, not a single clastic particle escaping. The mashing in the central and western parts of the district has been severe and the formation has been transformed to a schist. In the western part of the district, especially in the Republic trough, the alterations have been so great as to transform the feldspathic quartz rocks into micaceous quartz schists, or locally, where the mica is sufficiently abundant, into muscovite-biotite schists or biotite schists. In this change the feldspar has usually altered into quartz and mica, including both muscovite and biotite, especially muscovite.

Relations to adjacent formations.—The Goodrich quartzite rests unconformably upon the Negaunee formation. The evidence of this unconformity consists both in the discordance of strike and dip, varying from a few degrees up to perpendicularity, as at the Goodrich mine, and in the existence of conglomerates derived from the Negaunee formation at scores of localities along the contact. At many places, as has already been pointed out, the erosion between Negaunee and Goodrich time cut through the Negaunee formation. In these places the material of the Goodrich quartzite comes from the underlying formations, the Ajibik quartzite or the rocks of the Archean. There are few Lake Superior formations that have a more complete set of conglomerates at the base or that have clearer proof of unconformity with the rocks upon which they rest. The Goodrich quartzite, by the diminution of coarse fragmental quartz, grades above into the Michigamme slate, the Bijiki schist, or the Clarksburg formation. The nature of each gradation will be mentioned in connection with these formations.

Thickness.—The thickness of the Goodrich quartzite varies greatly from place to place. At the Goodrich mine it is calculated to be as great as 1,500 feet, but this is probably much beyond the average for the district.

BIJIKI SCHIST.

Name and distribution.—The Bijiki schist is given this name because typical exposures occur near the mouth of Bijiki River. It is confined to three narrow belts in the northwestern part of the district. North of the northernmost of these belts is the Goodrich quartzite and between the north and middle belts is the Michigamme slate. These two belts make a synclinal structure. The middle and southern belts unite at the east and represent the outcrop of an eroded anticline.

Lithology, including metamorphism.—Lithologically the Bijiki schist comprises two main varieties, one of which is characteristic of the eastern part of the belts and the other of the western part.

In the eastern part the least-altered phases consist of a sideritic chert interbedded with the Michigamme slate and probably representing a slightly higher horizon than the phase of the Bijiki schist described in the following paragraph. Not uncommonly the siderite is the predominating constituent. This slate has been extensively altered by weathering and metasomatic changes into ferruginous slates and ferruginous cherts, with subordinate amounts of grünerite-magnetite schist. In a few localities, where the ferruginous material is very abundant and the conditions of deposition are favorable, small ore bodies have been found. These are illustrated by the North Phenix, Pascoe, Hortense, Northampton, Marine, Phenix, and Bessie deposits. These ores differ from the soft ores of the Negaunee formation in that the iron oxide is largely limonite and the associated slates are carbonaceous and graphitic.

In the western area, which contains the chief exposures of the formation, the Bijiki is dominantly a banded grünerite-magnetite schist. This rock consists mainly of three minerals—quartz, grünerite, and magnetite. Here and there a small amount of residual siderite is seen. The rock is discriminated from the grünerite-magnetite schists of the Negaunee formation chiefly by its exceeding toughness and the difficulty with which it is broken parallel to the stratification.

One of the most conspicuous mineralogical features of the iron-bearing Bijiki formation near Michigamme is its content of large garnets, up to 2 inches in diameter, developed late in the metamorphism. These have been apparently altered to chlorite and amphibole, early described by Pumpelly as chlorite pseudomorphs after garnet.[a] Microscopic examination shows that although much of the matrix material is chlorite, the garnet is largely replaced by green amphibole and magnetite. Porphyritic biotite in a chloritic matrix is also a very conspicuous mineralogical feature of these rocks, giving them in the hand specimen a brilliantly spangled appearance. The garnet may be really a poikilitic development later than chlorite.

The two chief phases of the Bijiki schist may be in part at separate horizons, but there seem also to be gradations between the ferruginous slates and cherts and the grünerite-magnetite schist. As the schists are largely confined to the western parts of the belts, where there are important masses of intrusive igneous rocks, and occur in the part of the district where the Negaunee formation is also changed to a grünerite-magnetite schist, it is believed that the schist represents the original sideritic formation altered under the influence of igneous rocks while deeply buried and largely by the process of silication, whereas the eastern part of the formation, consisting of ferruginous slates and cherts and containing ore bodies, was altered after the formation was exposed at the surface, later than upper Huronian time, by the processes of weathering.

Relations to adjacent rocks.—Along the northern belt where the base of the Bijiki schist is exposed, rounded fragmental quartz appears near the bottom of the formation, and with an increase of this material the member grades downward into the Goodrich quartzite. The Bijiki schist grades above into the Michigamme slate.

In the central and eastern parts of the Marquette district the Bijiki has not been detected. Apparently in the greater portion of the district between the time of the Goodrich quartzite

[a] Pumpelly, Raphael, On pseudomorphs of chlorite after garnet at the Spurr Mountain iron mine, Lake Superior: Am. Jour. Sci., 3d ser., vol. 10, July, 1875, pp. 17-21.

and the Michigamme slate the conditions were not favorable for the deposition of the iron-bearing formation.

The iron-bearing Bijiki schist, though not thick or economically of as great consequence as the Negaunee, is of considerable significance in the matter of correlation, for it occurs at the same horizon as an important iron-bearing formation in other districts—notably the Menominee, Gogebic, and Mesabi.

Thickness.—The Bijiki schist apparently has a maximum thickness of about 520 feet and from this it ranges down to the disappearing point.

MICHIGAMME SLATE.

Name, distribution, and correlation.—The name Michigamme is given to the upper slate and mica schist formation because extensive exposures of it occur on the islands of Lake Michigamme and on the mainland adjacent to the shore.

The Michigamme slate is mainly in a single great area, which extends from a point about a mile west of Ishpeming along the axis of the Marquette synclinorium to the west end of the district. To Lake Michigamme the breadth of this belt is for the most part less than 2 miles, but at Lake Michigamme it broadens out into an area 5 miles or more in width, from which extend the Republic and southwestern arms. Beyond the limits of the Marquette district proper the formation continues to widen and covers a great expanse of country, extending to the Crystal Falls district on the south and well toward the Gogebic district on the west. It is the equivalent of and is continuous with the slate to which the name "Hanbury" has been given in previous reports. It is also probably the equivalent of the Tyler slate of the Penokee-Gogebic district, to judge from its relations with associated formations and from the probability (indicated by known outcrops) of direct areal connection, though outcrops are not sufficiently numerous to establish this connection absolutely.

Deformation.—The Michigamme slate in most of the district forms a great synclinorium, the secondary folds of which are, however, not sufficiently large to bring up the lower rocks to the erosion surface except in a central anticline at the east end of Lake Michigamme, where the Bijiki schist and Goodrich quartzite appear at the surface.

Lithology.—The formation is a pelite, which now comprises two main varieties—slates and graywackes and mica schists and mica gneisses—each of which includes both ferruginous and nonferruginous kinds. The slates and graywackes occur east of Lake Michigamme and the mica schists and mica gneisses at Lake Michigamme and to the west, including the Republic and southwestern arms. The slates and graywackes differ from each other chiefly in coarseness of grain, the two being interlaminated in many exposures. There are all gradations from aphanitic black shales or slates to a graywacke so coarse as to approach a quartzite or even a conglomerate. In color the rocks vary from gray to black. Where fine grained they have a well-developed slaty cleavage. In places they are graphitic, pyritic, and ferruginous. Two specimens showing the maximum amount of graphite analyzed 15.69 and 18.92 per cent of carbon.

The slates and graywackes differ in no essential respect from the similar rocks of the Siamo slate (see pp. 261–262) or from the Tyler slate of the Gogebic district (see pp. 232–233), therefore they will not again be described.

Metamorphism.—The slates and graywackes by increase in metamorphism pass into chlorite schists, mica schists, and even into mica gneisses. The process of alteration for the mica schists is identical with that already described in connection with the development of similar rocks for the Siamo slate and the Tyler slate. (See pp. 232–233, 261–262.) In many places where the rocks are completely crystalline garnet, staurolite, chloritoid, and andalusite are plentifully present. In the more coarsely crystalline rocks much feldspar has developed, and the rock thus becomes a gneiss. This material appears in bands which seem to be altered beds of the formation but which resemble granitic material. The appearance is that of a rock pegmatized throughout. These bands grade into ordinary mica schists. No independent granites have been discovered in connection with this extremely metamorphosed variety of rock, but it can not be asserted that such rocks are not somewhere present. Where the rocks have become schists the ferruginous constituents have been largely transformed to magnetite.

Relations to adjacent formations.—The Michigamme slate grades downward into the Bijiki schist or the Goodrich quartzite.

Thickness.—The thickness of the Michigamme slate is considerable, as is shown by the wide area which it covers. There are, however, so many subordinate folds and the metamorphism is so extreme that it is impossible to make even an approximate estimate of its thickness. Within the area described the thickness of the formation may not be more than 1,000 or 2,000 feet, or may be greatly in excess of this.

CLARKSBURG FORMATION.

Distribution.—The Clarksburg formation differs from the other Algonkian formations of the Marquette district in that it is dominantly a volcanic formation. It is confined to the south side of the Huronian area, extending from the region north of Stoneville to a point somewhat west of Champion, the largest and most typical areas being east of Clarksburg. It is clearly a local formation, not only in its eastern and western extent but in being confined to one side of the district. This is explained by its volcanic character, the vents being on the south border of the Algonkian area.

Lithology.—Petrographically the formation comprises massive greenstones of the general character of diorites; lavas that are interbedded with sediments and tuffs; tuffs that grade off imperceptibly into sediments, the material of which is mainly of volcanic origin; and, finally, greenstone conglomerates and fine-grained sediments, the material of which is mainly volcanic but has evidently been arranged by water. All these rocks are extremely altered and in places so much so that they are now schistose. The pyroclastic material may have been partly subaerial, but doubtless a large part of it fell upon the water. The volcanoes of Clarksburg time were very plainly of explosive type. The center of volcanic activity was east of Clarksburg, and in this vicinity are found the largest amounts of massive and coarse material, lavas, breccias, and conglomerates. Toward the east and west the formation becomes thinner and its material finer, until it dies out in both directions into the Michigamme slate.

It is not the purpose here to describe in detail the many different varieties of rocks of this volcanic formation. These are discussed in Monograph XXVIII of the United States Geological Survey.[a] This volcanic formation is similar to that of the volcanic formation at the east end of the Gogebic district, the chief difference being that the latter is much less metamorphosed. It is notable that both occur in the upper Huronian and mainly take the place of the great upper slate formation (Michigamme slate), although the beginning of the volcanic outbreak was early in upper Huronian time or earlier. In the eastern part of the district a small amount of volcanic material appears also to be associated with some of the earlier formations, especially with the Siamo slate.

Relations to adjacent formations.—The volcanic outbreaks of the Clarksburg began early in Goodrich time, or perhaps even in late Negaunee time, but the main volcanic deposits were in Michigamme time. Later in Michigamme time, by the dying out of volcanic activity, the sediments became more largely ordinary material, and thus the Clarksburg grades above into the Michigamme.

Thickness.—There is no way to ascertain the maximum thickness of the formation, but east of Clarksburg it must be several thousand feet thick. From this maximum it ranges down to a knife-edge.

INTRUSIVE IGNEOUS ROCKS.

Into all the formations of the Huronian series igneous rocks are intruded. These are of at least two ages; the older probably belong to the Huronian and the later to the Keweenawan period. Much the larger number of intrusive masses are distinctly of post-Huronian and

[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 460–486.

probably Keweenawan age. Many of them are distinctly bosses, laccoliths, and sills which in their upward movement have been stopped by the massive competent layers of the Negaunee or Goodrich quartzite, and therefore on the present erosion surface are likely to show close areal relations with the Negaunee formation. This is especially conspicuous in the vicinity of Ishpeming, Negaunee, and Spurr.

The intrusive rocks have been described by various authors under the terms diorite, diorite schist, chlorite schist, magnesian schist, soapstone, and paint rock. Part of them have been regarded by some geologists as metamorphosed sediments, but microscopical study of all the varieties shows that they were originally basic rocks of the composition of diabases. The great bosses of greenstone, commonly known as diorite, are a prominent feature of the topography in the general area covered by the iron-bearing Negaunee formation, and the relations of these greenstones to the genesis of the ores has already been described. During the folding there was much differential movement between the greenstone masses and the surrounding formations, and also the contact plane is one favorable to the action of percolating waters. As a result of this it is a common thing for the periphery of the greenstone knobs to be schistose.

In the area around Ishpeming and Negaunee the schistosity has obviously been the result of differential movement between the greenstones and the overlying Goodrich quartzite. The Goodrich quartzite has moved in the usual direction upward along the limbs of the folds, developing cleavage dipping more steeply than the contact of the greenstone and the quartzite. Where not heavily stained by iron these rocks are commonly called chloritic schists. Adjacent to the iron-bearing formation the rocks, besides having a schistosity, have been much leached and modified in composition and are commonly known as soapstones because of their greasy feel. The much-altered greenstones that have a strongly developed schistosity and have been stained by iron oxide are called paint rock by the miners. Even in the massive varieties of dikes, laccoliths, and bosses the original augite has extensively changed to hornblende and consequently the rock in the district has generally been called diorite.

In the western part of the district, both within the intrusive greenstone masses and in the adjacent formations, there have been important contact effects. This is shown by the extensive development of garnet in both the intrusive and intruded formations, by the less common development of biotite, and by the metamorphism of the iron-bearing formation into grünerite-magnetite schist and of the Michigamme slate into a mica schist. Grünerite has formed to some extent within the intrusive rocks also.

The intrusive character of these igneous rocks of Huronian age is shown not only by contact effects but by the manner in which they cut across the bedding of adjacent rocks and project dikes into them. However, evidence of this kind is not available for all the igneous masses, especially those of laccolithic and sheet form, and it is regarded as not at all unlikely that some of them may be really extrusive rocks put down contemporaneously with the adjacent sediments.

The latest intrusive rocks are fresh diabase dikes which are probably of Keweenawan age. They cut all the other formations of the district, including the older greenstones which have just been described. These rocks include diabase, quartz diabase, olivine diabase, porphyrites, and basalts.

CAMBRIAN SANDSTONE.

Upper Cambrian or Potsdam sandstone is exposed in an east-west belt along Carp River to the south of the city of Marquette and Mount Mesnard, where it rests unconformably upon the Kona dolomite.

QUATERNARY DEPOSITS.

The district is more or less covered by Pleistocene deposits. On the southeast it is so thoroughly covered that the bed-rock geology is not well known. The Pleistocene is discussed in Chapter XVI (pp. 427–459).

THE IRON ORES OF THE MARQUETTE DISTRICT.

By the authors and W. J. Mead.

DISTRIBUTION, STRUCTURE, AND RELATIONS OF ORE DEPOSITS.

The chief iron-bearing formation of the Marquette district is the Negaunee. It bears ore at various horizons. Ores also occur at the basal horizon of the Goodrich quartzite, where it rests upon and has derived débris from the Negaunee formation. Small quantities of ore are found in the iron beds of the Bijiki schist, associated with the Michigamme slate. Workable iron-ore deposits have been found at many places from a point east of Negaunee to Michigamme and Spurr. The Marquette district differs from the Mesabi and Gogebic districts in not having long stretches of nonproducing iron-bearing rocks.

The maximum depth of concentration of ores in the Marquette district is still unknown. On the Teal Lake range the depth is not more than 700 feet; in the Ishpeming and Negaunee areas depths as great as 1,500 feet are known. In the Champion area ore has been followed

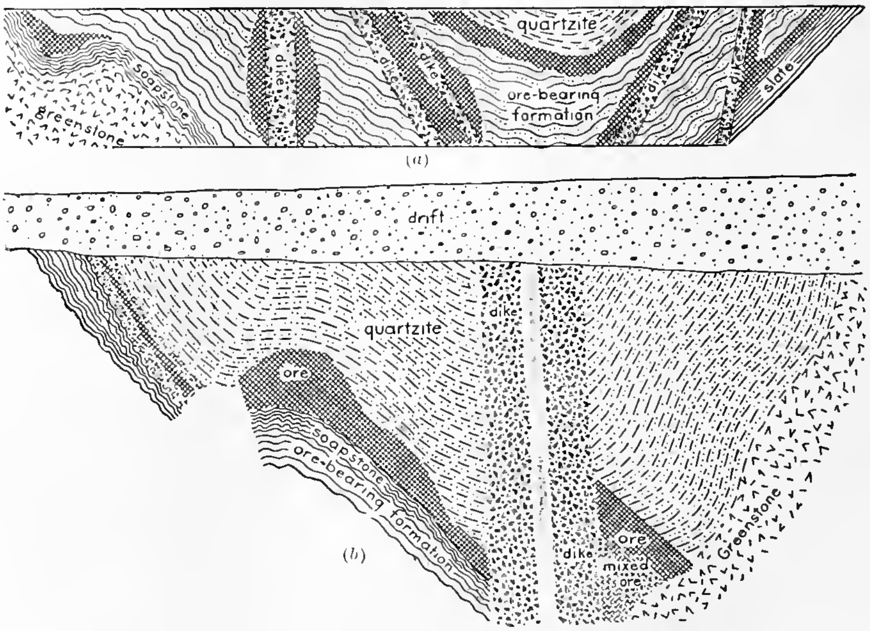


FIGURE 36.—Ore deposits of the Marquette district. (Both ore exploited and ore now in mine are represented as ore, as the purpose of this figure is to show the manner of the development of the ore rather than the present stage of exploitation.)

a, Generalized section in Marquette district, showing relations of all classes of ore deposits to associated formations. On the right is soft ore resting in a V-shaped trough between the Siamo slate and a dike of soapstone. In the lower central part of the figure the more common relations of soft ore to vertical and inclined dikes cutting the jasper are shown. The ore may rest upon an inclined dike, between two inclined dikes, and upon the upper of the two, or be on both sides of a nearly vertical dike. In the upper central part of the figure are seen the relations of the hard ore to the Negaunee formation and the Goodrich quartzite. At the left is soft ore resting in a trough of soapstone which grades downward into greenstone. (From Mon. U. S. Geol. Survey, vol. 28, 1897, Pl. XXVIII, fig. 1.)

b, Cross section of Section 16 mine, Lake Superior mines, in the Marquette district. On the right is a V-shaped trough made by the junction of a greenstone mass and a dike. The hard ore is between these and below the Goodrich quartzite. On the left the hard ore again rests upon a soapstone which is upon and contains bands of ore-bearing formation. The ore is overlain by the Goodrich quartzite. Scale: 1 inch=220 feet. (From Mon. U. S Geol. Survey, vol. 28, 1897, Pl. XXIX, fig. 1.)

down 2,000 feet and is known to extend farther. The Negaunee formation constitutes a part of the westward-pitching Marquette trough, and west of Ishpeming and Negaunee the central part of the trough goes beneath a considerable thickness of upper Huronian sediments. Because of this deep burial but little drilling has been done to ascertain whether or not the ores go down here, but the discovery of a large ore deposit at the very bottom of the Negaunee formation near Negaunee has led to deep drilling west of Ishpeming and Negaunee with such results as to indicate that the ores extend to unlooked-for depths in this direction.

In general the ores come to the rock surface along the middle slopes of the hills, but they also go under the lowest ground.

The ore deposits of the Negaunee formation and the associated ores may be divided, according to stratigraphic position, into three classes—(1) ore deposits at the bottom of the iron-bearing formation; (2) ore deposits within the iron-bearing formation (these ores in many places reach the surface but are not at the uppermost horizon of the formation); (3) ore deposits in the top layers of the Negaunee formation and the bottom layers of the Goodrich quartzite. (See fig. 36.) This last class of deposits runs past an unconformity. Some of these ore bodies are almost wholly in the Goodrich quartzite. Stratigraphically these deposits ought to be separately considered, but they are so closely connected genetically and in position with the Negaunee ore deposits that they are treated with the deposits of that formation. The first two classes of ore are generally soft, and the adjacent rock is ferruginous chert or "soft-ore jasper;" the deposits at the top of the iron-bearing formation are hard, specular ores and magnetite and the adjacent rock is jaspilite, also called "specular jasper" and "hard-ore jasper."

Although the larger number of ore bodies can be referred to one or another of the three classes above given, it not infrequently happens that the same ore deposit belongs partly in one and partly in another. Also the upper part of an ore deposit may be at the topmost horizon of the iron-bearing formation and be a specular ore, whereas the lower part may lie wholly within the iron-bearing formation and may be soft ore. In some places there is a gradation between the two phases of such a deposit, but more commonly the two bodies are separated by dikes, now changed to soapstone or paint rock.

1. The ore deposits at the bottom horizon of the Negaunee formation have been mined principally where the lowest horizon of the formation outcrops—that is, they are confined to that part of the formation resting upon the Siamo slate or the Ajibik quartzite, along the outer borders of the Negaunee formation. The best examples of these deposits are those occurring at the Teal Lake range and east of Negaunee. East of Negaunee the ore bodies occur at places where the slate is folded into synclinal troughs which pitch sharply to the west. Here the iron-bearing formation is in places cut by a set of steep vertical dikes, and the conjunction of these dikes with the foot-wall slate forms sharp V-shaped troughs, as in the Cleveland Hematite mine, where the ore bodies are found between a series of vertical dikes and the Siamo slate. By comparing this occurrence with the ore deposits of the Penokee-Gogebic district, it will be seen that they are almost identical, there being on one side of each of the ore bodies an impervious dike, the two uniting to form a pitching trough. The ore deposits of this horizon are being found by deep drilling to be extensive. The opening of the Maas mine at the east end of Teal Lake and the discovery of ore by deep drilling at this horizon in the western part of the Ishpeming area suggest that the beds of this horizon at great depth may ultimately be found to carry a larger tonnage of ore than those of any of the other horizons.

2. The typical area for the soft-ore bodies within the Negaunee formation is that of Ishpeming and Negaunee. Here are the Cleveland Lake, the Lake Angeline, the Lake Superior Hematite, the Salisbury, and many others. The large deposits rest upon a pitching trough composed wholly of a single mass of greenstone or on a pitching trough one side of which is a mass of greenstone and the other side a dike joining the greenstone mass. The underlying rock is called greenstone where unaltered; that immediately in contact with the ore is known by the miners as paint rock or soap rock or soapstone. The greenstone changes by minute gradations into the schistose soapstone, and this into the paint rock. Many of the thinner dikes are wholly changed to paint rock or to soapstone, or to the two combined. The larger number of these troughs are found along the western third of the Ishpeming-Negaunee area. Plate XVII (in pocket) shows several westward-opening bays occupied by the iron-bearing formation in the masses of greenstone. Conspicuous among these are the Ishpeming basin, the northern Lake Angeline basin, the southern Lake Angeline basin, and the Salisbury basin. The iron-formation embayments open out and pitch to the west. At Lake Angeline an eastward dike cuts across the basin south of the center, and this combined with the greenstone bluffs to the north and to the south forms two westward-pitching troughs, the northern of which has the greatest ore deposits of the Marquette district, containing many millions of tons of ore.

3. The hard-ore bodies, mainly specular hematite but in some deposits including much magnetite, are at the top horizons of the iron-bearing formation, immediately below and in the basal members of the Goodrich quartzite. Examples of this class are the Jackson mine, the Lake Superior Specular, the Volunteer, the Michigamme, the Riverside, the Champion, the Republic, and the Barnum. Also, as interesting deposits, giving the history of the ore, may be mentioned the Kloman and the Goodrich. In all these deposits the associated rocks of the iron-bearing formation are jaspilite or grünerite-magnetite schist, usually the former. Many of these ore deposits weld together the Goodrich quartzite and the Negaunee formation and can not be separated in description. As in classes 1 and 2, all the large ore deposits belonging to this third class have at their bases soapstone or paint rock. Where the soapstone is within the Negaunee formation it is a modified greenstone mass or this in conjunction with a dike or dikes. Where the ore deposits are largely or mainly in the Goodrich quartzite the basement rock may likewise be a greenstone or it may be a layer of sedimentary slate belonging to the Goodrich quartzite. These different classes of rocks are, however, not discriminated by the miners, but are lumped together as soapstone and paint rock. Wherever the deposits are of any considerable size the basement rock is folded into a pitching trough, or else an impervious pitching trough is formed by the union of a mass of greenstone with a dike, or by the union of either one of these with a sedimentary slate. Perhaps the most conspicuous example of this is at the Republic mine, but it is scarcely less evident in the other large deposits. A few small deposits of ore (chimneys and shoots) occur at the contact of the Negaunee and Goodrich formations, where no basement soapstone has been found.

As examples of ore deposits which are largely or wholly within the Goodrich quartzite may be mentioned the Volunteer, Michigamme, Champion, and Riverside. These are partly recomposed ores and differ in appearance from the specular hematite or magnetite of the Negaunee formation in having a peculiar gray color and in containing small fragmental particles of quartz and complex pieces of jasper; in many of them also sericite and chlorite are discovered with the microscope.

Ore deposits in the Bijiki schist, associated with the Michigamme slate, have slate as foot and hanging walls. They are illustrated by the Beaufort, Bessie, Ohio, and Imperial mines.

Although these different classes of ore bodies have the distinctive features indicated above, they have important features in common. They are confined to the iron-bearing formations. They occur upon impervious basements in pitching troughs. The impervious basement may be a sedimentary or an igneous rock, or a combination of the two. Where the ore deposits are of considerable size the plication and brecciation of the chert and jasper are usual phenomena. In many places this shattering was concomitant with the folding into troughs or with the intrusion of the igneous rocks.

In any of these classes the deposits may be cut into a number of bodies by a combination of greenstone dikes and masses. A deposit which in one part of the mine is continuous may in another part of the mine be cut into two deposits by a gradually projecting mass of greenstone which passes into a dike, and each of these may be again dissevered, so that the deposit may be cut up into a number of ore bodies separated by soapstone and paint rock. Some of the ore deposits have a somewhat regular form from level to level, but the shape of the deposits at the next lower level can never be certainly predicted from that of the level above. Horses of "jasper" may appear along the dikes or within an ore body at almost any place. The ore bodies grade above and at the sides into the jasper in a variable manner. As a result of the combination of these uncertain factors, most of the ore bodies have extraordinarily irregular and curious forms when examined in detail, although in general shape they conform to the above descriptions.

CHEMICAL COMPOSITION OF MARQUETTE ORES.

The following average partial analyses were calculated from cargo analyses in shipments for 1906 and 1909:

Average partial analyses of Marquette ores,[a] calculated from cargo analyses for 1906 and 1909.[b]

	Composition of ore dried at 212° F.					Loss on ignition.	Moisture (loss on drying at 212° F.).
	Per cent of total production.	Fe.	P.	SiO_2.	Al_2O_3.		
Average of entire district:							
1906	100.0	59.55	0.107	8.21	2.28	1.66	9.04
1909	100.0	57.05	.105	10.16	2.18	2.31	9.52
Upper horizon, 1906	21.5	59.60	.078	8.47	2.13	.57	1.24
Middle horizon, 1906	37.0	61.40	.094	6.40	2.34	2.61	11.75
Lower horizon, 1906	39.5	59.20	.082	8.11	2.54	2.20	11.32
Bijiki formation, 1906	2.0	53.70	.290	11.30	1.17	7.05	8.30

[a] Including ores of Swanzy district. [b] Calculated from analyses from Lake Superior Iron Ore Association booklet.

In addition to the constituents listed above the ores contain small amounts of manganese, lime, magnesia, sulphur, soda, and potassa. The range for the various constituents of the ores as shown by average cargo analyses for 1906 and 1909 is as follows:

Range of percentage of each constituent in the Marquette ores for 1906 and 1909.[a]

	1906.	1909.
Moisture (loss on drying at 212° F.)	0.51 to 14.33	0.50 to 15.75
Analysis of dried ore:		
Iron	43.90 to 64.61	40.20 to 65.69
Phosphorus	.029 to .402	.018 to .387
Silica	3.21 to 34.20	3.25 to 40.77
Alumina	.69 to 6.26	.42 to 2.98
Manganese	.04 to 2.72	.00 to 4.32
Lime	.18 to 2.00	.00 to 2.78
Magnesia	.09 to 1.18	.00 to 2.09
Sulphur	.004 to .062	.003 to .039
Loss by ignition	.18 to 7.07	.10 to 11.40

[a] Calculated from analyses from Lake Superior Iron Ore Association booklet.

The magnetites do not differ essentially in composition from the dominant hematites and limonites except in having less water.

CHEMICAL COMPOSITION OF IRON-BEARING NEGAUNEE FORMATION.

An average of 1,727 analyses representing 11,025 feet of drilling from the district away from the available ores gives 35.12 per cent of iron. This includes both the lean jaspers and the partly altered jaspers, but not the ores. Because of their great mass compared with the ores, this figure represents nearly the general average composition of the entire formation. If the unaltered jaspers alone are taken, the average is somewhat lower.

The composition of a typical amphibole-magnetite-quartz rock is as follows:

Average analysis of grünerite-magnetite schist.[a]

Loss	1.03	CuO	Trace.
SiO_2	50.02	Na_2O	0.08
Al_2O_3	.97	P_2O_5	.09
Fe_2O_3	10.05	CO_2	1.55
FeO	28.29	H_2O (above 110°)	.42
MnO	.74		
CaO	2.63		100.00
MgO	4.13	Total Fe	29.20

It will be noted that this differs but little from the average composition of the jaspers.

[a] Calculated from analyses given in Mon. U. S. Geol. Survey, vol. 28, 1897, p. 338.

MINERAL COMPOSITION OF MARQUETTE ORES.

The ores of the Marquette district are dominantly hydrous hematites and subordinately anhydrous specular hematites and magnetites. Owing to the presence of magnetite, the mineral composition can not be calculated from analyses in which ferrous and ferric iron are not separated.

The coarse specular hematites are made up mainly of large, closely fitting flakes of hematite, most of which take an imperfect polish and have, therefore, a gray, sheeny, spotted appearance. The flakes, which are parted along the cleavage, reflect the light like a mirror. The large number of individuals of this kind is appreciated only by rotating the sections under the microscope. This brings successively different flakes of hematite into favorable positions to reflect the light into the microscope tube. In some sections cut transverse to the cleavage the schistose character of the rock is apparent in reflected light, innumerable laminæ of hematite giving fine, narrow, parallel dark and light bands, which are comparable in appearance to the polysynthetic twinning bands of feldspar. As both the magnetite and the hematite are usually opaque, the two minerals in general can not be discriminated, although in some sections the crystal forms of magnetite are seen and a small part of the hematite, much of it in little crystals, shows the characteristic blood-red color. The important accessory minerals are quartz, grünerite, feldspar, and muscovite. Some of the small, detached areas of quartz and feldspar appear to be fragmental. The muscovite occurs mainly in small, independent flakes, but some of it is apparently secondary to the feldspar.

The fine-grained specular hematites differ from the so-called micaceous hematites chiefly in that much more of the hematite is translucent and hence at the edges and in spots in the slides is of a brilliant red color. The "slate ores" in reflected light show the laminated character of the rock, while the massive ores give the peculiar spotty reflections, exactly the same as magnetite.

The mottled red and black specular ores in reflected light present a peculiar appearance, the true specular material giving the usual brilliant, spotty reflections, whereas the soft hematite has a brownish-red color.

The soft hematites in transmitted light show in many slides the characteristic blood-red color of hematite, although for the most part the sections are so thick as to give a brownish appearance or are opaque. In the softest ores in reflected light a dark brownish-red color is everywhere seen, which is much less brilliant than that presented by the same mineral in transmitted light. In some of the soft hematites, however, within the mass of red material are many small areas which reflect the light in the same manner as the specular ores. The limonitic hematites differ from the pure hematites only in that, in both transmitted and reflected light, in many places the reddish colors are not so bright.

Under the microscope the magnetites are opaque in transmitted light; in reflected light they give the characteristic spotty appearance of that mineral. Where not pure the usual minerals contained in the iron formation appear with their ordinary relations. Those most plentifully seen are quartz, grünerite, muscovite, and biotite. Here and there garnet and chlorite as an alteration product are abundant. On the borders of the included material the magnetite invariably shows crystal outlines. As a result each area of included minerals has a serrated form. With the magnetite there is always more or less of hematite, a large part of which in many places results from the alteration of the magnetite. The hematite ranges from a subordinate to an important amount. Also at many places with the magnetite are varying quantities of pyrite and garnet and alteration products of the latter, chlorite and amphibole. The magnetites range in color from black to gray.

PHYSICAL CHARACTERISTICS OF MARQUETTE ORES.

The magnetites and specular hematites are called hard ores by the miners, and the hydrous red hematites are called soft ores. The magnetites range from very coarsely granular to finely granular magnetite.

As the ores are made up essentially of iron minerals and quartz, the mineral density varies directly with the iron content, ranging from as high as 5.1 in some of the dense hard ores to as low as 3.5 in some of the low-grade limonitic ores. Owing to the wide variation in the mineral composition of the ores, an average figure for the district would have no significance. The average density of the soft hematites, calculated from the 1906 cargo analyses, is 4.14.

The porosity varies from less than 1 per cent in the hard specular ores to over 40 per cent in the limonitic ores. The average moisture content of the ores of the middle horizon indicates a porosity of approximately 35 per cent, assuming the mineral density to be 4.14. This is probably not far from the true figure.

The number of cubic feet per ton varies from 7 in the pure hard hematites to as high as 14.5 in the limonitic ores. The average for the soft red hematites is approximately 11.9 cubic feet per ton, calculated from a mineral density of 4.14, a porosity of 35 per cent, and a moisture content of 11.75 per cent.

The following table, showing an average of a number of screening tests on the soft ores of the Marquette district, gives a good idea of the average texture of these ores. A comparison of the textures of the ores of the several Lake Superior districts is shown in figure 72, page 481. The screening tests, of which the following is an average, were made by the Oliver Iron Mining Company on 11 typical grades of ore mined in the Marquette district in 1909 and aggregating a total of 746,779 tons. For each grade of ore tested a sample was taken biweekly, quartered down monthly in proportion to the number of tons mined, and at the end of the year quartered down to 100 pounds, dried, and tested. The average was obtained by combining the results of the 11 screening tests in proportion to the number of tons represented by each of the 11 grades.

Composite of screening tests on typical soft ores of the Marquette district.

	Per cent.
Held on ½-inch sieve	28.15
⅛-inch sieve	42.22
No. 20 sieve	10.98
No. 40 sieve	4.90
No. 60 sieve	2.90
No. 80 sieve	1.23
No. 100 sieve	1.15
Passed through No. 100 sieve	7.19

SECONDARY CONCENTRATION OF MARQUETTE ORES.

Structural conditions.—The structural conditions controlling the circulation of water in the Marquette district are various. At the lower horizons of the Negaunee formation the impervious basement is formed by the pitching folds of the Siamo slate, as on the Teal Lake range. At the middle and upper horizons of the Negaunee formation the irregular bosses and intrusive masses of greenstone constitute impervious basements in the reentrants of which the ores are found. The greenstone and its altered form, soapstone, accommodated themselves to folding without extensive fractures and, while probably allowing more or less water to pass through, acted as practically impervious masses along which water was deflected when it came into contact with them. It is a common opinion among miners that a few inches of soap rock is more effective in keeping out water than many feet of the iron-bearing formation. On the other hand the brittle siliceous ore-bearing formation was fractured by the folding to which it was subjected, so that where this process was extreme water passes through it as through a sieve. It is evident that the tilted bodies of greenstone, or soap rock, especially those that occur in pitching synclines or that form pitching troughs by the union of dikes and masses of greenstone, must have converged downward-flowing waters. It is also clear that the weak contact plane between the Goodrich quartzite and the Negaunee formation was one of accommodation and shattering, favorable for the free movement of waters. Finally, the ores in the Bijiki schist of the upper Huronian have been developed by the percolation of waters along impervious slate basements with which the Bijiki schist has been folded.

Chemical and mineralogical changes in secondary concentration of Marquette ores.—The soft ores and the associated ferruginous cherts of the middle and lower horizons of the Negaunee formation are similar physically, chemically, and mineralogically to the ores of the Penokee-Gogebic district. They are derived by the same processes, under similar conditions, from cherty iron carbonate rocks which are practically identical with those of that district.

The hard ores have undergone not only this change but the additional anamorphic changes of deep burial and igneous intrusion, the result being that the hard ores differ from the soft ores chemically only in that they have less water and a little less oxygen, mineralogically in that they have developed in them certain anhydrous silicates and some magnetite, and texturally in that they are coarsely crystalline and in places schistose. To some slight extent also similar hard ores may have been developed directly from the original cherty iron carbonates by deep burial or igneous contact action, but it is shown elsewhere that such action usually results in lean silicated iron-bearing rock rather than in rich ore bodies. The associated ferru-

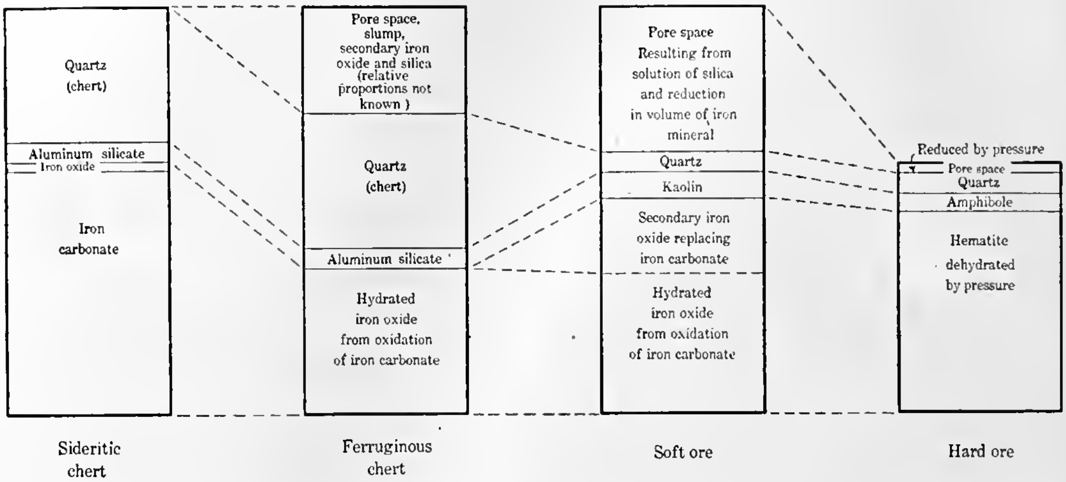


FIGURE 37.—Graphic representation of the volume composition of the principal phases of the iron-bearing Negaunee formation, showing the changes in volume and mineral composition involved in the concentration of the ores from the cherty siderite and the production of hard ore from soft ore by dynamic agencies.

ginous cherts or soft-ore jaspers undergo similar changes so far as the iron oxide layers are concerned. The chert beds are recrystallized, but not otherwise changed. The result is a hard-ore jasper or jaspilite differing from the ferruginous cherts in being more crystalline, having less pore space, and being less hydrated, and accordingly having red rather than yellow or brown colors.

Volume changes in secondary concentration of Marquette ores.—The volume changes in the concentration of the ores and the development of the hard ores are shown in figure 37. The volume composition of the four phases of the iron-bearing formation is represented, thus permitting a consideration of porosity as well as mineral composition. The mineral composition of the sideritic chert is calculated from a typical analysis.[a] The mineral composition of the ferruginous chert is calculated from the sideritic chert analysis, allowing for oxidation of the iron mineral. The result is about an average for ferruginous cherts, as shown by analyses. The indicated volume compositions of the soft and hard ores represent actual average partial analyses of all ore as mined and averages of porosity determinations.

When subjected to oxidizing solutions, the siderite of the cherty siderite is oxidized to a more or less hydrated iron oxide, involving a considerable reduction in volume (see Gogebic discussion, pp. 242 et seq.) ranging from 49.25 per cent when the product is hematite to 18.3 per cent when limonite is produced. If no iron were introduced, the actual amount of oxide resulting would be intermediate between these two figures and probably would not differ greatly

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, p. 337, second analysis.

from the hydrated oxide of the soft ores, which is represented by a ratio of hematite to limonite of 7 to 1. Even if a considerable amount of iron were introduced, the resulting rock would be banded ferruginous chert having a larger pore space than the original cherty siderite. The reduction in volume of iron mineral accompanying the alteration of the carbonate is partly compensated by several factors, the relative importance of which is not known—by mechanical slump and by the introduction of secondary iron oxide and quartz.

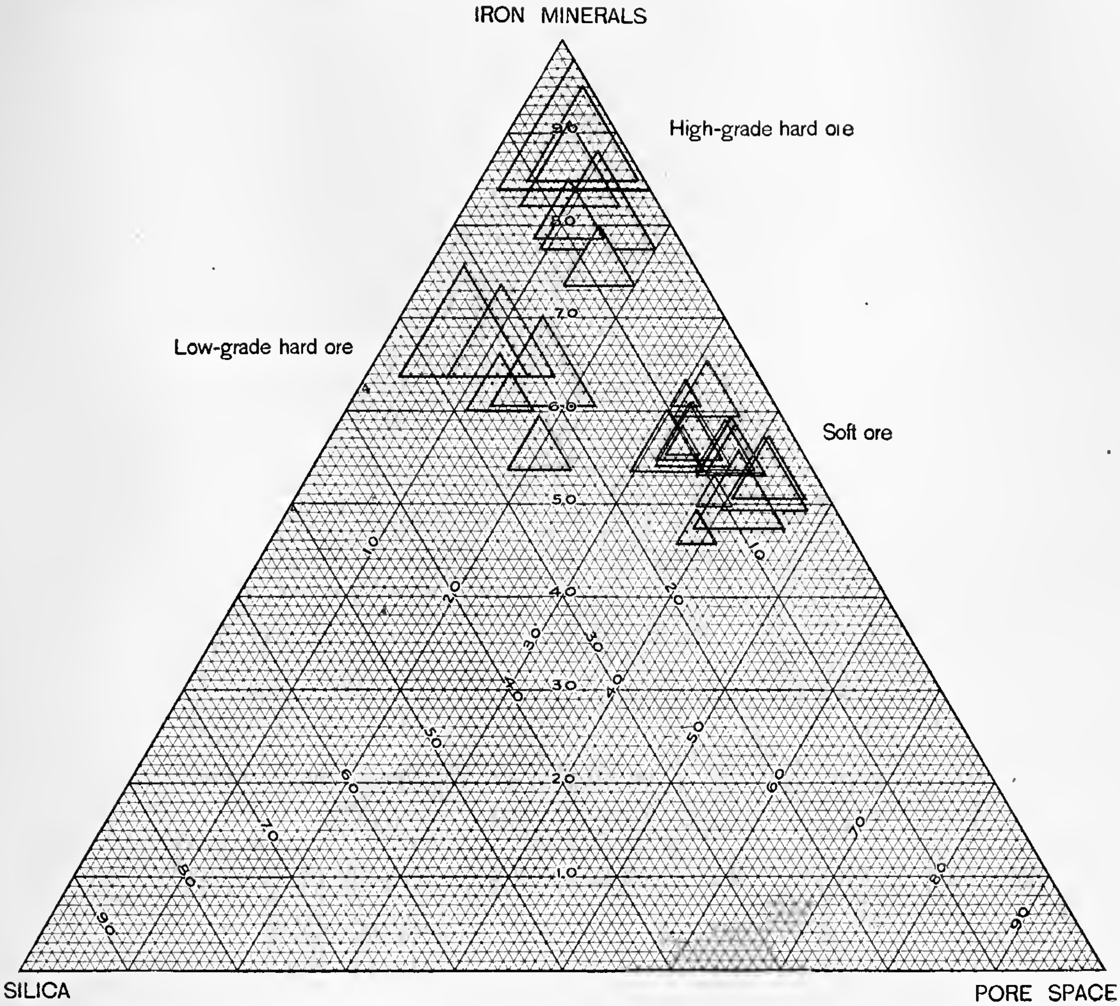


FIGURE 38.—Triangular diagram showing the volume composition of the several grades of ore mined in the Marquette district in 1906, in terms of pore space, iron minerals, and silica. The altitudes of the small triangles show in each case the amount of minor constituents (amphibole, clay, etc.)

The development of ore from the sideritic chert involves, in addition to the oxidation of the iron in place, the removal in solution of a considerable amount of quartz. This gives a still larger pore space, which again is partly compensated by slump and by infiltration of iron. Observation shows that the oxidation of the iron carbonate in place, producing ferruginous chert, mainly precedes the removal of the larger amount of silica. The oxidation of the iron is chemically more readily accomplished than the solution of silica; and, further, the consequent development of pore space affords opportunity for more abundant flow of solution to accomplish the solution of silica. When the passage of the ore bodies into the chert or jasper is examined in detail it is found that a siliceous band, if followed toward the ore, instead of remaining solid becomes porous and may contain considerable cavities. These places in the transition zone are lined with iron oxide. In passing toward the ore deposit more and more of the silica is found to have been removed, and iron oxide has partly replaced it. An examination at many of the localities shows this transition from the banded ore and jasper to take place as a consequence of the removal of the silica and the partial substitution of iron oxide. In many such instances the fine-grained part of the ore is that of the original rock, and the coarser crystalline material is a secondary infiltration. It is not uncommon, however, for the ore deposits to terminate abruptly along joint cracks or fractures.

The solution of quartz and the introduction of iron oxide ultimately produce the soft ores from the ferruginous cherts. These soft ores, as the diagram shows, have an average porosity of about 36 per cent and are made up essentially of hydrated iron oxide, quartz, and clay. The iron oxide largely represents siderite oxidized in place, but partly represents iron secondarily introduced.

The development of the hard ores is accomplished by pressure or igneous contact action on the soft ores, causing a reduction in volume of approximately 40 per cent or less, by decreasing the porosity, dehydrating the iron oxide, and developing some magnetite and certain metamorphic ferromagnesian, aluminum-bearing minerals, such as amphibole and garnet.

Representation of ores and jaspers on triangular diagram.—The volume compositions of the various phases of the iron-bearing formation are represented in the triangular diagram, figure 38. (For explanation see p. 189.) The lines of demarcation between the hard and soft ores and between the low and high grade hard ores are not as sharp as the grouping of the small triangles would indicate. Typical specimens of each grade were selected and intermediate phases were neglected. If all phases were represented the entire upper corner of the large triangle would be covered with small ones, indicating complete gradation between the various classes of ore.

SEQUENCE OF ORE CONCENTRATION IN THE MARQUETTE DISTRICT.

1. The alteration of the Negaunee formation began before upper Huronian time, when the formation had been slightly folded, eroded, and intruded by igneous rocks. Prior to upper Huronian time all the phases of the iron-bearing formation now known, except the specular hematites, had been developed, for all of them appear as pebbles in the basal conglomerate of the upper Huronian, and it is unlikely that such closely intermingled diversity of pebbles could have been developed from a single type of iron-bearing material after it had been deposited as pebbles in the conglomerate at the base of the upper Huronian. Erosion was not deep, and ores seem to have been developed only near the erosion surface which bevels at a low angle the upper beds of the Negaunee formation and now constitutes the horizon exposed nearest to the overlying upper Huronian conglomerate. That ores were formed at this time and place is indicated by the fact that at this horizon occur specular hematites having a secondary cleavage developed during the folding which followed the deposition of the upper Huronian and which preceded the second great period of ore concentration.

2. Inter-Huronian alteration of the formation was interrupted by the deposition of the upper Huronian (Animikie group), the base of which was made up of conglomerate carrying fragments of ferruginous chert and iron ore derived from the Negaunee formation. A higher formation (Bijiki schist) contained iron carbonate.

3. The deposition of the upper Huronian was followed by severe folding and both intrusion and extrusion of the basic igneous rocks. Much of the intrusion preceded the folding, for the cleavage in the sedimentary beds developed during the folding, and, having an attitude determined by the differential movement between the folds, affects also the intrusive rocks. Many of these post-upper Huronian (Keweenawan) intrusive rocks are now found in the area of the Negaunee formation. It is certain that some of them—as, for instance, those in the vicinity of Michigamme—represent laccolithic masses which were unable to penetrate above the massive Goodrich quartzite and spread out in the upper portion of the Negaunee formation. The intrusion and folding, with varying relative effectiveness in different parts of the range, anamor-

phosed the iron-bearing formations, but with widely differing results, depending on the conditions of the iron formation before the anamorphism. The ferruginous cherts and ores of the upper horizons of the Negaunee formation were changed to hard hematites and jaspers, becoming specular when folded. The iron-bearing conglomerate at the base of the Goodrich quartzite was similarly affected. The iron carbonate of the Bijiki schist of the upper Huronian was changed into a coarsely crystalline amphibole-magnetite rock. Portions of the formations farther removed from the intrusive rocks were less anamorphosed. These would include the part of the Bijiki schist near the Bessie mine and the lower part of the Negaunee formation, both of which up to this time still remained as iron carbonate.

Post-Keweenawan erosion exposed all phases of the iron-bearing Negaunee formation, together with the ferruginous detrital base of the upper Huronian and the still unaltered carbonates higher in the upper Huronian. The iron carbonates, both of the lower parts of the Negaunee formation and of the Bijiki schist, now for the first time exposed, became altered in the ordinary manner, producing soft ores associated with soft ferruginous cherts, now found typically along the Teal Lake range and in the Bessie mine of the western Marquette district. The other phases of the Negaunee formation, which had been previously altered to chert, jasper or iron ore, or amphibole-magnetite rocks, were also attacked to some extent, principally by the leaching of silica, which can be conspicuously observed in the loss of chert pebbles from the conglomerate at the base of the upper Huronian, and by alteration of garnets and amphibole to chlorite. The total effect of the alteration at this time on these harder phases, however, was probably not so essential in the concentration of the ore deposits as that which had gone on before.

The great varieties of phases of the iron-bearing rocks of the Marquette district are therefore the results of katamorphic and anamorphic processes described in earlier pages, acting alone or successively on different parts of the iron-bearing formations.

OCCURRENCE OF PHOSPHORUS IN THE MARQUETTE ORES.

DISTRIBUTION OF PHOSPHORUS.

The ores of the Marquette range are as a whole higher in phosphorus than those of the Vermilion, Mesabi, or Gogebic districts. They also show a greater range in phosphorus content than the ores of any of these three districts. Of the total shipments of ore from the Marquette range in 1906 approximately 18 per cent was of Bessemer grade. The lowest phosphorus grade was Sheffield (Fe = 64.61, P = 0.029, P/Fe = 0.000448), and the highest phosphorus grade was Cambridge (Fe = 59.60, P = 0.570, P/Fe = 0.00957).

The phosphorus and iron contents of the ores of the Marquette range are shown in the following table:

Phosphorus and iron content of Marquette ores.

	Iron.	Phosphorus.	Ratio of phosphorus to iron.
Average total shipments for 1906	59.55	0.1072	0.00180
Average ore from bottom horizon of the Negaunee formation	58.38	.103	.00176
Average ore from the middle horizon of the Negaunee formation	57.22	.096	.00168
Average of ore from upper horizon of the Negaunee formation	59.00	.063	.00107
Average ores from upper Huronian Bijiki schist	55.91	.359	.00642

Six hundred partial analyses of jasper carrying between 20 and 50 per cent of iron, representing 10,450 feet of drill holes in the area south of Negaunee, showed an average of 35 per cent of iron and 0.050 per cent of phosphorus.

The local distribution of phosphorus in the ores is extremely irregular. In many ore bodies the phosphorus content is found to increase as the greenstone or soap rock (altered greenstone) walls are approached. This is shown by the following analyses of ore and greenstone collected from the Chicago shaft of the Lake Superior Iron Company:

Partial analyses of ore and greenstone from Chicago shaft.[a]

	P.	Al_2O_3.	CaO.
Ore 2 feet from foot wall	0.112	1.12	0.19
Paint rock (altered greenstone) 2 feet from contact	.192	4.67	.15
Greenstone foot wall, soft, 8 feet from contact	.132	....	....
Greenstone foot wall, hard, 8 feet from contact	.134	7.89	.13
Greenstone foot wall, hard, 33 feet from contact	.064	....	....
Greenstone foot wall, hard, 70 feet from contact	.106	....	....
Altered greenstone (soap rock) at contact [a]	.181	6.41	.22
Fresh greenstone 80 feet from contact [a]	.090	15.30	.14

[a] The last two samples were from another part of the deposit.

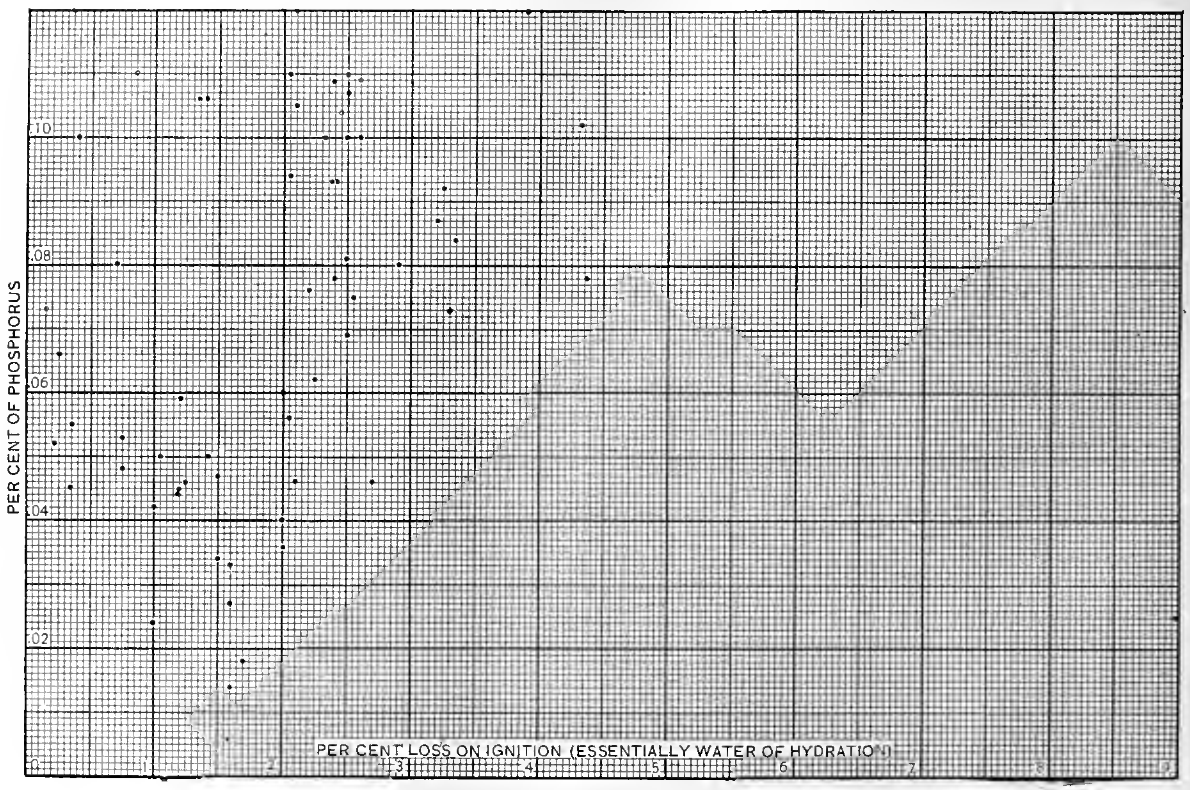


FIGURE 39.—Diagram showing relation of phosphorus to degree of hydration in Marquette ores.

Local variations in phosphorus also occur apparently independent of relations to greenstone walls or channels of flow, being due, perhaps, to original differences in the iron-bearing formation. Typical of this is an occurrence in the Volunteer mine, where high-phosphorus ore is found against hanging-wall jasper and low-phosphorus ore against the jasper foot wall.

The increase of phosphorus with degree of hydration is shown in figure 39.

Two washing tests similar to those made on Mesabi ores (see p. 193) were made on samples of soft red hematite ore from the Lake Angeline mine and the Hartford mine. The results of these tests are shown in the following table:

Partial analyses from washing tests on Marquette ores.

	Fe.	P.	Al_2O_3.	H_2O.
Lake Angeline mine:				
Heavy residue	65.00	0.078	0.89	2.12
Medium	62.55	.100	1.56	2.43
Finest material	61.20	.106	2.20	3.40
Hartford mine:				
Heavy residue	62.23	.126	2.36	1.82
Medium	60.39	.100	2.27	2.56
Finest material	60.07	.080	2.64	2.32

The test on the Lake Angeline ore gave results similar to those obtained from the tests on Mesabi ore, showing the association of phosphorus with the more hydrated parts of the ore. The washing test on the Hartford ore, however, does not show this relation.

MINERALOGICAL OCCURRENCE OF PHOSPHORUS.

Phosphorus is known to occur as apatite, dufrenite, and as aluminum phosphate. It probably occurs in a variety of combinations with iron, magnesium, calcium, and aluminum and in forms too minute to be identified. Apatite has been identified by Prof. Seaman[a] and others at a number of localities in the Negaunee formation and in the upper Huronian iron-ore deposits. In the chemical determination of phosphorus it is found that only a part of it is soluble in hydrochloric acid, the insoluble portion remaining with the siliceous residue. This seems to indicate that phosphorus is present in at least two combinations. The soluble phosphorus may be present in a variety of combinations, as iron phosphate, calcium phosphate, and some aluminum phosphates are soluble in hydrochloric acid. Charles T. Mixer and H. W. Dubois[b] analyzed the insoluble residue remaining after treating ore with hydrochloric acid (1.10 specific gravity) and found its composition in percentages of original residue to be Al_2O_3 9.55, CaO 0.92, P_2O_5 4.10, from which they concluded that the insoluble phosphorus is to a large extent combined with alumina. What this aluminum phosphate is it is impossible to say. It is of interest to note that the relative amounts of soluble and insoluble phosphorus are not uniform in the various ores; in some the insoluble form is entirely absent, but in others it makes up the greater part of the phosphorus present. It is believed by some of the chemists of the iron range that the insoluble phosphorus is highest in ores high in alumina. In order to ascertain the possibility of the phosphorus being present as apatite, the percentages of calcium oxide and phosphorus, in the different grades of ore produced in 1906, were platted as ordinates and abscissas in figure 40. The diagonal line indicates the relative amounts of the two constituents in apatite. It may be seen that most of the points fall below the line, indicating an excess of lime over the amount required to combine with the phosphorus present as apatite. It is of interest to note that the high phosphorus ores are correspondingly high in lime, indicating rather strongly the possibility of at least a large part of the phosphorus being present in apatite.

PHOSPHORUS IN RELATION TO SECONDARY CONCENTRATION.

As shown in the table on page 279, there is apparently a gradation in the phosphorus content of the ores of the Negaunee formation, from comparatively low phosphorus in those of the upper horizon to high phosphorus in those of the bottom horizon. The difference is most marked between the hard ores of the upper horizon and the soft ores of the middle horizon. The difference between the ores of the two lower horizons is very small and may be apparent rather than real. In explanation of the difference in phosphorus content between the hard and soft ores may be cited the opportunity for leaching of phosphorus from the upper strata during the erosion interval previous to the deposition of the Goodrich quartzite. Another possibility may be an original difference in the phosphorus contents of the ores at the two horizons.

[a] Personal communication.

[b] Jour. Am. Chem. Soc., vol. 19, No. 8, p. 619.

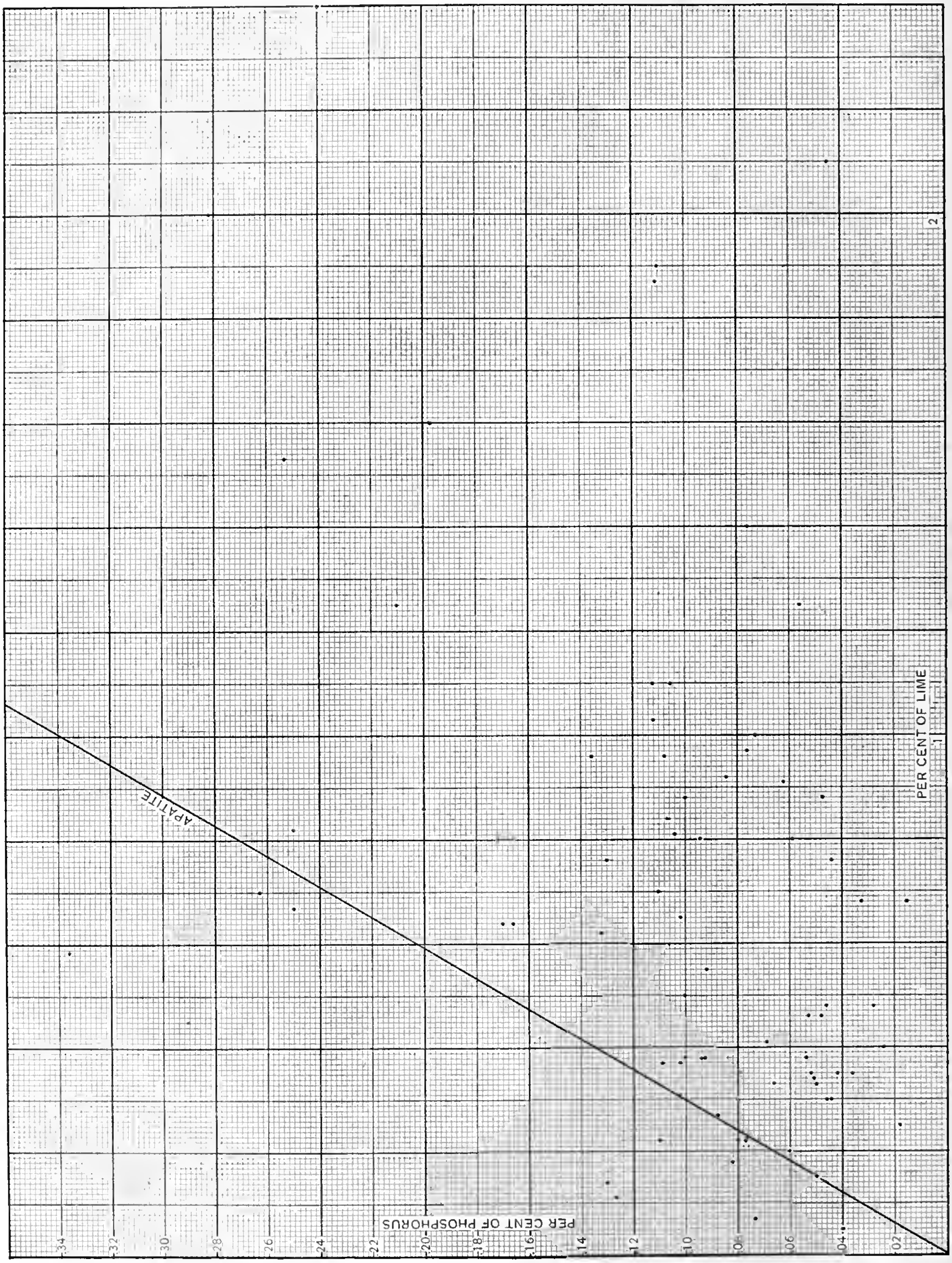


FIGURE 40.—Diagram showing relative amounts of phosphorus and lime in Marquette ores.

The abundant slaty phases of the Michigamme may have some bearing on the high phosphorus of the ores, as in all the iron districts the slates are higher in phosphorus than the iron-bearing formation proper.

The local occurrence of high-phosphorus ore near greenstone contacts is believed to be due to direct transfer of that constituent, leached from the greenstone during its alteration to soap rock or paint rock and deposited in the neighboring ores. The analyses on page 280 show that there is actually a loss of phosphorus in the alteration of the greenstone if alumina is assumed to have remained constant, although the actual percentage of phosphorus increases.

Local variations, apparently not related to greenstone contacts, are probably due to original differences in the phosphorus content of the formation and not to secondary transfer or infiltration.

SWANZY DISTRICT.

GEOGRAPHY AND TOPOGRAPHY.

The Swanzy iron district lies about 16 miles south of the city of Marquette, in T. 45 N., R. 25 W. (fig. 41). In 1908 the productive area was less than 2 miles long and about half a mile wide and contained five producing mines. Future exploration and development will undoubtedly extend the district to the south and east, but northward and westward extensions are apparently cut off by the granite area that bounds the district on these sides. The towns within the producing area are Gwinn and Princeton, both reached by the Munising Railway. The district occupies a range of hills typical of the granite area, and slopes on the south and east to a flat sand-covered plain above which stand a few monadnocks of pre-Cambrian rocks.

GENERAL SUCCESSION AND STRUCTURE.

The succession is as follows:

Quaternary system:
- Pleistocene .... Glacial deposits.

Cambrian sandstone.
Ordovician limestone.
Unconformity.
Algonkian system:
- Huronian series:
  - Upper Huronian (Animikie group):
    - Michigamme slate.
      - Bijiki iron-bearing member. In lenses and layers near base of Michigamme slate.
    - Goodrich quartzite. Quartz slate and quartzite, grading down into arkose or recomposed granite.

Unconformity.
Archean system:
- Laurentian series .... Granite.

The Swanzy district consists of a southeastward-pitching synclinorium of upper Huronian rocks, bounded on all but the southeast side by Archean granite. It is about 2 miles long; its width is for the most part not more than three-quarters of a mile, and at the narrowest point, near the Stevenson mine, is only half a mile. To the southeast it widens, but in this direction the structure is not known because of the deep overburden. The pitches of the minor folds at the Stegmiller, Princeton, and Swanzy mines are toward the northwest. The slates have developed a good cleavage, usually crossing the bedding. This structure does not affect the quartzite and the iron-bearing member.

ARCHEAN SYSTEM.

The Archean forms the basement upon which the Huronian sediments lie. It is represented by granites similar to the basal granites of the neighboring iron ranges.

The Archean bounds the district on the north, west, and southwest sides. Isolated exposures stand as monadnocks above the flat sand plains of the district.

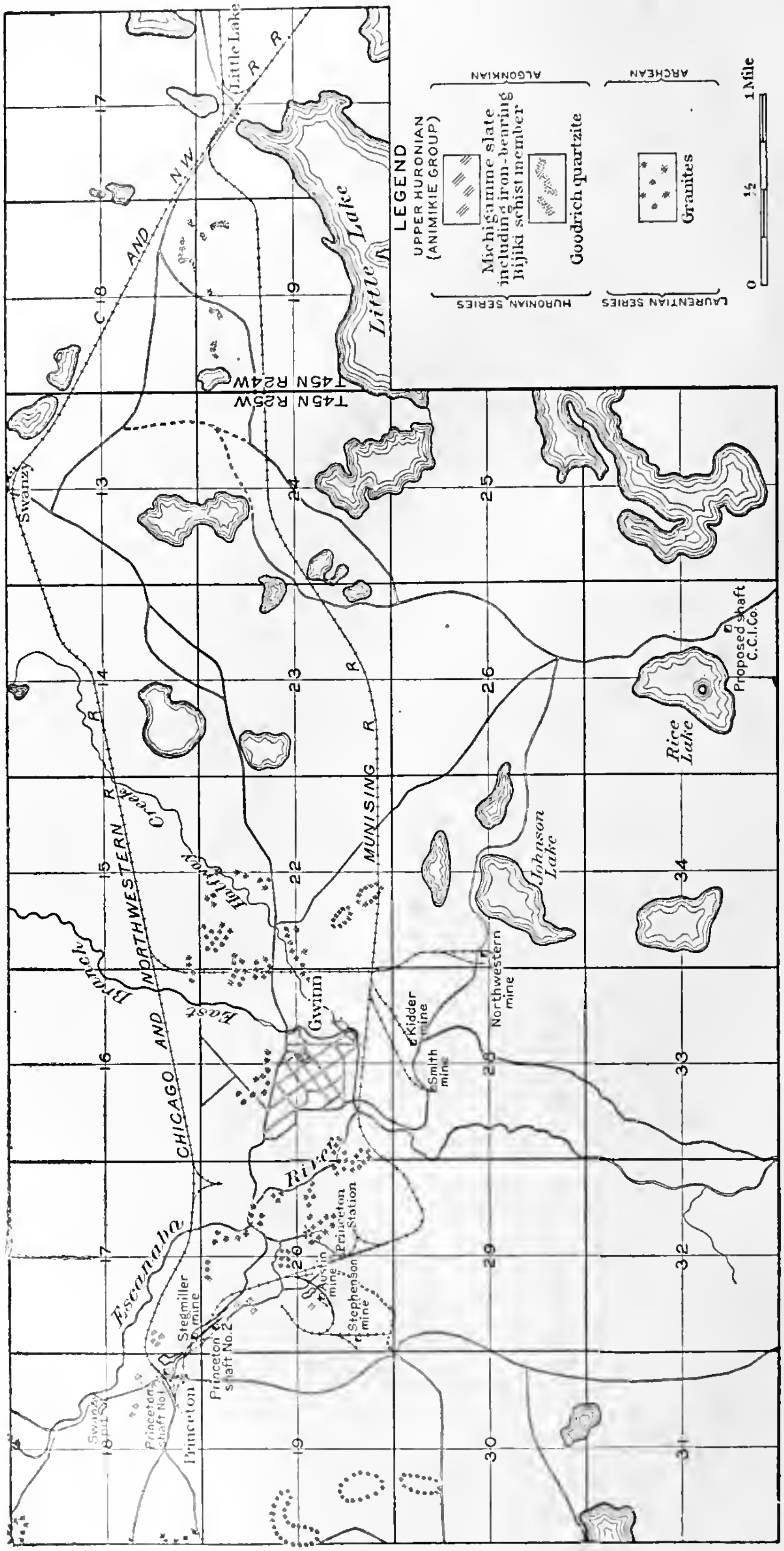


FIGURE 41.—Outcrop map of Swanzy district, Michigan. Compiled from information furnished by Cleveland-Cliffs Iron Company and others.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

UPPER HURONIAN (ANIMIKIE GROUP).

GOODRICH QUARTZITE.

The Goodrich sediments lie unconformably upon the Archean rocks. They consist of a coarse arkose or recomposed granite at the base, which grades upward through quartzite and quartz slate to the Bijiki iron-bearing member of the Michigamme slate. The arkose horizon represents a shore phase of sedimentation where disintegration was very active and rapid transportation of the disintegrated material prevented decomposition. In places the arkose is distinguished from the granite with difficulty. The quartzite is petrographically very similar to the Goodrich quartzite of the Marquette range and exhibits all phases of gradation between the arkose below and a thin-bedded quartz slate above. Both the quartzite and the quartz slate are locally iron stained, and in places the impregnation is so strong as to have attracted prospecting operations. The arkose phase is best exhibited in drill cores. The quartzite and quartz slate phases are well exposed in abundant outcrops on the north slope of the range of hills which crosses sec. 19, T. 45 N., R. 24 W. The quartzite also outcrops in a small hill near the northeast corner of sec. 18, T. 45 N., R. 24 W.

The thickness of the quartzite and the quartz slate varies and locally the slate and jasper lie directly on the recomposed granite or on the granite itself.

MICHIGAMME SLATE.

The Michigamme slate is best exposed at the old Swanzy open pit, near the center of sec. 18, T. 45 N., R. 25 W., where it is found in contact with the Bijiki iron-bearing member. It both underlies and overlies the iron-bearing beds, which are therefore treated as a member of the slate. The Michigamme forms much the larger part of the upper Huronian.

The iron-bearing member is a banded ferruginous chert or "soft-ore jasper" similar in appearance to part of the Bijiki schist of the Marquette range. Locally it grades into a ferruginous slate. It apparently occurs in lens-shaped beds in and near the base of the Michigamme slate, and therefore it is treated as a member of that formation. Drilling and mining operations have shown jasper with slate above and below, or slate above and quartzite below, or in places the iron-bearing member is found directly above the arkose and overlain by slate, the quartzite and quartz slate being absent. The iron-bearing member is exposed at several places in the vicinity of the Princeton, Stegmiller, and Austin mines and also in the old Swanzy open pit. An exposure near the center of the SE. $\frac{1}{4}$ sec. 18, T. 45 N., R. 25 W., shows typical banded soft-ore jasper with a nearly vertical dip. Near the southeast corner of the same section, just west of the Stegmiller mine, is a similar exposure. An exposure about 600 feet west of Princeton station shows the member folded and contorted.

PALEOZOIC SEDIMENTS.

On the east side of the district flat-lying sandstones and limestones belonging to the Cambrian and Ordovician overlap the pre-Cambrian formations unconformably. The nearest exposure of limestone is in the northeast corner of sec. 18, T. 45 N., R. 24 W., where a small hill of quartzite has a few remnants of a limestone capping.

QUATERNARY DEPOSITS.

Pleistocene sand flats of glacial origin cover most of the district. (See Chapter XVI, pp. 427–459.)

CORRELATION.

The upper Huronian (Animikie group) is very similar, both in stratigraphy and in lithology, to the upper Huronian of the Marquette district on the north and the Crystal Falls and Menominee districts on the south.

THE IRON ORES OF THE SWANZY DISTRICT.

By the authors and W. J. Mead.

GENERAL DESCRIPTION.

The ores of the Swanzy district are in the Bijiki iron-bearing member, which is interbedded with the lower part of the Michigamme slate of the upper Huronian and rests upon the Archean granite with only a comparatively thin intervening zone of quartzites, quartz slate, or recomposed granite, constituting the Goodrich quartzite. The upper Huronian constitutes a southeastward-pitching synclinorium, but some of the minor folds on its limbs pitch to the northwest. They are of the drag type so common to the Lake Superior region. (See fig. 12, p. 123.) The iron-bearing member takes part in this general structure. The ores therefore appear as much-folded deposits with foot wall of slate, quartzite, recomposed granite, or granite and with hanging wall of black slate. All the ore deposits reach the erosion surface either at the border of the synclinorium or on the eroded minor anticlines in the main synclinorium.

Five mines are in operation and several additional ore deposits are known. (See map, fig. 41.)

The ore is a soft hydrated non-Bessemer hematite containing a rather high percentage of moisture. The following is the average composition of ore shipped in 1906:

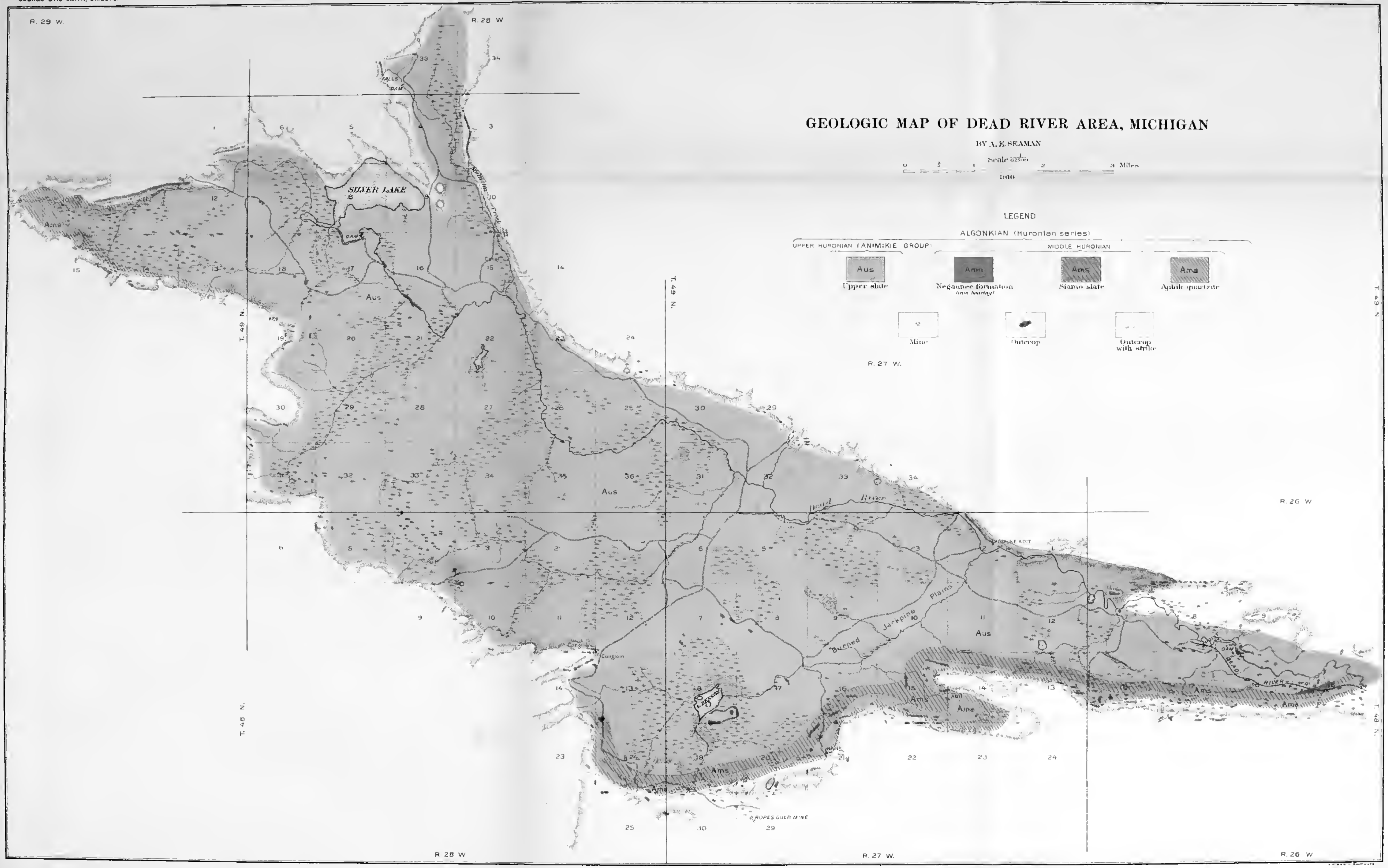
Average composition of ore shipped from Swanzy district in 1906.

Moisture (loss on drying at 212°)	13.50
Analysis of dried ore:	
Iron	58.60
Phosphorus	.211
Silica	10.20
Manganese	.71
Alumina	1.05
Lime	1.15
Magnesia	.46
Sulphur	.012
Loss by ignition	1.25

SECONDARY CONCENTRATION OF SWANZY ORE.

The structural conditions governing the concentration of the ores in the Swanzy district are a foot wall of granite, quartzite, or slate and a hanging wall of slate, conforming to the structure of a synclinorium that has a gentle southeastward pitch with many minor variations. Erosion has exposed the iron-bearing member near the borders of the synclinorium and along the arches of the minor anticlines. The circulation of the iron-bearing solutions has obviously been controlled not only by the impervious basement but by the overlapping impervious formations which determined their points of escape.

The ores and ferruginous cherts have been derived from the alteration of sideritic cherts and slates, accompanied by the removal of silica and the development of pore space.


GEOLOGIC MAP OF DEAD RIVER AREA, MICHIGAN
BY A. E. SEAMAN
Scale
3 Miles
1910
LEGEND
ALGONKIAN (Huronian series)
UPPER HURONIAN (ANIMIKIE GROUP)
MIDDLE HURONIAN
Aus
Upper slate
Amn
Negaunee formation
Ams
Siamo slate
Ama
Ajibik quartzite
Mine
Outcrop
Outcrop with strike
R. 29 W.
R. 28 W.
R. 27 W.
R. 26 W.
T. 49 N.
T. 48 N.
SILVER LAKE
Dead River
Burned Jackpine Plains
HOLYOKE ADIT
ROPES GOLD MINE
DAM
FALLS

DEAD RIVER AREA.[a]

The Dead River area lies north of the Marquette district along the Dead River. Its greatest extent is 18 miles west-northwest and east-southeast. Its maximum width is 6 miles. (See Pl. XX.) The basin is largely a low, flat sand-covered plain with an amphitheater of rock-exposed hills about it.

GENERAL SUCCESSION.

The general succession is as follows:

Quaternary system:
  Pleistocene deposits.
Unconformity.
Algonkian system:
  Huronian series:
    Upper Huronian (Animikie group) .... Slates and conglomerate.
    Unconformity.
    Middle Huronian .... { Negaunee formation (iron bearing). Siamo slate. Ajibik quartzite.
Unconformity.
Archean system:
  Laurentian series .... Granite intrusive into Keewatin series.
  Keewatin series, including Kitchi and Mona schists.

The Laurentian and Keewatin rocks occupy the hills surrounding the basin; the middle Huronian rocks outcrop along the margin of the basin, and the upper Huronian (Animikie group) occupies nearly all of the basin itself.

ARCHEAN SYSTEM.

KEEWATIN SERIES.

The Keewatin series forms hills along the northeast and southeast sides of the basin. The series includes on the south side the Kitchi and Mona schists, already described for the Marquette district, and on the north side schists entirely similar in aspect, even to their content of iron-bearing sediments consisting of jasper, cherty siderite, and cherty slate. Slate and conglomerate are well exposed at the German exploration in sec. 35, T. 49 N., R. 27 W., and in the Holyoke mine on the south side of the hill.

LAURENTIAN SERIES.

Laurentian granites and gneisses bound the Dead River district on the southwest, west, and northwest and also for a short distance along the southeast end. They are not different from the rocks of the northern complex of the Marquette district.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

Middle Huronian.—The middle Huronian is exposed along the south and southeast sides of the district and also at the extreme west end bordering the amphitheater of Keewatin and Laurentian rocks. The best exposed of these rocks is the Ajibik quartzite, forming the base of the middle Huronian, and showing unconformity between Laurentian and middle Huronian by discordance in structure and by conglomerates.

The Siamo slate outcrops in a narrow belt along the north side of the Ajibik quartzite where it follows the south boundary of the district.

The Negaunee formation (iron bearing) is exposed in only one area, in sec. 15, T. 48 N., R. 26 W., along the railway track and in pits. Here the iron-bearing formation, with the under-

[a] Mapped by A. E. Seaman, Michigan College of Mines.

lying Siamo slate and Ajibik quartzite is much folded. Overlying the iron-bearing formation (in direct contact in pits) is the basal conglomerate of the upper Huronian, containing fragments both of middle Huronian and Keewatin.

Upper Huronian (Animikie group).—The upper Huronian consists principally of slates, similar in all respects to the Michigamme slate of the Marquette district. They outcrop in isolated exposures over the area and their presence is further indicated by the prevailing low relief of the basin. The base of these rocks is probably marked by the conglomerate resting unconformably on the Keewatin series at the Holyoke mine and eastward at intervals to the east end of the basin; also by the conglomerate covering the Negaunee formation, already referred to. The slates have not been connected directly with the conglomerate, but the fact that the conglomerate contains fragments not only of Keewatin but of middle Huronian rocks seems to require its correlation with the upper Huronian.

Greenstone dikes cut the slates. One of them constitutes the falls of Dead River where it cuts through the slates in sec. 9, T. 48 N., R. 26 W.

PERCH LAKE DISTRICT (INCLUDING WESTERN MARQUETTE).

GEOGRAPHY AND TOPOGRAPHY.

The Perch Lake district includes territory extending west from the Marquette district and north from the Crystal Falls and Iron River districts to a line extending from L'Anse Bay on the northeast to the south end of Lake Gogebic on the southwest. The area thus defined includes roughly 1,200 square miles. (See fig. 42; Pl. XXI, in pocket.) A topographic map has been prepared of the area around Perch Lake, extending from 88° 30′ to 88° 45′ west and 46° 15′ to 46° 30′ north. The remainder of the country has not been surveyed topographically. As a whole the country is characterized by morainal topography with much local irregularity, but has no conspicuous ranges characteristic of the principal ore-producing districts.

GENERAL SUCCESSION.

The succession is as follows, from the top downward:

Quaternary system:
- Pleistocene or glacial deposits.

Cambrian sandstone.

Algonkian system:
- Huronian series:
  - Upper Huronian (Animikie group):
    - Michigamme slate (slates and graywackes with possible iron-bearing lenses). Equivalent and areally continuous with the Michigamme slate of the Crystal Falls, Iron River, and Menominee districts.
    - Goodrich quartzite (quartzites and conglomerates).
  - Middle Huronian:
    - Intrusive diorite.
    - Negaunee formation (iron bearing).
    - Siamo slate.
    - Ajibik quartzite.

Unconformity.

Archean system:
- Laurentian series .... Granite and syenite.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

The Laurentian granite and syenite bound the district on the northeast. They show no features different from the Laurentian of the contiguous Marquette district. The rocks are abundantly exposed. The topography of the Archean area is as a whole rougher and more irregular than that of the Algonkian on its southwestern margin, affording a very satisfactory guide for discrimination in the field mapping. The Archean underlies the Huronian unconformably.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

Middle Huronian.—Between the upper Huronian slates and graywackes (Michigamme slate) and the Archean granite on the northeast there appears a belt about 5 miles long extending from the Marquette district northwest, in which are exposed middle Huronian sediments and upper Huronian Goodrich quartzite. (See fig. 42.) The middle Huronian Ajibik quartzite and Siamo slate show no features different from those of the Marquette district. They rest unconformably against the Archean. On the northwest and along their trend they become covered by glacial materials until they can no longer be followed. Presumably they extend

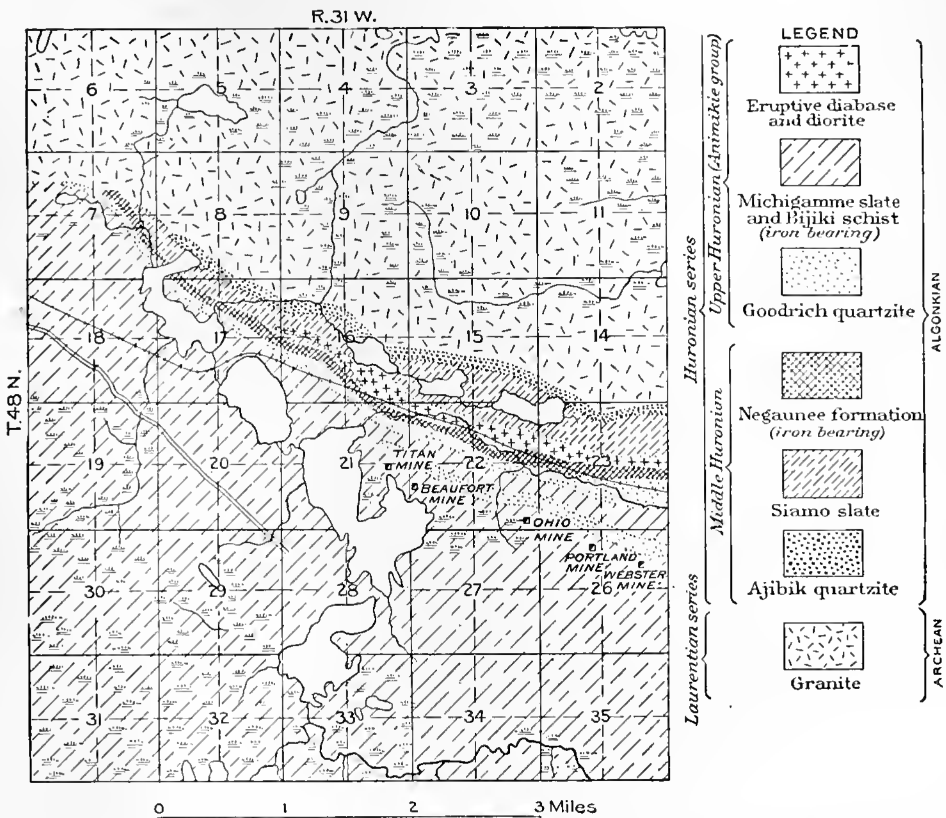


FIGURE 42.—Geologic map of west end of Marquette district, Michigan. By W. N. Merriam and M. H. Newman.

considerably farther than the map indicates. The Negaunee formation also is similar to the Negaunee formation of the Marquette district. It is followed, however, principally by magnetic observations to the point indicated on the map, where it is lost beneath the covering of later drift. Whether it extends farther or whether this represents the end of the originally deposited iron-bearing lens is not known.

Upper Huronian (Animikie group).—The district is underlain principally by upper Huronian slates and graywackes, known as the Michigamme slate. On the northeast they rest unconformably against the Archean granite and middle Huronian rocks. On the northwest they are overlain by Cambrian sandstone, the relations of the two locally being obscured by faulting. The Goodrich quartzite of the upper Huronian is exposed only in the northeastern part of the area bordering the middle Huronian and at the northwest end, presumably overlapping on the Archean. Its characteristics are similar to those of the Goodrich quartzite of the Marquette district. The Michigamme slate covers much the larger part of the Perch Lake area. Exposures are fairly abundant, especially in the Perch Lake district. Presumably contemporaneous basic volcanic rocks are associated with these slates, to judge from the facts observed to the south, but their detailed distribution is not known. There is difficulty in identifying horizons in the slate and graywacke, and therefore in working out the structure of this area. From the abundance of exposures, however, it is probable that this may be accomplished in the future. The locations of most of the exposures have been noted in commercial surveys, but the Geological Survey has not examined this area in detail to work out the structure. From the promising development in similar series in the adjacent Iron River district, it would seem that this area would warrant careful examination for iron-bearing lenses.

QUATERNARY DEPOSITS.

Pleistocene glacial deposits cover all of this area. (See Chapter XVI, pp. 427–459.)

CHAPTER XII. THE CRYSTAL FALLS, STURGEON, FELCH MOUNTAIN, CALUMET, AND IRON RIVER IRON DISTRICTS OF MICHIGAN AND THE FLORENCE IRON DISTRICT OF WISCONSIN.

The Crystal Falls, Sturgeon, Felch Mountain, Calumet, and Iron River iron districts of Michigan and the Florence iron district of Wisconsin together form the ore-producing area between the Marquette district on the north and the Menominee district on the south. (See fig. 43.) The ores of all these districts occur in the upper Huronian (Animikie group) and have many similarities in kind and relations, and the limits of the several districts are poorly defined. They are accordingly grouped together in one chapter.

CRYSTAL FALLS IRON DISTRICT.[a]

LOCATION AND AREA.

The Crystal Falls district is centered in the town of that name in the Northern Peninsula of Michigan. (See Pl. XXII, in pocket.) As the term is here used it includes an area of about 540 square miles, covering all the territory between the Marquette and Menominee districts as these have been limited on the maps of the United States Geological Survey. In commercial parlance the Menominee district includes the Crystal Falls and southwestward extensions, and reports of shipments for the Menominee district include these districts. However, they are geologically and structurally more or less independent and have been treated in two reports,[b] hence here the Crystal Falls district will be treated independently of the Menominee district. The Felch, Sturgeon, and Calumet troughs bordering the Crystal Falls district on the southeast are also discussed in this chapter, as well as the Iron River and Florence districts, which lie to the south and southwest.

GENERAL SUCCESSION AND STRUCTURE.

The succession is as follows:

Quaternary system:
- Pleistocene drift.

Cambrian sandstone (in southern and eastern parts of district).

Algonkian system:
- Huronian series:

Upper Huronian (Animikie group)	Volcanic rocks interbedded with slates. Michigamme slate. Thickness unknown, but probably several thousand feet. Vulcan iron-bearing member, 300 feet.
Unconformity (?).	
Middle Huronian (?)	Negaunee (?) formation (iron bearing). Ajibik quartzite. Hemlock formation (volcanic), 1,000 to 10,000 feet. Includes at top iron-bearing slate member, 1 to 1,900 feet thick, formerly called "Mansfield slate."
Unconformity (?).	
Lower Huronian	Randville dolomite, 500 to 1,500 feet. Sturgeon quartzite, 100 to 1,000 feet.

Unconformity.

Archean system:
- Laurentian series ... Granites and gneisses.

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[a] For further detailed description of the geology of this district see Mon. U. S. Geol. Survey, vol. 36, 1899, and references there given.

[b] Clements, J. M., and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899. Bayley, W. S., The Menominee iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 46, 1904.

The northeastern part of the area is underlain by Archean granites. Bordering this main Archean area on the southwest, with longer axes parallel and striking north-northwest and

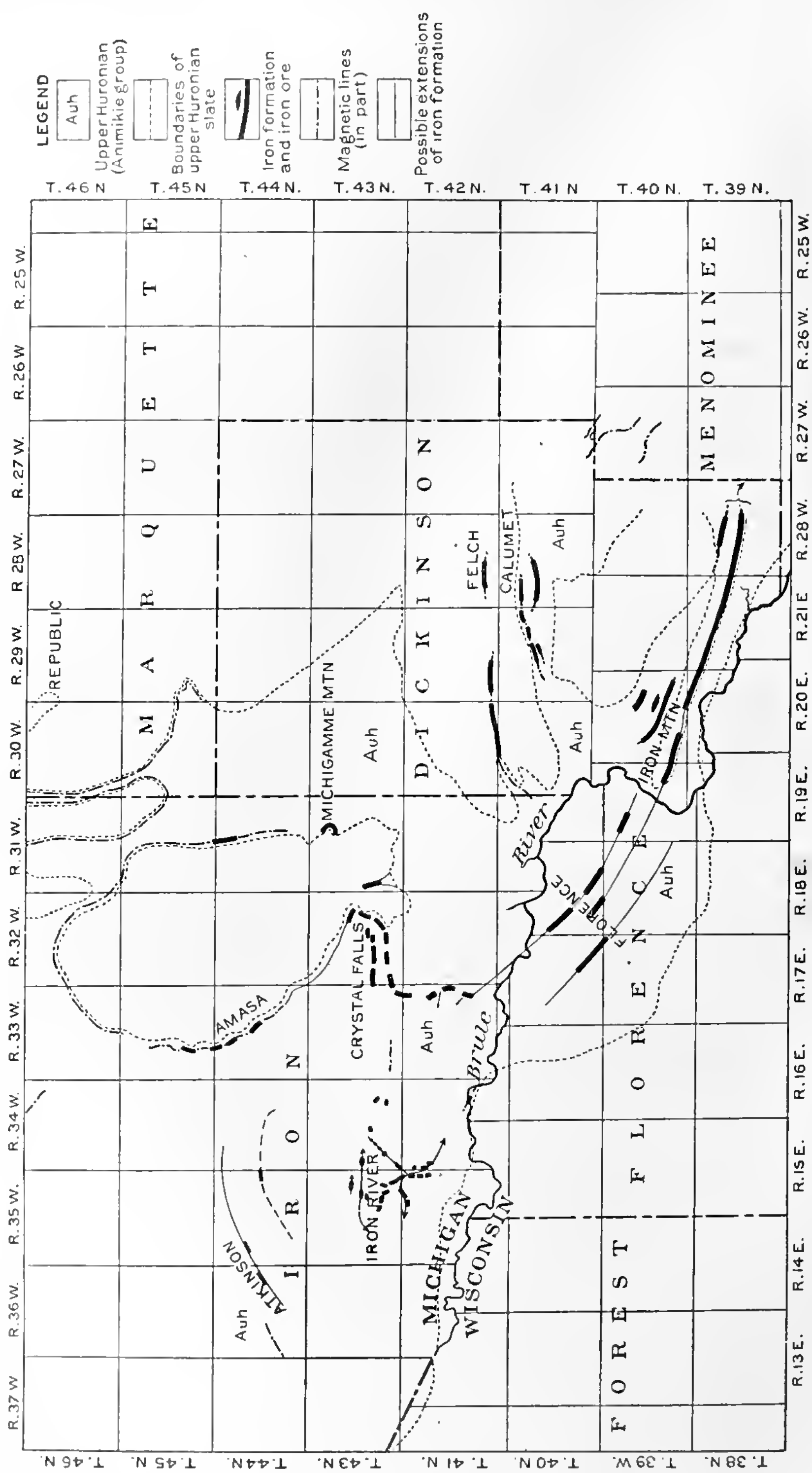


FIGURE 43.—Sketch map to show general relations of iron-bearing rocks, principally upper Huronian, in Crystal Falls, Iron River, Florence, and Menominee districts.

south-southeast, are two minor oval areas of Archean granite. Huronian sediments and basic igneous rocks, exposed principally in the western part of the district, lap around the Archean ovals and against the main Archean area to the northeast, and their general structure is determined by their relations to the Archean ovals. The Crystal Falls and Amasa districts are on the southwest side of one of these Archean ovals. Therefore both the dip and the pitch of the minor folds of the upper Huronian occupying these areas are in southwesterly directions.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

The Archean or basement rocks occupy the northeastern part of the district, filling the angle between the Crystal Falls and Marquette districts. To the west of this they also appear in two elliptical cores with longer axes north-northwest and south-southeast, approximately parallel to the axes of the major folds of the district.

The Archean rocks consist mainly of massive and schistose granites and of gneisses. Nowhere in them have any rocks of sedimentary origin been discovered. They have been cut by igneous rocks, both basic and acidic, at different epochs. These occur in the form both of bosses and of dikes, the latter in places cutting but more ordinarily showing a parallelism to the foliation of the schistose granites. The Archean granites and gneisses and the earlier intrusive rocks alike have been profoundly metamorphosed, and at several places have been completely recrystallized. In the westernmost oval there is to be observed a distinct arrangement of feldspar crystals with their longer dimensions parallel to the contact with the Huronian rocks.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER HURONIAN.

STURGEON QUARTZITE.

In the central part of the district the Sturgeon quartzite is represented only by thin fragmental layers at the base of the overlying Randville dolomite. These are too thin to be mapped. Its principal outcrops are to the southeast in the Felch Mountain and Sturgeon districts, described later in this chapter.

RANDVILLE DOLOMITE.

The Randville dolomite completely surrounds the Archean oval northeast of the town of Crystal Falls. Here it constitutes the base of the sedimentary series and rests directly upon the Archean with only thin intervening layers of fragmental quartzose dolomite and recomposed granite, all more or less altered to quartz schist and in many places difficult to distinguish from schistose phases of the granite itself.

On the west side of the western Archean oval the dolomite is poorly exposed and its thickness is not estimated. On the east side the belt is about half a mile wide and the thickness about 1,500 feet. The formation constitutes here an eastward-dipping monocline with minor plications. In the scattered outcrops of the Michigamme Mountain area the dolomite strikes and dips toward all points of the compass as a result of the gentle arching from the general northwest-southeast axis, combined with sharp local folds which run nearly east and west.

Petrographically the formation ranges from coarse saccharoidal marbles, in places very pure but usually filled with secondary silicates, to fine-grained, little-altered limestones, which are here and there so impure as to be calcareous or dolomitic sandstones and shales. The prevalent colors are white, but various shades of pink, light and deep blue, and pale green occur. Some of the varieties are oolitic. This structure does not seem to have been previously noted in limestones of pre-Cambrian age in the Lake Superior region.

MIDDLE HURONIAN (?).

HEMLOCK FORMATION.

Distribution and general character.—The volcanic Hemlock formation occupies a large area in the Crystal Falls district. It is believed almost to surround the westernmost Archean oval and also to occur in a great area northwest of Crystal Falls and in one isolated area near the Mastodon mine, south of Crystal Falls. Its general stratigraphic position is conformably above the Randville dolomite and beneath the upper Huronian slates, but like most volcanic formations its relations differ in different parts of the district in ways which will appear below. Well-bedded cherty slates, iron-bearing lenses, and limestone are interbedded with the Hemlock formation and also both underlie and overlie it. The volcanic extrusions may be regarded as interruptions of otherwise continuous deposition of sediments. The lack of continuity of the volcanic flows and of the interbedded sediments, and the difficulty of correlating the beds of either in different parts of the district, make it practically impossible to use geologic names for these sediments which will have anything more than very local significance. One of the principal local sedimentary units within the Hemlock formation has been described and mapped in the United States Geological Survey monograph on the Crystal Falls district[a] as the "Mansfield slate." Limestone and slate layers appear abundantly in the Hemlock formation near Hemlock River immediately northeast of the town of Amasa and in several other localities.

Area south and west of the westernmost Archean oval.—Exposures of the Hemlock formation are numerous west and south of the western Archean oval, and where erosion has removed the drift the formation has a marked influence on the topography. The thickness is estimated from the dip to reach 23,000 feet, but this is probably illusory because of reduplication due to folding. The formation here consists mainly of bedded surface basic extrusive rocks and crystalline schists derived from them. Sedimentary rocks play a subordinate part. The Hemlock rocks are similar in all respects to the Keewatin volcanic rocks and to the volcanic Clarksburg formation of the Marquette district. The formation is cut by a few acidic dikes and by numerous dikes and enormous bosses of basic rock. On the former Survey map of the district[b] certain of these were discriminated, but they are not discriminated on the accompanying map (Pl. XXII, in pocket), because more study has shown a most intimate association of extrusive and intrusive phases of the formation throughout the area. The acidic intrusive rocks include rhyolite porphyry and aporhyolite porphyry. The rhyolite porphyry shows interesting micropoikilitic textural characters. Acidic pyroclastic rocks are scarce and were derived from the aporhyolite. The basic lavas correspond to the modern basalts. They are much altered and are called "metabasalts." The basic lavas include nonporphyritic, porphyritic, and variolitic and ellipsoidal types. Clements[c] has described the ellipsoidal textures and concludes that basalts possessing this structure were originally very viscous and correspond to the modern aa lavas, probably of submarine origin. The pyroclastic rocks comprise eruptive breccia, including friction breccias and flow breccias, and volcanic sedimentary rocks. The eolian deposits, which are described as tuffs, grade from fine dust up to those in which the fragments are bowlders. The water-deposited volcanic fragmental rocks are known as volcanic conglomerates, and likewise range from those of which the particles are minute to those of which the fragments are very large. At many places occur clastic rocks which are now schistose and whose exact mode of origin—that is, whether eolian or water-deposited—could not be determined.

The crystalline schists of Bone Lake include rocks of completely crystalline character, which by field and microscopic study have been connected with the volcanic rocks and are considered to have been derived from rocks similar in nature to them.

In general some of the volcanic rocks are submarine. The greater proportion, however, were derived from volcanic vents, which could not be located, but were probably situated near the Huronian shore line. Clements suggested that volcanic activity began in the north and

[a] Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 54-73. [b] Idem, Pl. III. [c] Idem, pp. 112-124.

moved to the south, and that some of the volcanic deposits to the north are contemporaneous with the so-called "Mansfield slate."

Fence River area.—In the Fence River area the Hemlock formation occupies a belt between 2,000 and 3,000 feet in width, between the Randville dolomite on the west and the Negaunee formation on the east. The best exposures occur on the sections made by Fence River. No folds have been observed within the formation. The thickness probably ranges up to 2,300 feet as a maximum. The rocks of the formation in this area are chiefly chlorite and ophitic schists, with which are associated schists bearing biotite, ilmenite, and ottrelite, greenstone, conglomerates or agglomerates, and amygdaloids. As evidence of the origin of these schists several facts may be cited. First, they include no rocks possessing any sedimentary characters; next, lavas and also greenstone conglomerates or agglomerates are undoubtedly present in the series; furthermore, the minerals which compose the schist are those which would result from the alteration in connection with dynamic metamorphism of igneous rocks of basic or intermediate chemical composition; and finally, the grain and character of the groundmass and in some slides the presence of plagioclase microlites disposed in oval lines point directly to an igneous origin and to consolidation at the surface. The conclusion is reached that the Hemlock formation of the Fence River area is composed of a series of old lava flows varying in composition from acidic to basic.

Other areas of the Hemlock formation.—Other areas of volcanic rocks similar to those of the Hemlock formation appear to the north and west of the town of Crystal Falls, near the Mastodon mine, and elsewhere, as shown on the accompanying general map of the Crystal Falls district (Pl. XXII). Whether these are of the same age as the main mass of the Hemlock formation and owe their distribution to folding, or whether they are later extrusions, is not yet known.

Iron-bearing slate member ("Mansfield slate") of the Hemlock formation.—The so-called "Mansfield slate," which is interbedded near the top of the Hemlock formation, is best exposed in the vicinity of the town of Mansfield. It here occupies a valley through which flows Michigamme River. Petrographically the member includes graywackes, clay slate, phyllite, siderite slate, chert, ferruginous chert, and iron ores, with several metamorphic products derived from them. The strike is north and south and the dip on an average 80° W. The maximum thickness of the belt is 1,900 feet. Southward from the point of maximum thickness it rapidly thins out and disappears.

The iron-bearing beds form a belt 32 feet wide or less between black slate walls. The strike and dip are the same as those of the slate. A single ore body of commercial importance has been mined. (See p. 324.)

The Hemlock formation both east and west of the main belt of this slate carries thin bands of slate with similar strike and dip. In general, in this vicinity, there is a monoclinical westward-dipping succession of volcanic rocks extending 2 miles or more east of Mansfield and about the same distance west, containing interbedded layers of slate, which in the vicinity of Mansfield are in considerable abundance and include also iron-bearing beds. These rocks may be best seen on the hill just east of Michigamme River, southeast of the Mansfield mine, where eight or ten layers of cherty slate from a few inches to 10 feet or more in width are interlayered with westward-dipping ellipsoidal basalt flows. The centers of the flows are usually homogeneous and coarse grained, and the ellipsoidal structures appear only within a few feet of the top or bottom of the flow immediately next to the slate. As a whole the contact between the basalt and the slate is a plane surface, making it possible to follow a bed of slate even 2 feet thick for hundreds of feet. In detail, however, the contact may be very irregular, following interstices in the ellipsoidal surface as if deposited upon an initially irregular surface.

Slates mapped as "Mansfield" by Smyth also outcrop on Michigamme Mountain and thence at intervals for 6 miles to the northwest. The area northwest of Michigamme Mountain, mapped as Pleistocene on Plate XXII, is believed to be largely underlain by slate from its appearance in a few pits and exposures. The information is so meager, however, that it is not thought desirable to map this area as slate. On Michigamme Mountain the geologic position of the so-called "Mansfield" rocks is free from doubt. In the principal syncline of sec. 32, T. 44 N., R. 31 W., they overlie the dolomites and pass downward into them by a relatively slow gradation; on the borders of the Michigamme Mountain syncline they underlie the iron-bearing Negaunee ("Groveland") formation. The passage to the higher formation likewise is graded, though rapidly, and is marked in certain bands by an increase in clastic grains and by changes in the character of the matrix in which these are set. The average thickness of the formation in this mountain is not less than 400 feet.

NEGAUNEE (?) FORMATION.

Magnetic belts northeast of Fence River.—By reference to the map (Pl. XXII, in pocket) it will be noted that there is a magnetic line marked "A" along the west side of the main northeastern area of Archean rocks. That this magnetic line is caused by and marks the position of the iron-bearing Negaunee formation there can not be much doubt, according to Smyth,[a] for that rock outcrops in a few scattered localities, occurs abundantly in the drift, and has been found in test pits and drill holes here and there along this line. The underlying quartzite outcrops beneath the iron-bearing formation near the north end of the line, but farther south it is entirely covered by the drift, so far as the territory has been examined. The overlying upper Huronian rocks are also known to be present just west of the Negaunee formation as far south as sec. 19, T. 46 N., R. 30 W. The dip along the "A" line is probably therefore, on the whole, toward the west, although the observed dips at the few localities where determinations have been made are either vertical or slightly inclined from the vertical toward the east. In an east-west section of drill holes in secs. 18, 19, 29, and 30, T. 46 N., R. 30 W., cutting the magnetic belt "A," the iron-bearing formation is found to be amphibole-magnetite rock cut by intrusives.

Around the immediately adjacent Archean oval on the west the magnetic line "B" has been traced for 25 miles without a single exposure. The known facts with reference to the "B" line, according to Smyth,[b] are these: (1) It represents a magnetic rock; (2) this magnetic rock completely encircles an Archean core. It may further be inferred with practical certainty that this formation, which carries such constant magnetic properties for 25 miles, must be sedimentary. With regard to its structure the foregoing considerations would necessarily involve the conclusion that it dips away from the Archean core on all sides, and this conclusion is fortified by the unsymmetrical separation of the horizontal maxima on the magnetic cross sections.

East of the "B" line, between it and the "A" line, is found the basal member of the upper Huronian. The rock which is manifest in the "B" line must, therefore, be older than any member of the upper Huronian. The Negaunee formation, represented in the "A" line, dips west, but the rock of the "B" line dips east. They are both older than the basal member of the upper Huronian and are both younger than the Archean. They are both strongly and persistently magnetic. For 8 or 10 miles they run parallel to each other less than half a mile apart. Their broad structural relations to the Archean basement of the region are precisely similar. Therefore, although the rock that gives rise to the "B" line has never yet been seen, it may be concluded with confidence that it is the Negaunee formation, and that the "A" and "B" lines represent this rock brought up in the two limbs of a narrow and probably deep synclinal fold.

Negaunee (?) formation at Michigamme Mountain and in the Fence River area.—The known outcrops of iron-bearing formation (previously mapped as "Groveland" formation) in this belt are limited to three localities—the vicinity of Michigamme Mountain, in sec. 33, T. 44 N., R. 31 W., and sec. 3, T. 43 N., R. 31 W.; the exposures and test pits at the Sholdice exploration, in sec. 21, T. 45 N., R. 31 W.; and the test pits at the Doane exploration, in sec. 16, T. 45 N., R. 31 W. The last two localities are 1 mile apart, and the more southern is 8 miles north of Michigamme Mountain.

[a] Van Hise, C. R., Clements, J. M., and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, p. 453.

[b] Idem, p. 454.

Magnetic lines connect the outcrops on Michigamme Mountain with those to the north. The magnetic line also extends beyond the outcrops around the north side of the western Archean oval. The eastern belt was not traced farther than a mile southeast of Michigamme Mountain. In the central and southeastern portions of T. 43 N., R. 31 W., however, in the direct prolongation of the anticlinal axis, is a broad belt of slight magnetic disturbance, along the western margin of which lie volcanic rocks, dipping west. In sec. 26, T. 43 N., R. 31 W., this magnetic belt splits into two branches, one of which runs directly east for a mile and then southeast indefinitely, while the other maintains a general southerly course to the south line of the township. In sec. 26 large angular bowlders, evidently derived from the iron-bearing formation, are found in the zone of magnetic disturbance, but no outcrops have been discovered. There can be little doubt that these disturbances roughly outline the position of the Vulcan formation in the axial region.

Except in Michigamme Mountain, the most elevated point of the district, the iron-bearing formation is not topographically prominent. In the Fence River area it produces a more subdued and somewhat lower-lying surface than the underlying formation, but the difference is slight and is of little moment in comparison with the confusing effects of glaciation.

At Michigamme Mountain the iron-bearing formation caps the hill in a well-marked syncline, the axis of which runs northwest and southeast. The structure is distinctly shown by the attitude both of the ferruginous rocks and of the underlying phyllites ("Mansfield slate"). At the Interrange exploration, half a mile to the south, is found a secondary but more open embayment of the same syncline. These are the only folds of the Michigamme Mountain area sufficiently deep to include the iron-bearing rocks. The thickness of the formation can only be guessed at, as no complete section is exposed, and the data for determining its upper limit are decidedly shadowy. The magnetic observations indicate a breadth of 400 to 600 feet, and as in the Fence River area it is certainly much thinner than the two lower formations its thickness may be approximately 500 feet.

The rocks are interbanded ferruginous quartzite and actinolite and grünerite schists, which still contain evidence of detrital origin. The formation contains less iron than the Vulcan formation of the Felch district, and consequently the lighter-colored varieties are more abundant, it contains more detrital material, and in the Michigamme Mountain area the texture is generally closer and less granular. Moreover, in passing north from the Michigamme Mountain area to the Fence River area we find at the Sholdice and Doane explorations that the lower portion of the formation is composed of ferruginous quartzite, which is succeeded higher up by actinolite schists and grünerite schists similar in all respects to the characteristic rocks of the Negaunee formation in the western Marquette district.

The stratigraphic position of the iron-bearing formation is above the Hemlock formation on Michigamme Mountain; to the west of the mountain the formation is apparently below the Hemlock formation; to the north of the mountain, in the Fence River area, it is above the Hemlock formation. In the last-named area nothing is known of the nature of the overlying rocks.

This iron-bearing formation is doubtfully called Negaunee because of its lithologic character and because it comes within 2 miles of the "B" line of attraction, regarded by Smyth as Negaunee, suggesting that it is the same belt brought up again on the west side of this intervening gap of 2 miles by synclinal structure. On the other hand, it is nearly connected by a magnetic belt around the north side of the oval with the Vulcan formation and for this reason its correlation has been regarded as doubtful. However, by reference to the map (Pl. XXII, in pocket), it will be noted that this belt of supposed Negaunee, extending around the north side of the oval and south as far as the north line of T. 45 N., R. 33 W., fails to connect by nearly 2 miles with the known Vulcan formation, which is represented by a magnetic line running as far north as sec. 16, T. 45 N., R. 33 W. Moreover, at the north end, near the Red Rock mine, the Vulcan is associated with conglomerate carrying fragments of an earlier iron-bearing formation very suggestive of unconformity. Still further, the iron-bearing Vulcan formation where last seen is associated with red slates and apparently unaltered, while the rocks associated with the magnetic line to the north, supposed to represent the Negaunee, are micaceous and amphibolitic slates and schists showing a much higher degree of metamorphism.

Ferruginous quartzite associated with iron-bearing formation north of Michigamme Mountain.—Ferruginous quartzite is found in isolated exposures in secs. 27 and 34, T. 44 N., R. 31 W., Michigan, lying immediately east of the eastward-dipping Randville dolomite and west of a belt of attraction forming the southward extension of a belt that is taken to represent the iron-bearing Negaunee (?) formation.

UPPER HURONIAN (ANIMIKIE GROUP).

The upper Huronian occupies a large part of the western half of the district, lapping around the oval areas of older rocks and coming into contact for the most part with the Hemlock formation. It is directly continuous with the upper Huronian rocks of the Marquette district on the north and with those of the Menominee district on the south and also extends far west of the boundaries of the area mapped into the Iron River and Florence districts. The exposures are scanty. The formation influences the topography very slightly, being for the most part heavily drift covered.

The upper Huronian in this district is essentially a great slate formation interbedded with small quantities of graywacke and chert, called the Michigamme slate, and near its base with iron-bearing lenses called Vulcan iron-bearing member.

MICHIGAMME SLATE.

General character.—The formation known as the Michigamme slate consists principally of slates with some graywacke, like that of the Menominee district. In previous reports on this district it has been called upper Huronian slate, but as the formation seems to be equivalent to and continuous with the Michigamme slate of the Marquette district, the name Michigamme will be applied to it in this monograph. True water-deposited conglomerates are usually absent in this formation, being known in only two places in this district, and in these places their stratigraphic position is unknown. For the most part the slates have good cleavage and locally they are highly graphitic, chloritic, sericitic, and micaceous, and rarely staurolitiferous and garnetiferous. The cleavage usually stands nearly vertical, but the bedding may have gentle dips. In general the rocks may be said to lap in broad folds around the lower Huronian, but everywhere with minor plications. The result is that in the ore-producing parts of the district, in the Crystal Falls and Amasa areas, the dip and pitch of the minor folds are in general westerly and southwesterly directions. Away from the base of the formation it is difficult to identify horizons in the slates, and this fact, together with lack of exposures, has thus far prevented the working out of the structure satisfactorily. In general, however, the strikes and dips at these horizons away from the base of the formation are similar to those near the base; that is, the strikes are in northerly and northwesterly directions, and the dips and pitches of the minor folds are westerly and southwesterly. The exposures immediately above Crystal Falls seem to be part of a much crenulated southwestward pitching syncline. It has been assumed further that the area of volcanic rocks associated with the upper Huronian slates northwest of the town of Crystal Falls is of Hemlock age, and hence that it represents an anticline brought up by folding. If these volcanic rocks should be really later in age than the Hemlock, as is entirely possible (see p. 299), then there is left no evidence for this anticlinal structure in this locality. As mining explorations furnish more data it should be possible to work out the structure.

Vulcan iron-bearing member.—The Vulcan iron-bearing member is similar to and is correlated with the Vulcan formation of the Menominee district. In the Crystal Falls district it consists principally of ferruginous chert, ferruginous slate, iron ore, and iron carbonate, interbedded in layers and lenses in the Michigamme slate. It is therefore treated as a member of the Michigamme slate in this district. The immediately adjacent wall rocks of slate are as a rule highly carbonaceous and pyritiferous. The iron-bearing layers range in thickness from a few inches to 300 feet, and are even thicker where repeated by buckling. This buckling is of a drag type, giving steep pitches and not materially changing the dip and trend of the member as a whole. Folds of similar types are characteristic of the Iron River and Menominee districts. (See pp. 324, 347.) Explorations are not yet sufficient to correlate the individual iron-bearing layers in different parts of the district satisfactorily, and it is impossible now to say whether there are one, two, or more independent layers separated by slate, though the probability is in favor of there being at least two principal horizons near the base of the upper Huronian, as in the Menominee district.

The map of the Crystal Falls district (Pl. XXII, in pocket) shows that the distribution of the Vulcan iron-bearing member has certain linear characteristics. One belt follows the base of the upper Huronian. Beginning 4 miles north of Amasa, it has been followed by magnetic lines and intermittent mines and explorations southeastward past Amasa and Balsam; thence southeastward to the vicinity of the Hollister and Armenia mines near the east side of T. 43 N., R. 32 W.; thence southwestward and westward through the Lee Peck, Hope, West Hope, Morrow, May, Kimball, and Tobin mines south of Crystal Falls; and thence southward through the Dunn and Mastodon mines. The real continuity of this belt has not been established at every point, but the probability of continuity is so great that exploration is being vigorously conducted at many points along the belt. Another belt of iron-bearing rocks extends from the Crystal Falls mine east of Crystal Falls westward through the Great Western, Paint River, Lamont, and Bristol mines. This belt may be at a higher horizon in the upper Huronian. It has not yet been connected with the one previously noted, though it is too early to say that a connection may not exist. A possibility of connection seems to be indicated by certain explorations between the two belts just east of Paint River east of the town of Crystal Falls. Developments in the Iron River district have shown the iron-bearing member to extend eastward toward the Crystal Falls district, raising the question of connection with one of the iron belts in the vicinity of Crystal Falls, but so far as the Crystal Falls district itself is concerned such a connection is not yet shown by explorations.

The magnetic belt marking the extension of the iron-bearing member of the Amasa district to the north and south is caused partly by the iron-bearing member and partly by magnetic surface portions of the ellipsoidal basalts of the Hemlock formation near their contact with the upper Huronian. At certain places, as in the vicinity of the Hollister mine, there are really two parallel magnetic belts rather than a single belt. One of these belts follows the magnetic phase of the greenstone and the other the iron-bearing member immediately adjacent. It is apparent, therefore, that not much reliance may be placed on the assumption that the iron-bearing member exists everywhere beneath the magnetic belt.

It is an unexplained fact that parts of the Vulcan iron-bearing member away from the Hemlock formation, particularly near Crystal Falls and farther south, are but slightly magnetic. This is also true of the Vulcan iron-bearing member in the Iron River district to the west.

INTRUSIVE AND EXTRUSIVE ROCKS IN UPPER HURONIAN.

The upper Huronian is penetrated in this district by intrusive rocks of acidic, intermediate, and basic composition. Some of these have been intruded before the folding and are very schistose. Most of them, however, are later.

Basaltic extrusive rocks, identical in all features with the Hemlock formation, appear in isolated areas in the upper Huronian. The principal areas are immediately northwest of Crystal Falls and in the vicinity of the Mastodon mine. There is as yet no evidence to show whether these extrusive rocks are the correlatives of the main mass of Hemlock formation and owe their present distribution to folding or whether they are really later extrusives interbedded with the upper Huronian Michigamme slate.

RELATIONS OF THE UPPER HURONIAN TO UNDERLYING ROCKS.

In general the dip and the distribution of the upper Huronian about the cores of older rocks show it to be distinctly younger than these rocks. The next underlying rocks for the most part are those of the Hemlock formation.

The upper Huronian is doubtfully unconformable structurally with the Hemlock formation. In the earlier Geological Survey reports on this district the two were described as unconformable, largely because of their marked difference in lithology and because of the fact than an unconformity exists at the base of the upper Huronian of the Marquette district, with which the upper Huronian of the Crystal Falls district is satisfactorily correlated. No direct evidence is yet available to show that there is not some time break between the Hemlock formation and the upper Huronian slates, but the apparent structural conformity, together with the conformable relations of the upper Huronian to underlying formations in the Menominee and Felch Mountain districts, seems to point to the possibility of nearly if not quite continuous deposition of Huronian sediments beginning with the Randville and Sturgeon formations and continuing through the upper Huronian. On the other hand, the existence of an unconformity is strongly suggested by the relations of the two magnetic belts taken to represent respectively the iron-bearing Vulcan and Negaunee formations northward from the Red Rock mine, where there is a break in the magnetic field and a difference in lithology and metamorphism, and where a conglomerate at the base of the upper Huronian carries pebbles of an earlier (supposedly Negaunee) iron-bearing formation. (See p. 297.)

CAMBRIAN SANDSTONE.

In the southern and eastern portions of the district the edges of the tilted older rocks are partly covered by a blanket of gently dipping sandstones of Cambrian age, very soft and easily disintegrating. These rocks appear near Michigamme River as detached outliers. To the south and east from that river the separated patches become larger and more abundant, until finally a few miles beyond the eastern limit of the Felch Mountain range they unite and entirely cover the pre-Cambrian formations.

STURGEON RIVER DISTRICT.[a]

LOCATION AND AREA.

The Sturgeon River area of Algonkian sediments, like the Felch Mountain area, is an east-west tongue, very narrow at its eastern extremity and widening out toward the west until it finally plunges under drift deposits that separate it from the large Huronian area of the Crystal Falls district. The tongue occupies the western portions of T. 42 N., R. 27 W., and the central and northern portions of T. 42 N., Rs. 28, 29, and 30 W. The best exposures of the rocks constituting the tongue are found in secs. 7, 8, 17, and 18, T. 42 N., R. 28 W., and secs. 1 and 3, T. 42 N., R. 29 W., on or near the northwest branch of the east branch of Sturgeon River; hence the name Sturgeon River tongue.

GENERAL SUCCESSION.

The succession is as follows:

Algonkian system:
- Keweenawan series (?) .... Sandstone.
- Huronian series:
  - Middle Huronian (?) .... { Basic igneous rocks, largely intrusive. / Negaunee (?) formation (iron bearing).
  - Unconformity (?).
  - Lower Huronian .... { Randville dolomite. / Sturgeon quartzite.

Unconformity.

Archean system:
- Laurentian series .... Granites and gneisses.

[a] Bayley, W. S., The Sturgeon River tongue: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 458–487.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

Laurentian granites and gneisses bound the Algonkian sediments on the north and south. Also between the northern and the southern boundaries of the sedimentary area as defined, and in the midst of the sediments, are two areas of granite, the rock of one of which is unquestionably and that of the other presumably older than the conglomerates within the tongue. The better defined of these two areas lies in the northern portions of secs. 7 and 8, T. 42 N., R. 28 W., and sec. 12, T. 42 N., R. 29 W.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER HURONIAN.

STURGEON QUARTZITE.

In this district the Sturgeon quartzite is represented by schists, conglomerates, arkoses, and quartzites 1,000 feet or more thick. Nowhere is there any marked discordance between the schistosity of the Archean and Sturgeon rocks, but the conglomerate indicates a marked unconformity.

RANDVILLE DOLOMITE.

In the Sturgeon River trough the dolomites have relatively more fragmental material with them than in the Felch Mountain trough. Exposures are few and occupy here the central portion of the trough. The dolomites do not themselves show the synclinal structure of the Sturgeon trough, but the fact that they are bounded by the quartzite on the northeast and southwest and this in turn by the Archean granite suggests trough structure. No definite contacts of Archean granites and the dolomites are known.

MIDDLE HURONIAN (?).

NEGAUNEE (?) FORMATION.

Bordering the north side of the dolomite in secs. 34 and 35, T. 43 N., R. 29 W., is nonmagnetic red and black hematitic chert, associated with red slate, shown in the Deerhunt mine explorations. Neither hanging or foot wall was determined in the exploratory work and the relations of the iron-bearing formation to the other formations are therefore unknown. The iron-bearing formation is doubtfully correlated with the Negaunee.

IGNEOUS ROCKS.

Associated with the sedimentary rocks are great masses of basic igneous rocks. Some of these are unquestionably intrusive masses, as shown by their relations to the conglomerates; others appear to be interleaved sheets. A very few, apparently bedded greenstones, on close examination seem to be composed of intermingled sedimentary and igneous material. These may be altered tuffs.

KEWEENAWAN SERIES (?).

In the SW. ¼ sec. 34, T. 43 N., R. 29 W., are white calcareous sandstones associated with purple slates, with dips ranging from 35° to 40°. These are similar in all respects to the upper series in the east end of the Felch Mountain trough, and there are the same elements of doubt with reference to their correlation. They are provisionally assigned to the Keweenawan, but they may prove to be of Cambrian age.

FELCH MOUNTAIN DISTRICT.[a]

LOCATION, STRUCTURE, AND GENERAL SUCCESSION.

The Felch Mountain district is an east-west synclinorium constituting a narrow strip nowhere more than 1½ miles and usually less than a mile wide, which as a whole runs almost exactly east and west for a distance of over 13 miles. It lies in the southern portion of T. 42 N., Rs. 28, 29, and 30 W. On the north and south it is bordered by the older Archean. The lowest member of the Algonkian occupies parallel zones next to the Archean on both the north and the south and is succeeded toward the interior of the strip by the younger members. Although the general structure, therefore, is synclinal, a single fold of simple type has nowhere been found to occupy the whole cross section of the Algonkian formations, but usually two or more synclines occur, separated by anticlines, which may have different degrees and directions of pitch and different strikes, or may be sunk to different depths, and complicated besides both by subordinate folds and by faults.

The succession is as follows:

Intrusive rocks (basic and acidic).
Algonkian system:
  Keweenawan series (?) .... Mica schists and ferruginous and micaceous quartzites.
  Unconformity.
  Huronian series:
    Upper Huronian (Animikie group).. { Vulcan formation (iron bearing). / Felch schist. }
    Unconformity (?).
    Lower Huronian .... { Randville dolomite. / Sturgeon quartzite. }
Unconformity.
Archean system:
  Laurentian series .... Granites and gneisses.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

The Laurentian series is the same as that of the other areas in Michigan here described. The contact between the Laurentian and Huronian is not exposed, but the existence of conglomerate elsewhere along the contact and the fact that the contact is followed uniformly by quartzite are believed to indicate unconformity.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER HURONIAN.

STURGEON QUARTZITE.

In the Felch Mountain district the Sturgeon quartzite, less than 500 feet thick, forms two bands in contact with the Archean granite bordering the Felch Mountain syncline. It is here principally quartzite but contains conglomerate near the contact. It is in most places extremely difficult to determine the attitude of the quartzite owing to its massive and homogeneous character. Closely associated with the massive quartzites are mashed quartzites or micaceous quartz schists.

RANDVILLE DOLOMITE.

Owing both to its great thickness and to its intermediate position, the Randville dolomite in the Felch Mountain range covers a larger share of the surface than any other member of the Algonkian succession. No actual contacts between the Sturgeon and Randville for-

[a] Smyth, H. L., The Felch Mountain range: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 374–426.

mations have been found, but from their close association and continuity, as well as from the structural characters, where these are determinable, they seem everywhere to be strictly conformable. The best sections give a wide range of thickness, from a minimum of about 500 feet near Felch Mountain to a maximum of nearly 1,000 feet in the western part of the district. Though the discrepancies may be partly due to lack of precision in the data, it is probable that the thickness of the formation is not uniform but really increases from east to west.

UPPER HURONIAN (ANIMIKIE GROUP).

FELCH SCHIST.

In the Felch Mountain district schists not more than 200 feet thick lie between the dolomite on the one hand and the Vulcan formation on the other. They do not outcrop but have been pierced by many drill holes. The greater part of them are fine-grained mica schists, containing garnet and tourmaline. Near the contact with the overlying Vulcan formation the schists become more siliceous and more ferruginous and there is a passage between the two formations. These schists were called "Mansfield schists" by Smyth[a] and correlated with the slates at Mansfield and Michigamme Mountain. The slates at Mansfield, however, are regarded in this report as older than the schists of the Felch Mountain district, and in any event not certainly to be correlated with them. The new name "Felch schist" is therefore introduced for this formation from its typical development at Felch Mountain.

VULCAN FORMATION.

In the Felch Mountain district the Vulcan formation is magnetic and has been traced by means of compass and dip needle. Excellent natural as well as numerous artificial exposures render the data concerning the distribution of the formation very satisfactory.

On the west the iron-bearing formation is exposed in ledges and test pits in sec. 5, T. 41 N., R. 30 W., from which a line of attraction extends southwestward through sec. 6 into sec. 12, T. 41 N., R. 31 W., where it is lost. The presence of the Vulcan formation through secs. 34, 35, and 36, T. 42 N., R. 30 W., is shown by one principal and other minor lines of attraction, as well as by test pits and outcrops. The principal line of attraction begins in sec. 34, near the southwest corner, and runs to the northeast, in conformity with the strike of the northern belt of dolomite, finally ending in the northeastern portion of sec. 36. This line of attraction is very vigorous and strongly marked. Two other lines, parallel with the principal line but more feeble and much shorter, cross the boundary between secs. 35 and 36, and on the northern of these lines ferruginous rocks outcrop in the western part of sec. 36. Another line, marking the west end of the Groveland syncline, begins near the center of sec. 36 and continues for 1½ miles eastward to the eastern portion of sec. 31, T. 42 N., R. 29 W. Along the western portion of this line are many test pits and in sec. 31 occur the fine exposures of the Groveland hill.

Another line of attraction begins 400 paces north of the center of sec. 32, T. 42 N., R. 29 W., which may be followed eastward without interruption nearly to the east line of sec. 33 of the same township. Along this line, which is comparatively feeble and crosses wet ground, there are but few test pits. In the eastern part of sec. 33, beyond the point at which the attraction ceases, many pits have been sunk to and into the Felch schist, which is there somewhat ferruginous. From this point eastward for 4 miles the Vulcan formation has not been recognized.

In the northern part of secs. 32 and 33, T. 42 N., R. 28 W., the ferruginous rocks are well exposed on Felch Mountain for nearly a mile along the strike, and may be identified for half a mile farther by the vigorous disturbances produced in the magnetic needles. In the SE. ¼ sec. 33 the Vulcan formation is again encountered in a small and much disturbed area, in faulted contact with the Archean.

[a] Van Hise, C. R., Clements, J. M., and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 411-415.

The most prominent hills in the Algonkian belt owe their relief to the fact that they are underlain by the Vulcan formation.

Petrographically two main kinds of rock may be recognized in this formation. The more common kind consists of quartz and the anhydrous oxides of iron; the other and much rarer kind consists essentially of an iron amphibole with quartz and the iron oxides as associates. Both of these kinds are clearly of detrital origin. The conclusion is reached, based on certain microscopic structures, that iron and silica were originally present largely in the form of greenalite. Between the ferruginous quartzites of the Vulcan formation and the ferruginous cherts of the Mesabi range there is a very close resemblance, especially in structure. The essential difference is that the former contain little or no chalcedony, the silica being crystallized quartz, whereas the latter have a great deal of chalcedonic silica. Also the former contain small amounts of detrital material, which the latter generally lack; but the essential difference between them is one of degree of crystallization only.

In Smyth's report on this area[a] the iron-bearing formation of the Felch Mountain district was called the "Groveland" formation from its occurrence at the Groveland mine. The evidence is now regarded as sufficient for correlating it with the Vulcan formation of the Menominee and Crystal Falls districts, and hence the name "Groveland" is discarded.

KEWEENAWAN SERIES (?).

In the east end of the Felch Mountain range the Huronian rocks are overlain unconformably by a series of soft iron-stained mica schists, with thin interbanded beds of ferruginous and micaceous quartzite. From their structures and general relations they are believed to have been derived from sedimentary rocks by metamorphism. At an old open pit just west of Felch, on the east side of sec. 33, this series may be seen to rest in unconformable contact with the Randville dolomite, the basal conglomerate being heavily ferruginous and having been mined as iron ore. These rocks are tentatively assigned to the Keweenawan series, although they may prove to be of Cambrian age.

INTRUSIVE ROCKS.

Basic and acidic intrusive rocks cut the Huronian at several localities. Some of the basic intrusives are in the form of sheets, some of them highly schistose and greatly altered.

PALEOZOIC SANDSTONE AND LIMESTONE.

The Paleozoic is represented by the Lake Superior sandstone, supposedly of Upper Cambrian age, and the overlying calciferous limestone. These formations were originally laid down over the upturned edges of the older rocks in flat sheets or with low initial dips and have not since suffered relative displacement to any notable degree. As has already been stated, subsequent erosion has to a great extent removed this overlying blanket and laid bare the older rocks, except for the covering of recent glacial deposits. The Cambrian sandstone and to a less extent the calciferous limestone still, however, occupy considerable outlying areas, detached from one another throughout most of the district but gradually coalescing beyond the east end, where they completely cover the older rocks and limit all further geologic study of those rocks in that direction.

CORRELATION.

Laurentian series.—The correlation of the main mass of granite gneiss north and south of the Felch Mountain district with the Laurentian series of the Archean is fairly certain in view of its essential unconformity beneath the Sturgeon quartzite, but granitic dikes also penetrate the Huronian series, suggesting that a part at least of the Laurentian complex may be intrusive. Such part has not been discriminated.

[a] The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 415-423.

Lower Huronian.—The correlation of the Sturgeon quartzite and the Randville dolomite respectively with the Mesnard quartzite and the Kona dolomite of the lower Huronian of the Marquette district seems to be reasonable, the rocks of both areas being highly folded, much metamorphosed, and near the base of the lower Huronian, and no evidence being known in the Upper Peninsula of the existence of a second dolomite series.

Upper Huronian (Animikie group).—The Felch schist grades up into the iron-bearing Vulcan formation and undoubtedly constitutes a fragmental base of the iron-bearing formation. Contacts of the Felch schist with the underlying dolomite are lacking. From the sheared nature of the slate it seems likely that the contact is schistose and that any evidence of conglomerate at the base may have been obliterated, but the structure of the Felch and Vulcan formations is essentially conformable, so far as can be determined, with that of the Randville dolomite and Sturgeon quartzite below. The two have been folded together. There has been question whether the Felch and Vulcan formations should be assigned to the middle Huronian, which includes the Negaunee formation, or to the upper Huronian, which includes the Vulcan formation of the Menominee district. Both the middle Huronian and the upper Huronian have an unconformity at the base, and hence the lack of evidence of unconformity at the base of the iron-bearing formation of the Felch Mountain district does not aid in the selection of one of these alternatives. The iron-bearing formation of the Felch Mountain district is geographically separated from both the Negaunee formation of the Marquette district and the Vulcan formation of the Menominee district. At the west end of the Felch Mountain district the formation may be followed by magnetic work to the west under the main area of the upper Huronian. A few miles south, in the Calumet trough, an iron formation similar to the Vulcan and underlain by slate and schist of the Felch variety may be traced to the west and southwest with reasonable continuity and with uniform lithology into the broad area of upper Huronian joining areally with the upper Huronian of the Menominee district. To the southeast also there is probable connection with the Menominee district. The lithology of the iron formation in the Felch Mountain district is more like that of the Vulcan than that of the Negaunee formation. These facts suggest strongly that the iron-bearing formation of the Felch Mountain district is an eastward projection of the main upper Huronian of Michigan, other eastward extensions of this area being found in the Menominee, Calumet, and Marquette districts. If not, the line of demarkation between the upper Huronian and the iron-bearing formation of the Felch district is not yet known. The evidence for correlating the iron-bearing formation of this district with the Vulcan formation of the Menominee and Crystal Falls districts is regarded sufficient, and the old name "Groveland," as heretofore used in this district, has therefore been abandoned for Vulcan. The apparently conformable relations of the Felch and Vulcan formations with the underlying Randville and Sturgeon formations do not disprove unconformity. The relations may really be the same as in the Menominee and other adjacent districts.

Keweenawan series(?).—The purple sandstones overlying the Vulcan formation at the east end of the trough look in many of their outcrops like Cambrian rocks, and were it not for their dip of 30° or thereabouts they would probably be mapped as Cambrian, for farther east the Cambrian is flat-lying. It is entirely possible that the Cambrian has been tilted up in this place. However, a similar series of sandstones in the Sturgeon trough is also tilted up, and this, in connection with the reddish-purple color of the beds, suggests the possibility of Keweenawan sediments intervening between the Huronian on the one hand and the Paleozoic on the other. Their position above the Vulcan formation and their friable character, however, seem to preclude the probability of their being Huronian.

CALUMET DISTRICT.

LOCATION AND GENERAL SUCCESSION.

The Calumet district is an east-west trough south of the Felch Mountain trough, extending through T. 41 N., Rs. 27 to 30 W. (Pl. XXIII).

The succession is as follows:

Cambro-Ordovician	Hermansville limestone.
Cambrian system	Sandstone (Potsdam sandstone).
Algonkian system:	
Huronian series:	
Upper Huronian (Animikie group)	Michigamme slate. Vulcan formation (iron bearing). Felch schist.
Unconformity (?).	
Lower Huronian	Randville dolomite. Sturgeon quartzite.
Unconformity.	
Archean:	
Laurentian series	Granites and gneisses.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

The Laurentian series consists of granites similar in all respects to those of other districts, and will not be here described. It borders the trough on both the north and the south and forms a nearly isolated area in the vicinity of Granite Bluff.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

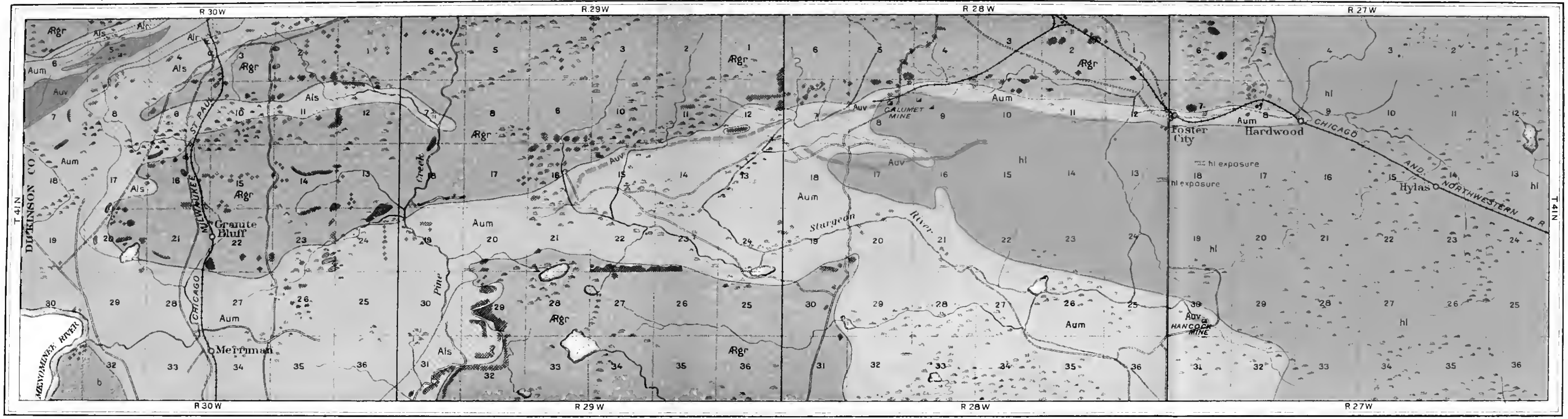
LOWER HURONIAN.

STURGEON QUARTZITE.

The Sturgeon quartzite is exposed principally in the western part of the district. One belt, continuous with that of the Menominee district, swings northward from the northwest side of the Menominee district into secs. 20 and 29, T. 41 N., R. 29 W. Another belt extends from the southwest end of the southern Felch Mountain-Sturgeon quartzite belt and swings southward around the granite mass to sec. 20, T. 41 N., R. 30 W. An eastward embayment carries this belt into secs. 9 and 16, T. 41 N., R. 30 W., and this may possibly also connect still farther east with quartzite in secs. 9 and 16, T. 41 N., R. 29 W. There is some difficulty in all these places in discriminating this quartzite from the base of the upper Huronian. On the whole, however, the Sturgeon quartzite is much more massive and cherty and stands at steeper angles than the upper Huronian quartzite, which is more or less thinly bedded with slate, is infolded into gentle rolls, and has been rendered micaceous and schistose along the slaty layers.

RANDVILLE DOLOMITE.

The underground workings at the Calumet mine indicate a descending succession of upper Huronian slate, iron-bearing formation, schist, cherty or quartzitic rock, and dolomite. The dolomite occurs, with southward dip, only a short distance south of the Archean granite, and may with reasonable certainty be correlated with the Randville dolomite.



GEOLOGIC MAP OF THE CALUMET DISTRICT, MICHIGAN

Compiled by C.K.Leith from surveys by W.S.Bayley, R.C.Allen, Edward Steidtmann, and others

Scale $\frac{1}{90000}$

1 0 1 2 3 Miles

1909

LEGEND

ORDOVICIAN AND CAMBRIAN

hl — Hermansville limestone and Upper Cambrian sandstone

ALGONKIAN (HURONIAN SERIES)

UPPER HURONIAN (ANIMIKIE GROUP)

b — Basalt extrusives

Aum — Michigamme slate with some basalt extrusives

Auv — Vulcan formation (iron bearing)

LOWER HURONIAN

Alr — Randville dolomite

Als — Sturgeon quartzite

ARCHEAN

LAURENTIAN SERIES

Agr — Granite

Exposure, dip and strike not shown

Exposures with observed dip and strike

Shaft or pit

UPPER HURONIAN (ANIMIKIE GROUP).

FELCH SCHIST.

The slate and quartz-schist formation forming the base of the upper Huronian is exposed north of the iron-bearing Vulcan formation and south of the Laurentian granite at Calumet. Its characters here are identical with those of the Felch schist of the Felch Mountain trough. To the south it appears again near the south quarter post of sec. 16 and along Sturgeon River in secs. 19, 20, and 21, where it contains somewhat more quartzite but still maintains its essential character as a micaceous slate. The formation extends from this locality westward into the west end of the Calumet trough, where it opens out into the great area of upper Huronian connecting with the Michigamme ("Hanbury") slate of the Menominee, Crystal Falls, and Florence districts. Quartz schist which may belong to this formation appears in the minor trough extending eastward from secs. 9 and 10, T. 41 N., R. 30 W., but as already indicated in the discussion of the Sturgeon quartzite, it has not been satisfactorily discriminated from the Sturgeon quartzite in this trough.

VULCAN FORMATION.

The iron-bearing formation is best exposed at the Calumet mine, where it has been crosscut for 700 feet. It is here interlayered with slate. Its dip is steep to the south. Magnetic attractions, drill holes, and test pits show iron-bearing formation and ferruginous quartzite also through the northern part of secs. 16 and 17, a mile to the south, where the dip is low to the north, suggesting that this is the same belt as the Calumet brought up by anticlinal folding. Magnetic work shows that these two belts extend to the west and coalesce against the south margin of the granite through secs. 14 and 15. West of this locality no trace of it has been found. East from the Calumet mine the belt has been shown, principally by magnetic work, to extend for several miles.

To the southeast, in the southwest corner of T. 41 N., R. 27 W., at the Hancock mine, is a heavily ferruginous micaceous slate and quartzite which may be correlated with the iron-bearing formation at the Calumet mine or may belong at a higher horizon in the upper Huronian. Still farther southeast, in the southeastern part of the same township and the north-central part of T. 40 N., R. 27 W., there is a magnetic field with trend suggesting its correlation with the iron-bearing formation of the Calumet district. A drill hole on the magnetic belt in sec. 3 of this township discloses ferruginous slates and quartzites similar to those at the Hancock mine.

MICHIGAMME SLATE.

Slates and micaceous quartzites overlie the iron-bearing formation at the Calumet mine and occupy most of the Algonkian area of the Calumet trough. Thence they presumably extend southeastward through T. 40 N., R. 27 W., and probably connect with the Michigamme ("Hanbury") slate of the Menominee district in this direction. West and southwest from the Calumet mine they also connect with the upper Huronian slate of the Menominee district.

PALEOZOIC LIMESTONE AND SANDSTONE.

Cambrian sandstone (Potsdam) and Cambro-Ordovician limestone (Hermansville) rest in flat beds over much of the Calumet area and its eastward extensions. They cover most of the upper Huronian of T. 41 N., R. 28 W., and T. 40 N., Rs. 27 and 28 W., and thicken rapidly to the east. These rocks form a serious obstacle to exploration in this district.

CORRELATION.

The correlation of the rocks of this district is discussed in connection with the Felch trough (p. 305) as well as in the general correlation chapter (pp. 597 et seq.).

IRON RIVER DISTRICT.

By R. C. Allen.[a]

LOCATION AND EXTENT.

The Iron River district lies west of the Crystal Falls district and extends southward a few miles beyond Brule River into Wisconsin, to the granites and green schists of the Archean. North, east, and west of this boundary, which is a natural one, only arbitrary limits may be drawn. Recent detailed studies have been made of the area in Michigan extending from Brule River north to latitude 45° 15′, east to longitude 85° 30′, and west to longitude 85° 45′, embracing an area of 201.5 square miles. (See Pl. XXIV, in pocket.)

TOPOGRAPHY AND DRAINAGE.

The topography is of glacial origin, slightly affected by preglacial forms and modified little by postglacial erosion. In general the area presents a series of hills or parallel chains of hills elongated in a direction about S. 20° W., which is the direction of ice movement as recorded on striated and grooved rock surfaces in the southwestern and northern parts of the area. The ridges are separated by corresponding hollows, which hold swamps and lakes connected by creeks forming the minor drainage courses. The major drainage is independent of the natural northeast-southwest "grain" of the country, for the larger streams, Brule, Iron, and Paint rivers, cross diagonally the general southwest trend of the hills and valleys. Paint River in the northern part of the district follows in general the strike of the underlying rocks, outcrops being comparatively numerous along its course. The same may be said of the Brule in the southern part of the district. Both of these streams seem to follow modified preglacial courses. However, this is certainly not true of Iron River, for this stream is known to cross at least two well-defined drift-filled preglacial valleys which fall toward the northeast nearly at right angles to the course of the Iron. These valleys are separated by a rock ridge which protrudes through the drift in Stambaugh Hill, on which is built the village of Stambaugh. (See Pl. XXIV, in pocket.) In contrast to the independence of the major streams, the minor drainage is controlled absolutely by the topography of the drift mantle, which may be readily inferred from a study of the map. Many of the lakes occupying depressions between the ridges are likewise elongated in a northeast-southwest direction. The best examples are Stanley and Iron lakes; others are Minnie, Chicagon, and Trout lakes, occupying parts of the same depression in the eastern part of the area. Most of the lakes are drained by streams, but some, as Bennan, Snipe, and Scott lakes, have no outlets.

The combination of elongated ridges and corresponding depressions above described forms a distinctly drumloid type of topography. However, there are but few typical drumlins. The most perfect example occurs just north of Iron River village, crossing the south line of sec. 23, T. 43 N., R. 35 W. It will be interesting to note that a terminal moraine formed by the Langlade lobe (Weidman) of the Wisconsin ice sheet occurs not far to the south in Wisconsin, following a general course at right angles to the trend of the drumloid hills of this area. This is the characteristic relation between drumlins and terminal moraine found elsewhere, notably in New York and southern Wisconsin.

The thickness of the drift ranges from a knife-edge up to more than 300 feet. It is of course least along the depressions and drainage courses, where the underlying rocks are exposed at many places, and greatest in the hills between them; but this is not everywhere true, as is abundantly demonstrated in drill borings. Some postglacial and preglacial valleys coincide in general trend and carry greater thicknesses of drift than the bordering hills. This is true of the valley extending diagonally northeastward through sec. 1, T. 42 N., R. 35 W., and secs. 31 and 29, T. 43 N., R. 34 W. (See map, Pl. XXIV.) Although the elevation of many of

[a] State geologist of Michigan. Based on survey by W. S. Bayley for the United States Geological Survey, on private surveys by C. K. Leith and R. C. Allen, and on recent survey for the Michigan Geological Survey by R. C. Allen. See Allen, R. C., The Iron River iron-bearing district of Michigan: Michigan Geol. Survey, Pub. 3 (Geol. ser. 2), 1910.

the hills is accounted for by the relatively great thicknesses of drift under them, there is abundant evidence that the preglacial topography of this region was more rugged and presented greater vertical range between hills and valleys than does the present surface.. The highest hills are in the southwestern part of the district and are of preglacial origin. Sheridan Hill, in sec. 20, T. 42 N., R. 35 W., has an altitude of 1,840 feet and rises 460 feet above the lowest point in the district, the valley of Paint River, where it leaves the area in sec. 36, T. 44 N., R. 34 W. The elevation of the rock surface near the center of sec. 29, T. 43 N., R. 34 W., is 1,280 feet. Thus the maximum difference in elevation was in preglacial time at least 100 feet greater than it is now.

CHARACTER OF THE GLACIAL DRIFT.

The ridges and higher lands in general are composed of bowldery till intercalated with lenses of sand and gravel. The till is in many places composed almost entirely of clay but is more commonly somewhat sandy and maintains good tilth under cultivation. The soil of the till areas is, in general, excellent and supports a heavy stand of hardwood. Where cultivated it produces good crops of small grains, hay, and vegetables adapted to the climate. The general abundance of bowlders is the main obstacle confronting the farmer on the till areas, but this is not insurmountable, as is abundantly shown by the many prosperous farms in the central and eastern parts of the district.

The valleys of Brule, Iron, and Paint rivers are partly filled with sandy and gravelly outwash of glaciofluvial origin. In places sand and gravel plains of considerable extent have formed, notably at the junction of the Iron and Brule, in the valley of Net River, and north, west, and south of the junction of the north and south branches of Paint River.

GENERAL SUCCESSION.

The general succession of rocks in the Iron River district from youngest to oldest, is as follows:

Quaternary system:	
Pleistocene deposits	Bowlder till, sand, and gravel.
Unconformity.	
Ordovician system	Limestone, sandstone, and conglomerate.
Unconformity.	
Algonkian system:	
Huronian series:	
Upper Huronian (Animikie group)	Intrusive and extrusive greenstones. Michigamme slate, containing Vulcan iron-bearing member.
Unconformity (?).	
Lower Huronian	Saunders formation (interbedded cherty dolomite and quartzite and slates, believed to be equivalent of Randville dolomite and Sturgeon quartzite).
Unconformity (?).	
Archean (?) system:	
Keewatin series (?)	Ellipsoidal greenstone, green schists, and tuffs.

ARCHEAN (?) SYSTEM.

KEEWATIN SERIES (?).

Basaltic extrusive rocks with surface textures similar to those of the Quinnesec schist of the Menominee district and the Hemlock formation of the Crystal Falls district are exposed in isolated outcrops north and south of Brule River in an east-west belt across the southern part of the district. These rocks possess no lithologic or structural characteristics which may safely be used as a basis for their correlation. Most of the outcrops are north of the adjacent Saunders formation, but a few are south of it. However, detailed mapping has not been done south of the Brule, and consequently the extent of the volcanic rocks in this direction is not yet known. They are nowhere exposed in contact with the Saunders formation, hence their stratigraphic position can be determined only by their areal relation to the Saunders formation in reference to the structural attitude of the latter. The available data, though not absolutely conclusive for all parts of the Saunders formation, indicate a general northward dip. By applying this criterion, the volcanic rocks north of the Saunders are stratigraphically above it and those south of it are stratigraphically below it.

The volcanic rocks in the southern part of secs. 19, 20, 21, and 22, T. 42 N., R. 35 W., are the only greenstones in the area which are known to lie south of the Saunders formation. Being probably below the Saunders formation they are tentatively correlated with the Keewatin schist. It is possible that they may be interbedded with the Saunders formation or they may be of later age, in which case their occurrence here may be explained as the result of faulting.

The greenstones tentatively referred to the Archean are of basaltic composition. Ellipsoidal structure is well developed. The ellipsoids have been elongated in an east-west direction parallel to the east-west axes of major folding in this part of the district. Agglomeratic structures are less common and in one outcrop the rock is a green chloritic shist.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

LOWER HURONIAN.

SAUNDERS FORMATION.

Distribution.—The Saunders formation occurs in a belt of varying width extending in a general direction a little north of west across the southern part of the district and westward an unknown distance. Outcrops are few, on the whole, and are absent in large areas supposed to be underlain by this formation. It is well developed in Sheridan Hill in sec. 20, T. 42 N., R. 35 W., and vicinity. This hill owes its altitude, 1,840 feet, to the resistive character of the Saunders formation. East of Saunders village and south of Brule River in Wisconsin this formation again assumes topographic prominence in an east-west ridge about 2 miles long. In secs. 26 and 35, T. 42 N., R. 35 W., slaty and dolomitic phases are exposed in a number of pits and an outcrop occurs on the west side of Brule River a short distance southwest of the north quarter corner of sec. 34.

Lithologic characters.—The Saunders formation embraces a wide variety of facies. Cherty dolomite and quartzite are the most prominently developed. Associated with them are massive white and pink dolomite, impure carbonate slates, and talcose slates.

Cherty dolomite and quartzite are best developed in Sheridan Hill and vicinity and in the ridge south of Brule River southeast of Saunders. In both these localities the rock is exceedingly brecciated. The crushed and fractured cherty fragments are embedded in the greatest confusion in secondary infiltrated silica and carbonate, silica being dominant. In the Saunders ridge are masses of almost pure quartz associated with pure massive white dolomite and banded chert and cherty dolomite. The more siliceous bands stand out prominently on weathered surfaces, producing a ribbed appearance.

A highly ferruginous phase of the Saunders formation is exposed in a cut on the Connorsville branch of the Chicago and Northwestern Railway about 2,100 feet south of its crossing of Brule River. In general the rock is intensely sheared, with marked slaty structure of nearly vertical dip and an almost east-west strike. Here there are gradations to more massive bluish phases, which are seen under the microscope to consist chiefly of carbonate with coarse interlocking texture. Inclosed in the carbonate are areas of finely granular silica. Sericite occurs as a secondary mineral, ferric oxide is abundant, and pyrite occurs commonly in aggregates of small grains. The ferruginous character of the carbonate is evident from the abundance of ferric oxide developed in weathering.

The abundance of iron oxide in weathered portions of these rocks has invited explorations for iron-ore deposits, particularly in the SW. ¼ sec. 26 and the NW. ¼ sec. 35, T. 42 N., R. 35 W., where a number of pits have been dug. The deepest of these which have penetrated the weathered mantle are bottomed in a bluish carbonate rock described above. Apparently interbedded here with the purer carbonate rocks are impure slaty phases showing crumpled bedding laminæ which are cut in general at a high angle by the plane of schistosity.

Schistose slaty phases of the Saunders formation are exposed on the west bank of Brule River, a short distance southwest of the north quarter corner of sec. 34, T. 42 N., R. 35 W., and on the north bank of this stream in the NW. ¼ sec. 19 of the same township.

Talcose ferruginous slates are exposed in pits 400 paces west and 75 paces south of the northeast corner of sec. 20, T. 42 N., R. 35 W.

Structure.—Satisfactory structural observations can not be made on known exposures of this formation. In the cherty and quartzitic phases bedding is destroyed by excessive brecciation, in the slaty phases it is obscured by schistosity, and in the purer massive dolomitic phases bedding is not shown, being doubtless destroyed by recrystallization and rearrangement of the minerals in the rock. In the north face of the ridge southeast of Saunders there are banded cherty phases showing steep northward dip, but the folding and brecciation are here of such character as to indicate that these dips may be local. Where developed the schistosity is as a rule steeply inclined northward and is parallel to the trend of the formation. Distinct bedding is shown in slaty fragments on the dumps of pits in the SW. ¼ sec. 26, T. 42 N., R. 35 W., but here the pits are filled with débris and the rock could not be observed in place. At this place the schistosity cuts the crumpled laminæ nearly at right angles. As the schistosity is elsewhere steeply inclined northward, it may be inferred that the dip of the bedding is here northward at a lower angle. These observations are unsatisfactory, but considered with the position of the Saunders formation between the older rocks south of them and rocks to the north, which are certainly younger, they seem to indicate a general northward dip.

East of sec. 21, T. 42 N., R. 35 W., the Saunders formation seems to widen and swing southeastward. This is probably due to flattening of dip on an anticlinal cross fold. If the axis of this fold is extended northward it coincides approximately with the direction of the axis of a broad anticline in the northern part of the district. As will be pointed out later, it is probable that the entire district has been folded on this axis thus extended.

Thickness.—A close estimate of the thickness of the Saunders formation can not be made. If the width of the formation across Sheridan Hill is taken at 4,000 feet and the dip assumed to be 75°, the thickness will be 3,750 feet. Doubtless the formation is very thick, but the above figures may be a thousand feet or more too great.

Relations to adjacent formations.—Contacts between the Saunders formation and overlying and underlying rocks are not exposed. The dip of the Saunders is, on the whole, steeply north, from which it is inferred that it is probably younger than the Keewatin (?) rocks. Whether the latter are unconformably below or are interbedded with the Saunders formation is not here apparent. In the southern part of the Florence district the Quinnesec schist is bounded on the north by quartzites and conglomerates, which are clearly unconformable upon the Quinnesec schist and whose bedding and contact planes trend northwestward toward the Brule River section of the southern Iron River district. The quartzites and dolomites of the Saunders formation may be the extension of the quartzite and conglomerate belt of the southern Florence district, and if so they would be unconformably above the Keewatin (?) rocks.

The Saunders formation is structurally beneath the upper Huronian, with probable conformity. It is paralleled on the north by a belt of scattered outcrops of volcanic greenstones, by which it is overlain and with which it may be to some extent interbedded.

UPPER HURONIAN (ANIMIKIE GROUP).

MICHIGAMME SLATE.

DISTRIBUTION AND GENERAL CHARACTERS.

The Michigamme slate occupies much the larger part of the district. It is limited on the south by the Saunders formation and extends north, west, and east beyond the limits of the district, on the east connecting with the upper Huronian (Michigamme) slate of the Menominee, Crystal Falls, and Florence districts.

The rocks of this formation include a wide variety of facies. Graywackes, with textures varying from conglomeratic to fine grained, and their schistose equivalents are dominant in the northern part of the area. Here they are interbedded with lenses of black pyritiferous and carbonaceous slates, micaceous and chloritic slates, and narrow iron-bearing lenses which occur in the vicinity of Atkinson, in sec. 24, T. 44 N., R. 35 W., and doubtless in other areas which are drift covered. Toward the south the clastic rocks become finer grained on the whole and perhaps less metamorphosed. Slates are dominant and the iron-bearing member is more extensively developed. However, graywackes and fine conglomerates are not lacking and are here and there associated with the Vulcan iron-bearing member. Black pyritiferous and carbonaceous slates are common associates of the iron-bearing member.

The relations between the various facies of the Michigamme slate are those of gradation and interbedding. Any single type of the rock may grade by mineralogical and textural variations into any other type. The variations take place both in the direction of the bedding and across it, with the result that in general the entire formation is made up of dovetailed lenses of various dimensions and compositions, with indefinite gradational borders between them. Although gradation is the rule, abrupt transitions across the bedding from one type to another are not uncommon, especially between black slates and iron-bearing beds, the former forming the footwalls of many of the ore bodies.

Ellipsoidal, agglomeratic, and tuffaceous extrusive basaltic greenstones are interbedded at various horizons with the Michigamme slate. They seem to be especially abundant at the base of the formation just north of the Saunders formation and at higher horizons in the northern part of the district. Of less common occurrence are igneous rocks of similar composition but with well-developed interlocking crystalline texture. These are probably intrusive.

GENERAL STRUCTURE.

In attempting to work out the general structure there is the same difficulty in identifying horizons in the slates which has prevented satisfactory structural work in the Crystal Falls district. Rocks of identical character are repeated at different stratigraphic horizons and the same stratigraphic horizon may exhibit, even in a small area, facies which are of very different composition and texture. Inasmuch as this fact is not appreciated by many who explore for iron ore in this district, it should be emphasized here.

(1) The rocks at any particular horizon of the Michigamme slate can not be depended on to maintain the same character over any considerable area. It follows that (2) cross sections through the same stratigraphic horizons may differ widely in a given small area and consequently (3) similar sequence of formations in adjacent areas does not necessarily imply stratigraphic equivalence unless the beds are known to be continuous from the one area into the other. Especially is this true if the two areas compared are widely separated. Observations in the field and in mine workings and microscopic study of the rocks establish beyond doubt the truth of the above statement.

Guides to the structure in the southern part of the district are found in the iron-bearing layers and in the structure of the underlying and presumably conformable Saunders formation. In the northern part of the district structures are well brought out by graywacke phases, abundantly exposed, exhibiting bedding.

The general east-west trend of the steeply inclined Saunders formation and the east-west strike of the secondary structures in it and the adjacent greenstones indicate the main structural line for this part of the district. As the upper and lower Huronian are probably in structural conformity here as well as farther east in the Crystal Falls and Menominee districts, the Michigamme slate, with its interbedded lenses of the Vulcan iron-bearing member which are best developed in the southern part of the area, may be expected to extend beneath the drift west of Iron River, beyond the limits of the district. The westernmost exposure of the Vulcan member is in the SW. ¼ SW. ¼ sec. 33, T. 43 N., R. 35 W.

The folding along the main east-west axis is considerably modified in the central and northern parts of the district by folding along an axis trending north of east and south of west. Beginning on the east side of T. 44 N., R. 34 W., along Paint River, the rocks are observed to strike slightly west of north and to dip vertically or steeply to the northeast. Upstream along Paint River to its junction with the Net and thence westward toward Atkinson, the strike swings sharply westward and then south of west, the dip varying from north to northwest. Southwest of Atkinson, to the limits of the district, and at least several miles beyond, the southwesterly trend becomes more marked and the dips are to the northwest. Brittle layers have been gashed by tension cracks, in general normal to the strike. Cleavage is subordinate to bedding in the northeastern part of the district, but toward the west the rocks become more and more schistose until the bedding is mainly obliterated. This is due chiefly to a change in the character of the sediments. The rocks in the northeastern part of the area are commonly coarse grained to finely conglomeratic, becoming finer grained toward the west. In this direction the dip of schistosity becomes on the average flatter and where compared with the bedding the two structures both dip northward, the schistosity being the more steeply inclined.

From the data given above it seems that the structure of the northern part of the district is that of a broad northward-pitching asymmetrical anticline, with steeper limb on the east and axis trending 15° or 20° east of north. If this axis is projected southwestward across the center of the district it will coincide, with slight allowance for change in direction, with the axis of the anticlinal cross fold affecting the Saunders formation and indicated in the widening and the southeastward swing of the formation in the big bend of Brule River.

The existence of this north-south cross axis of folding is further indicated by the trend of the iron-bearing member, which enters the district from the southeast, bends to the west in the central part of the district as it crosses the cross fold, and then extends southwestward.

VULCAN IRON-BEARING MEMBER.

Distribution and exposures.—There are few exposures of the Vulcan iron-bearing member. Knowledge of its distribution is based mainly on occurrences in underground workings and in drill holes put down in search of iron ore and therefore is largely limited by the extent to which these operations have been conducted. On the map (Pl. XXIV, in pocket) are indicated those areas which are known to be underlain by this member and the position of the drill holes in which the member has been penetrated. Most of the drill cores were examined, but some are unavailable; in the latter case it has been necessary to rely on the superintendent's and drill runner's records. An attempt has been made to discriminate between the more unaltered iron-bearing rocks on the one hand and ferruginous cherts and slates and iron ores on the other. There are all gradations between the various phases of the iron-bearing member, but as the ores and highly oxidized phases are related to structural conditions that largely influence ore concentration, it is thought that the discrimination attempted will have some practical usefulness in suggesting lines for further exploration.

The known main occurrences of the Vulcan member may be referred to three different areas—(1) the Jumbo belt, just south of Brule River in Florence County, Wis., about 1½ miles east of Saunders; (2) the central area of unestablished boundaries extending north, east, south, and west of Iron River; and (3) the northern area, including the Morrison Creek belt, in sec. 24, T. 44 N., R. 35 W., and the Atkinson belt, southwest of Atkinson.

Possible extensions of these belts are to be inferred from the general structure of the district already described. These are specifically discussed under later headings. Of especial interest in this stage of development are the possibilities of connection with iron-bearing belts in the Florence and Crystal Falls district, toward which much exploration is being directed.

Relations to Michigamme slate.—All the iron-bearing areas include more or less slate, and interbedded slate is shown in many of the drill holes which are indicated as cutting the Vulcan member. It will be seen by a study of the data on Plate XXIV that in the central part of the district the areal relations between slate and iron member are exceedingly complex and for the most part it is impossible to exclude the slate from any considerable area. The explanation lies in the interbedding of the slate and iron-bearing member, coupled with complicated folding.

From the foregoing statements it is evident that the Vulcan member is not confined to a single horizon in the Michigamme slate. From analogy with the Vulcan beds of the Menominee and Crystal Falls districts it might be inferred that the member occupies at least two horizons near the base of the Michigamme slate, but it is reasonably certain that there are at least four horizons of iron-bearing rocks in the Iron River district, without making allowances for the possible occurrence of two or more horizons in the producing part of the areas near Iron River and Stambaugh. From the general structure of the district it is probable that the several areas of iron-bearing rocks occupy as many different general horizons of the Michigamme slate, the southernmost belt being at the lowest horizon, the central area being somewhat higher, and the northern area being higher still. In fact, slate and iron-bearing member are interbedded in such a way that the rocks at any horizon of the Michigamme slate may somewhere become iron bearing. There are areas where the facts are more nearly expressed by the phrase "Vulcan formation containing lenses of Michigamme slate" than "Michigamme slate containing Vulcan iron-bearing member," and this is especially true of the central and southern parts of the district. Any attempt to unravel the structure of the slate and the iron-bearing member which does not take into account these relations will certainly lead to erroneous results.

Thickness and structure.—The iron-formation bands probably do not exceed 300 feet in thickness except where repeated by local buckling. They are closely and intricately folded with the associated slates and are as a rule steeply dipping. Erosion has cut deeply into the series, doubtless removing the iron-bearing member over considerable areas where it once existed. Where exposed, it occurs at the surface mainly in narrow bands, many of them twisting and contorted, but some retaining an approximately straight course for distances at least greater than 2 miles. With this general idea in mind, it will be readily understood that any attempt to draw boundaries of the Vulcan member will be more misleading than helpful. The major structure of the Vulcan member is discussed under the general structure of the district.

Lithologic characters.—The Vulcan member is made up of ferruginous cherts and slates, cherty iron carbonate rocks, magnetitic sideritic slates, and iron ores. The various facies possess no characteristics which are peculiar to this district and therefore will not be described in detail. The relations between the different types are those of gradation. The original iron-bearing rock was mainly a cherty iron carbonate similar in all respects to those which occur in neighboring iron-bearing districts.

However, there are two characteristics which are worthy of notice in this place. Microscopic study of these rocks has revealed the original presence of small quantities of greenalite. The altered forms of this mineral are abundant in some sections, but generally they are not shown. It is probable that greenalite was originally present in much greater abundance than might be inferred from an examination of the rock sections. It was only after identification of better-preserved forms in a few sections that its original presence in others was determined.

In the more highly altered phases all traces of original greenalite have been obliterated by recrystallization and rearrangement in different combinations of the elements forming the minerals in the rock. Various later stages of the alteration of the greenalite granules are observable in thin sections, but nothing approaching unaltered greenalite has yet been found.

A second characteristic of the Vulcan member which should be noted is the abundance of associated clastic material and resulting alteration products. Fragmental quartz grains are abundant in many specimens and are clearly distinguishable from the matrix of crystalline silica of fine interlocking texture in which they are locally inclosed. Less commonly there are grains of feldspar. By increase in the relative proportions of quartz and feldspar grains the rock takes on the characters of a graywacke. If the intermixed clastic material is of very fine grain, impure siderite and ferruginous slates result and these by decrease in the carbonate and the cherty constituents grade into ordinary slate. By metamorphism the impurities in the iron-bearing rocks give rise to secondary products, mainly chlorite, which is nearly always associated with biotite and lesser amounts of sericite. Carbonaceous impurities are especially abundant and are responsible for the dark color of much of the chert of the iron-bearing member. Pyrite is a common associate of the carbonaceous impurities but may occur in smaller amount in the purer phases of the iron-bearing rocks. In the least-altered rocks the iron is present mainly as carbonate, being changed to limonite and hematite as oxidation progresses, but by anamorphism occasionally giving rise to magnetitic chloritic slates, usually carrying more or less residual iron carbonate. Such rocks occur on the top of Stambaugh Hill near the village of Stambaugh and are indicated in a small magnetic field in the SW. ¼ sec. 33, T. 43 N., R. 34 W. (See Pl. XXIV, in pocket.)

In short, the typical iron-bearing rock of the Vulcan member—mainly a cherty iron carbonate—shows all possible gradational phases, on the one hand to slate, which is nearly always highly chloritic, usually biotitic and sericitic, and in places more or less carbonaceous, grading into highly graphitic varieties, and on the other to graywacke; and further, it is to be noted that the purer forms of iron-bearing rocks are subordinate in amount. A laboratory study of these rocks discloses the characters that they may be inferred to possess from their intimate field relations to various types of interbedded slates and graywackes. It is impossible to describe the rocks of the Vulcan member without ref ˜ence to the clastic rocks with which they are so closely associated.

Distribution and local structure.—(1) The only natural exposure on the so-called Jumbo belt occurs on the east side of Brule River about 200 paces east of the southeast corner of the NE. ¼ SE. ¼ sec. 22, T. 42 N., R. 34 W. The rock is mainly a finely banded cherty iron carbonate, locally altered to ferruginous chert and interbedded with carbonaceous and pyritic black slate. The strike is east and west and the dip is about vertical on the average, although it varies widely on the limbs of the minor folds. From this exposure the member is traced eastward for three-quarters of a mile by numerous test pits of the old Jumbo exploration. The pits are now filled with débris, but the dumps disclose slate and iron-bearing member of the characters shown in the outcrop. In the dump of the old Jumbo shaft at the east end of the belt are found an abundance of much altered greenstone, black carbonaceous and pyritic slate, roughly banded iron-bearing rocks carrying plentiful pyrite and secondary quartz and a little lean iron ore. The relations between the Vulcan member and the greenstone are not shown, but these rocks are probably interbedded. Interbedded siliceous chloritic pyritiferous slate and much-altered greenstone are well exposed in an outcrop on the south bank of Brule River just north of the Vulcan member and seem to lie conformably above it. The Jumbo belt of iron-bearing member and slate is overlain on the north, in probable conformity, by extrusive ellipsoidal greenstone, which is well exposed in numerous outcrops north and south of the Chicago and Northwestern Railway. It is underlain by the Saunders formation, which occurs about one-quarter of a mile farther south. The Jumbo belt extends east and west beyond known limits.

(2) The boundaries of the central area, the iron-ore producing area of the Iron River district, are not yet definitely known and are being rapidly widened by exploration. If Iron River and Stambaugh are taken as a center, the iron-bearing member is known to occur northward to the southern part of sec. 11, T. 43 N., R. 35 W.; eastward to the Chicagon mine, in the NE. ¼ sec. 26, T. 43 N., R. 34 W.; southeastward to the NW. ¼ NW. ¼ sec. 16, T. 42 N., R. 34 W.; and westward to the SW. ¼ SW. ¼ sec. 33, T. 43 N., R. 35 W. The area seems to be limited on the south by greenstone. By connecting the scattered outcrops of greenstone occurring just north of the Saunders formation a belt of varying width is outlined extending across the entire district. Although it is certain that this belt as shown on the map (Pl. XXIV, in pocket) contains considerable interbedded slate and possibly iron-bearing member, it seems to mark in a general way the south limit of the main Michigamme slate and Vulcan member. Beginning at the outcrops in sec. 23, T. 42 N., R. 34 W., a magnetic line probably marking the north edge of the greenstone extends slightly north of west for about 2 miles and dies out. If extended, this line would pass just north of the greenstone exposure in the NW. ¼ NW. ¼ sec. 21. Thence the boundary swings more to the north and passes through the Wildcat shaft near the center of the S. ½ sec. 18, and thence just north of the outcrops of greenstone in the

N. ½ N. ½ sec. 13, T. 42 N., R. 35 W. Farther westward the boundary can not be followed, from lack of exposures and exploration.

Data for drawing a north boundary of this area are entirely inadequate. Probably it has no well-defined north limit. A few greenstone outcrops occur in a broad belt of country several miles wide, beginning about the middle of the east side of the district, where they connect with the greenstone area that extends eastward almost to Crystal Falls, and extending thence northwestward to the middle of the district and thence southwestward. In this belt there are a greater number of square miles of territory than there are outcrops, and those that occur are confined to the eastern, central, and western parts. However, the wide distribution of the few outcrops that are known indicates a belt composed dominantly of greenstone extending across the district in a curving course in line with the structure of the graywacke and slate area north of it.

Of the structure and distribution of the Vulcan member within this area the available information is by no means full. Exploration has been very active for the last few years, but is still far from adequate. Locally, in the mine workings, the structure is well known, but it may be very difficult to connect the structure and stratigraphy shown in workings on a single 40 acres with those of an adjacent 40 acres. The explanation for this complexity has already been discussed. In a later publication details of structure and distribution so far as known will be given, but here a general outline will suffice.

To begin in the southeastern part of the district, the iron-bearing member is found in the drill holes in the NW. ¼ NW. ¼ sec. 16, T. 42 N., R. 34 W., and thence, in a curving line parallel to the north boundary of the greenstone, northwestward to the Zimmerman mine. Eastward from sec. 16 the iron-bearing member extends in all probability through secs. 15 and 14, and perhaps still farther east, but in this direction exploration has not yet been carried. It is a favorable line for exploration. North and east of this belt borings have generally penetrated black slate. From the Zimmerman and Baltic mines the general course of the member is northwestward up the valley of Iron River. In detail the structure is exceedingly complex, and thorough understanding would involve a description of the structure and succession in every mine on the belt. The Vulcan member is here very generally underlain and interbedded with black slate and is usually in a highly inclined position. It attains its greatest known width on the Caspian mine location, where, with allowances for repetition by cross folding, it is probably over 300 feet thick. At the Hiawatha mine and thence westward for about a mile the Vulcan member strikes a little north of east and seems to dip on the whole steeply northward. Farther west this belt has not been traced. From the Caspian mine northeast to the SW. ¼ SW. ¼ sec. 21, T. 43 N., R. 34 W., drill holes have penetrated what seems to be a more or less continuous belt of the Vulcan member. This belt is about at right angles to the belt along Iron River, with which it and the extension of the Hiawatha belt form a cross.

North of Iron River the strikes are prevailingly about east and west. The Vulcan member occurs in one main belt at least, more than 2½ miles long, extending from the James mine slightly south and east through the Spies and Hall explorations to the NE. ¼ sec. 19, T. 43 N., R. 34 W., and slightly north of west to the SE. ¼ SE. ¼ sec. 15, T. 43 N., R. 35 W. The thickness of this belt in the James mine appears to be not over 250 feet, making due allowance for thickening by minor folding. Black slate here forms both foot and hanging walls. The dip varies, but is vertical or steeply southward or northward. Other lenses of the iron-bearing member occur both north and south of the James belt, but their importance and extent have yet to be proved by exploration.

(3) In the northern area the Morrison Creek belt is a narrow band of ferruginous chert and sideritic slate disclosed in the dumps of numerous test pits following the north boundary of the S. ½ SW. ¼ sec. 24, T. 44 N., R. 35 W. A few outcrops of sideritic slates occur on the banks of Morrison Creek in an east-west line with the pits. The dip is vertical or slightly northward. The iron-bearing member is here underlain by and probably interbedded with black carbonaceous slate. The overlying rock is a sericitic schist, a metamorphosed equivalent of the graywacke exposed to the east and north in numerous outcrops. On the south the slate seems to

be underlain by volcanic greenstone, which outcrops for about a mile to the south along the line between T. 44 N., R. 34 W., and T. 44 N., R. 35 W.

Southwest of Atkinson the Vulcan member occurs in a double belt, separated by a belt of volcanic greenstone breccia. The dip of the greenstone and associated iron-bearing member and slate here seems to be uniformly northwest at an angle of about 55°.

It will be interesting to consider in some detail the Atkinson section, for the interbedded relations of the various rocks in the Michigamme slate are here best exhibited. The southernmost rock is mainly black slate, carrying considerable but varying amounts of carbonaceous matter and in places becoming cherty and ferruginous, especially toward the top of the formation, where it gives place to thin iron-bearing rock about 80 feet thick, according to plats of the McColman exploration furnished by the Verona Mining Company. The Vulcan member at this horizon has not been followed beyond the McColman workings. The iron-bearing member, as shown by an examination of the rocks on the dump of the McColman shaft, includes hard limonitic iron ore, ferruginous chert, and brownish and gray banded sideritic slate. The slaty phases are sericitic, chloritic, and biotitic, and in one place abundant titanite was found. The ore occurs in lenses in the slaty phases of the member. From an inspection of the Verona Mining Company's plats it appears that the highly sericitic, biotitic, and chloritic slates are abundant just under the overlying greenstone.

The greenstone belt extends from the northeast corner of sec. 18, T. 44 N., R. 35 W., northeastward into the SW. ¼ NE. ¼ sec. 9 of the same township and doubtless farther in both directions where exposures are lacking. Its thickness ranges from 700 or 800 feet up to possibly 1,400 or 1,500 feet at the northwest end. In places this rock is very schistose, but usually its original agglomeratic structure is retained. Brecciation is common, but the resulting structures can usually be discriminated from its original agglomeratic structure, the fractures of the former cutting indifferently across the latter. The rock is extremely altered. Weathered surfaces have the green colors of chlorite and epidote and show abundant secondary calcite and dolomite filling fracture planes and disseminated through the rock.

The greenstone is overlain by a belt of ferruginous slates and cherts, which become more siliceous in the upper horizons. Near the underlying greenstone, black carbonaceous slates are found, but these seem to be less prominent in the higher beds, which are composed dominantly of very lean ferruginous granular chert. Only one natural exposure is known, but numerous pits and a few drill holes disclose the character of the rocks. This belt is less than a quarter of a mile wide. North of it are sericitic slates, and these in turn grade northward into micaceous schists and graywackes, which are the dominant rocks in the northern part of the Iron River district.

While little is known of the extent of the Vulcan member in the Atkinson district, it should be noted that to the southwest, on the strike of these beds, in the SE. ¼ sec. 14, T. 44 N., R. 36 W., lean ferruginous white granular cherty beds of the character of similar beds at Atkinson are associated with black slate and overlain by micaceous schistose graywacke. Similar white granular chert occurs on the strike of the Atkinson rocks in the bed of Paint River in the SW. ¼ NE. ¼ sec. 1, T. 44 N., R. 35 W. These two occurrences seem to be at about the horizon of the beds in the Atkinson district, but it should not be inferred that the iron-bearing member is continuous from one locality to the other along this indicated belt. The probabilities are that the reverse is true.

Local magnetism in the Vulcan iron-bearing member.—Although in general the Vulcan member is nonmagnetic, there are a few local areas in which magnetism is well developed. Other magnetic areas would probably be discovered were the district carefully magnetically surveyed. Reference has already been made to the magnetic line apparently following the northern edge of the greenstone in secs. 21, 22, and 23, T. 42 N., R. 34 W. Whether this line is caused by magnetism in the greenstone or in one of the lower members of the Michigamme slate is not known.

A magnetic field of irregular and widely varying strength in different parts covers about 60 acres on the crest of Stambaugh Hill, in the W. ½ sec. 36, T. 43 N., R. 35 W. (See Pl. XXIV, in pocket.) Here the rocks are well exposed in numerous outcrops. The dip is about vertical and the strike slightly west of north, which is the direction of elongation of the field. Under the microscope the rocks are seen to contain innumerable small grains of magnetite associated with abundant chlorite and finely crystalline quartz and considerable siderite.

A magnetic field of about the same size and shape occurs in the SW. ¼ sec. 33, T. 43 N., R. 34 W. (see Pl. XXIV), but here the field is elongated in a northwest-southeast direction, which is likewise believed to indicate the strike of the rocks at this place, although no exposures occur.

Local magnetism occurs also in separated patches in secs. 35 and 36, T. 43 N., R. 34 W. Here the magnetic rock is mainly a graywacke carrying abundant magnetite associated with chlorite, biotite, and siderite.

To the west of the Iron River district proper a belt of magnetic attraction has been traced in an area of heavy drift from a point near the center of T. 43 N., R. 37 W., westward to the Michigan boundary and thence probably into Wisconsin.

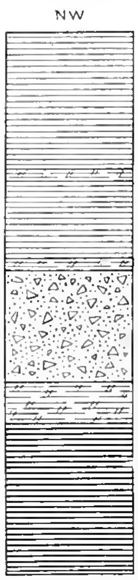


FIGURE 44.—Section showing roughly the succession of beds in the Vulcan iron-bearing member near Atkinson, in the Iron River district, Michigan.

INTRUSIVE AND EXTRUSIVE ROCKS IN THE UPPER HURONIAN (ANIMIKIE GROUP).

Igneous rocks of basaltic type are abundant in the upper Huronian. The distribution of those now known is indicated on the accompanying map of the Iron River district. (See Pl. XXIV, in pocket.) There is much difficulty in determining the general distribution of these rocks, because the relations to the slates are so intricate that it is never safe to conclude that adjacent exposures are or are not separated by slate.

The rocks are principally of extrusive type and have surface textures, especially the ellipsoidal and agglomeratic textures, that are characteristic of the Hemlock formation and of the volcanic rocks associated with the upper Huronian of the Crystal Falls district. Some of these extrusive rocks are distinctly contemporaneous with the slates. Southwest of Atkinson agglomeratic and tuffaceous phases of the greenstone are interbedded with upper Huronian slate and iron-bearing member (fig. 44). In the southern part of the district, in sec. 23, T. 42 N., R. 34 W., ellipsoidal and tuffaceous greenstone occurs north of the upper Huronian slates in a northward-dipping series. From the lack of contact metamorphism and the abundance of tuffaceous phases and effusive rocks they were probably nearly all deposited contemporaneously with the sediments. The deposition was probably submarine. (See pp. 510–512.) Definite evidence of relations is lacking for many of the greenstones, especially those not adjacent to slates or some of those which have been developed by mining operations and explorations.

RELATIONS OF UPPER HURONIAN (ANIMIKIE GROUP) TO UNDERLYING ROCKS.

No direct evidence of the relations of the upper Huronian with the underlying Saunders formation is yet available. Certain slates conformable with the Saunders formation in Sheridan Hill may be upper Huronian slates and may therefore indicate the conformable relations between the upper Huronian slates and the Saunders formation. The fact that rocks of the Saunders type form a continuous belt between the upper Huronian slates and the supposed Archean shore to the south is evidence of nearly conformable relations. It is noted in the sections on the Crystal Falls, Menominee, Felch Mountain, and Calumet districts that the succession from underlying quartzite and dolomite to the upper Huronian shows similar relations. (For discussion of correlation and nomenclature, see pp. 597 et seq.)

ORDOVICIAN ROCKS.

Remnants of flat-lying Paleozoic rocks occur in the southern part of the district, on Sheridan Hill and vicinity and farther southwest in the SW. ¼ sec. 27, T. 42 N., R. 35 W., also in the SE. ¼ sec. 24, T. 44 N., R. 35 W.

The base of these rocks on Sheridan Hill is a conglomerate made up almost entirely of material from the underlying Saunders formation. Angular fragments of chert and vitreous quartzite up to 2 inches in diameter lie in a matrix of materials of the same general composition, but finer grained. The rock is cemented mainly with iron oxide and calcium carbonate. The thickness of the conglomerate is unknown but is not great. The rock has not been found in natural exposure, but is abundant on the dumps of pits which have been sunk through it into the Saunders formation.

The conglomerate is overlain by a coarse quartz sandstone of buff and red color and generally very friable texture. The cement is mainly iron oxide. Under a slight tap of the hammer the rock falls apart into its constituent sand grains. The thickness of this sandstone is not known, but it probably ranges from a knife-edge up to perhaps 35 or 40 feet.

In the southeast corner of sec. 24, T. 44 N., R. 35 W., a film of red sandstone is found mantling black slate. Here the rock carries considerable iron oxide, doubtless derived from the Vulcan member occurring about a quarter of a mile north of it.

The conglomerate and sandstone of these areas have the lithologic characters of the lowermost Cambrian beds in the Menominee district and were formerly correlated with the Cambrian. Also Seaman has suggested that they perhaps represent the base of the upper Huronian. Recent fossil discoveries, however, in flaggy limestone beds in the S. ½ SW. ¼ sec. 27, T. 42 N., R. 35 W., have fixed within narrow limits the age of these rocks. In this area there is one natural exposure on the east side of Brule River and several pits, all showing nonmagnesian dove-colored to buff flaggy limestone of the same general characters. The rock seems to be flat-lying, although the beds in the outcrop on the Brule, where observations were made and where most of the fossils were found, have been disturbed by slump, following undercutting by the river. From the position of this outcrop in reference to an exposure of the Saunders formation on the west side of the river about 500 paces south, it would seem that these rocks are not far above the eroded surface of the Saunders formation. Whether they are underlain by the conglomerate and sandstone of Sheridan Hill is not known. The beds are practically undisturbed in both areas, but the lowermost known occurrence of the conglomerate on Sheridan Hill is about 150 feet higher and the uppermost known beds of sandstone are about 300 feet higher than the limestone outcrops on Brule River in sec. 27. It would seem from this that the conglomerate and sandstone on Sheridan Hill are stratigraphically higher than the limestone of sec. 27. Doubtless the conglomerate originally formed a continuous mantle at the base of the Paleozoic rocks, but owing to the rugged character of the surface over which the sea advanced there was probably a considerable time interval between the submergence of the lower areas and that of the tops of the hills. Consequently the relative age of the basal member formed at any point is a function of its altitude at that place. The occurrence of sandstone on Sheridan Hill at an altitude of about 1,760 feet makes it certain that the entire district was almost if not entirely covered by a Paleozoic sea.

The lowest exposure of the Paleozoic beds is the limestone member in sec. 27, T. 42 N., R. 35 W. This limestone is correlated by E. O. Ulrich on paleontologic grounds with the Lowville of New York and the Platteville limestone of Wisconsin—that is, with the Middle Ordovician. The following is Mr. Ulrich's report to T. W. Stanton:

I beg leave to report as follows on the fossils collected in the Iron River district, Michigan, by R. C. Allen and forwarded to the Survey for examination and report by C. K. Leith November 18, 1909:

This discovery of fossils in northern Michigan is of great interest, as it adds an important link in proving the former connection of the early Mohawkian limestone of Minnesota and western Ontario across northern Wisconsin. In discussing the Lowville limestone in my paper on revision of Paleozoic systems I state my conviction that this and perhaps other Mohawkian formations must have originally extended from New York through Ontario, northern

Michigan, and northern Wisconsin to Minnesota and Iowa. This direct westerly connection was indicated by the great similarity in fauna and lithology noted in comparing the Lowville limestone in New York and the more typical part of the Platteville limestone of southern Minnesota, Iowa, southern Wisconsin, and northwestern Illinois. I objected to communication via southeastern Wisconsin because there the beds supposed to correspond in age to the Lowville are dolomites instead of pure limestone, with no indication of transition in lithic characters northward. Hitherto the northern connection could not be established farther west from New York than Escanaba, Mich. This Iron River occurrence, which is of the same fine-grained nonmagnesian dove-colored limestone everywhere characterizing the Lowville and lying well up on the old "Wisconsin Peninsula," may therefore justly be regarded as tending to establish a view hitherto based only on inference.

The following 20 species are more or less confidently identified. All are older than the Trenton limestone and younger than the latest Stones River.

?Corematocladus densus.
Tetradium cellulosum (fragment of tube only).
Rhinidictya cf. nicholsoni and mutabilis-minor (fragment).
R. cf. major (fragment).
Escharopora angularis.
?Homotrypa arbuscula.
Rafinesquina minnesotensis.
Strophomena incurvata (Lowville var.).
Zygospira recurvirostris (Lowville var.).
Ctenodonta sp. undet. (near C. levata).
Leperditia fabulites.
Leperditella tumida.
L. germana.
Bythocypris granti var.
Eurychilinia reticulata.
E. subradiata.
E. n. sp.
Isotelus cf. obtusus.
Thaleops cf. ovatus.
Pterygometopus sp. undet. (pygidium).

The fossils of the above list indicate a horizon at the extreme top of the Platteville limestone in the Lead district. Compared with the New York section the bed corresponds in age to the uppermost beds of the Lowville, as described by Cushing, or to the cherty bed at the base of the Black River limestone, as defined by the same author.

FLORENCE (COMMONWEALTH) IRON DISTRICT OF WISCONSIN.

LOCATION AND GENERAL SUCCESSION.

The Florence district is the westward geographic extension into Wisconsin of the Menominee district beyond Menominee River. It is essentially included between the two tributaries of the Menominee, the Brule on the north and the Pine on the south (Pl. XXV, in pocket). On the east it is separated from the Menominee district, as this is limited on the geologic map, by Menominee River. The area is one of low relief, like the Iron River district to the northwest. Exposures are relatively few except along the rivers and lakes.

Part of the Florence district has been studied by members of the United States Geological Survey, and a complete outcrop map of the district has been prepared by Mr. W. N. Merriam and assistants for the Oliver Iron Mining Company. As yet, however, the district has not been studied with sufficient exhaustiveness to definitely establish the succession and structure. Such a study is now being conducted by W. O. Hotchkiss, State geologist of Wisconsin. So far as the facts are now known, including those developed in recent work of Hotchkiss, the succession in the Florence district seems to be as follows:

Quaternary system:	
Pleistocene deposits.	
Paleozoic rocks	Patches of sandstone, probably Cambrian.
Algonkian system:	
Keweenawan (?) series	Granite and gneiss.
Huronian series: Upper Huronian (Animikie group)	Quinnesec schist, intrusive and extrusive greenstones and green schists. Michigamme slate, including the Vulcan iron-bearing member (interbedded with base of the slates), and also quartzites and conglomerates of doubtful age but believed to be phases of the slate.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

UPPER HURONIAN (ANIMIKIE GROUP).

MICHIGAMME SLATE.

General character and distribution.—The Animikie group seems to occupy nearly all the area of the Florence district north of the Quinnesec schist belt, except where small patches of intrusive or extrusive greenstone appear at the surface. The rocks are chiefly slate. In less quantity occur conglomerate, quartzite, tuffs, and iron-bearing rocks. It has not been proved that all these rocks belong to one group, but as yet they have not been certainly separated.

The Michigamme slate is poorly exposed in the district as a whole, except along Brule River, in the vicinity of Keyes Lake, and northwest and southeast of Florence. It is almost identical in petrographic characters with the upper Huronian slates of the Menominee and Crystal Falls districts, and has been regarded as belonging to the same formation.

Quartzites, associated with more or less conglomerate, appear in three main areas—(1) at Island Rapids, on Menominee River, in secs. 13 and 14, T. 40 N., R. 18 E.; (2) in a belt running north of Keyes Lake; and (3) in a belt running through sec. 28, T. 39 N., R. 18 E., north of Pine River. The quartzite at Island Rapids stands vertical or dips steeply to the south, and the top is to the south. In the Keyes Lake belt the rock is vertical or dipping steeply to the southwest. The relations of these two belts with the slates are not known definitely, but are probably conformable. The southern belt of quartzite just north of Pine River dips southwestward at a lower angle. It is thought by Hotchkiss to rest unconformably upon the slates to the north of it. If this is true the so-called upper Huronian of this district consists really of two groups, the correlation of which is doubtful. The southern quartzite is overlain conformably by slates which upward become interbedded with tuffs and eruptives belonging to the Quinnesec schist.

Vulcan iron-bearing member.—The Vulcan iron-bearing formation is somewhat widely distributed through the upper Huronian area, but here it is so interbedded with the slates that it is difficult to map independently. In this district, therefore, as in some other districts, it is treated as a member of the Michigamme slate. In the Florence district there are only five areas in which the ferruginous phases of the upper Huronian are now known sufficiently well to warrant a separate color on the map—one is immediately northwest of Florence in secs. 20 and 21, T. 40 N., R. 18 E., and in a belt extending northwestward to Brule River; two southeast of Commonwealth, in secs. 33 and 34, T. 40 N., R. 18 E.; one extending east and west south of the greenstone belt in secs. 8 and 9, T. 39 N., R. 19 E. These three exposed areas are connected by a belt of magnetic attraction, indicating that the iron formation is probably continuous from Brule River on the northwest nearly to Menominee River on the southeast. Another area is in the vicinity of the Buckeye mine, just to the southwest of Commonwealth. This connects with a magnetic belt running southeastward to Menominee River, in sec. 22, T. 39 N., R. 19 E. To the east, across the river, this magnetic line connects with the principal iron-formation belt of the Menominee district. Another belt of iron-bearing formation outcrops west of Keyes Lake, whence it is followed by magnetic lines to the southeast to about the east side of T. 39 N., R. 18 E., and northwestward toward the northwest corner of T. 40 N., R. 17 E. Belts of attraction not connected with any well-exposed areas of iron formation are known elsewhere in the district. Particularly to be mentioned are the belts extending northwestward from Pine River from sec. 28, T. 39 N., R. 18 E.

The iron-bearing member is magnetic in places, especially along the contacts with the intrusive greenstones. The map shows a number of disconnected magnetic lines which have been traced in this area. Some of these may represent altered iron-bearing rock.

The Vulcan iron-bearing member consists of (1) ferruginous chert, siderite, and hydrated hematite; (2) various phases intermediate between these and the slates, called sideritic slates and ferruginous slates; and (3) grüneritic and magnetic slates. They are similar, except for type 3, to the rocks of the Vulcan iron-bearing member in the Iron River and Crystal Falls districts. Iron ores are exploited at the Florence mine, immediately northwest of the town of Florence; at the Commonwealth and Badger mines, southeast of the town of Commonwealth; and at the Buckeye mine, south of Commonwealth. (See p. 323.) The ores seem to be in minor drag folds, pitching steeply northwestward in the Florence and Commonwealth mines. The major trend of the iron-bearing exposures of magnetic belts and of exposures of other rocks is north of west in this district, a trend which would tend to connect the iron-bearing belts with those of the Menominee district on the southeast and with those of the Mastodon area in the southern part of the Crystal Falls district on the northwest. (See p. 292.) Exploration has been very slight, as there has been little to guide it. However, there is a large territory along the trend here noted which must soon receive attention.

The horizon in the upper Huronian slates at which the iron-bearing member of this district occurs has not been determined. The proximity to the upper Huronian iron formation of the Menominee district suggests its occurrence near the base of the upper Huronian.

INTRUSIVE AND EXTRUSIVE GREENSTONES AND GREEN SCHISTS.

Quinnesec schist.—The Quinnesec schist outcrops in an east-west belt 1 to 3 miles wide along the south side of the district, probably constituting the northwestern extension of the southern Quinnesec schist belt of the Menominee district. The best exposures are along Pine River, especially in secs. 29 and 30, T. 39 N., R. 18 E. The schists are chiefly hornblendic gneiss, locally micaceous. They are cut by basic and acidic intrusive rocks, the former being the more abundant. The detailed petrographic description of these schists given in the Menominee chapter will suffice for this district.

The continuation of these schists along the south side of the Menominee district has been assigned to the Keewatin series of the Archean in previous reports of the United States Geological Survey.[a] Later work showed this assignment to be a very doubtful one, and the question of the correlation of the schists has been largely left open for the Menominee district. The work of Hotchkiss along the south side of the Florence district shows clearly an interbedding of upper Huronian slate with tuffs and eruptives of the Quinnesec schist in a manner showing the main body of schist to be later in origin than the upper Huronian to the north of it.

Intrusive and extrusive greenstones and green schists other than Quinnesec.—Massive and schistose intrusive and extrusive greenstones appear in several small areas in the upper Huronian. Two of them cross Menominee River on the east, where they join the northern Quinnesec schist area of the Menominee district. Another group is exposed along Brule River and others between the Brule and Florence. Isolated outcrops of green schistose and tuffaceous rocks of doubtful structural relations are somewhat widely distributed through the district. They are in places associated with amphibole-magnetite schists, some of which represent phases of the intrusive rocks, but some of which doubtless also are metamorphosed phases of the Huronian ferruginous slates.

Petrographically these rocks are very similar both to the Hemlock formation and to the Quinnesec schist, and the description of the northern Quinnesec schist area of the Menominee district will apply to them.

The areas of intrusive rocks are longer from east to west than from north to south. Evidence of the intrusive character of the greenstones is found along Brule and Menominee rivers in T. 40 N., R. 18 E. Especially good evidence is the area just west of Keyes Lake. In sec. 9, at several points along the Brule, are to be found outcrops of the massive greenstones in contact with the slates. Invariably the slates are more micaceous near the contact than elsewhere. In fact, they become mica schists, and here and there is seen a slight development of some secondary mineral, probably garnet. In every outcrop along the Brule the contacts of the greenstones and sediments are not sharply defined, the greenstones being schistose and chloritic at the contacts. In sec. 13, T. 40 N., R. 18 E., greenstone is found in contact with a micaceous

[a] Mon. U. S. Geol. Survey, vol. 46, 1904; Menominee special folio (No. 62), Geol. Atlas U. S., U. S. Geol. Survey, 1900.

quartzite. The actual well-defined contact may be seen here, and the intrusive character of the greenstone is clearly shown. A wedge of the greenstone cuts the quartzite at 1,650 paces north and 200 paces west of the southeast corner of sec. 13, T. 40 N., R. 19 E. The quartzite at this place is much fissured and shattered.

Brule River, where it crosses the E. ½ sec. 9, T. 40 N., R. 18 E., is a favorable place to see the way in which the intrusive greenstones stand out prominently as hills in the slate area. The river here cuts through the slates and greenstones, giving a well-exposed cross section. The conclusion is here forced on the observer that the outcrops of the greenstones of this area represent with a very fair degree of accuracy the actual distribution of the greenstones. The greenstone outcrops are many times longer east and west than north and south, as has been noted. This, however, does not justify the correlation of greenstone knobs because they happen to align in the direction of their long dimensions. The areas mapped as intrusive and extrusive greenstones and green schists on the Florence map (Pl. XXV, in pocket) may therefore be regarded as containing much slate in lower, covered ground.

GRANITE AND GNEISS INTRUSIVES.

Bordering the Quinnesec schist on the south is an area supposed to be underlain by granites and gneisses. Exposures are few, but to the east, south of the Menominee district, they are more abundant. The relations are those of intrusion into the Quinnesec schist, and the rocks are doubtfully correlated with the Keweenawan.

PALEOZOIC SANDSTONE.

A few patches of Paleozoic sandstone lie unconformably upon the pre-Cambrian rocks. These are well shown just west of the Buckeye mine and north of Keyes Lake.

QUATERNARY DEPOSITS.

This district is covered by Pleistocene glacial drift. (See Chapter XVI, pp. 427–459.)

THE IRON ORES OF THE CRYSTAL FALLS, IRON RIVER, AND FLORENCE DISTRICTS.

By the authors and W. J. Mead.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The principal ores of this region are found in iron-bearing layers infolded with upper Huronian slate in the vicinity of Florence, Commonwealth, Crystal Falls, Amasa, and Iron River, and in the middle Huronian slate near Mansfield. These districts are usually considered as a part of the Menominee district in returns of ore shipments, and their ores are similar, geologically and structurally, to those of the Menominee district. Though not directly continuous with the iron formation of the Menominee district, so far as explorations yet show, they mainly belong in a formation which is closely correlated with that iron-bearing formation (the Vulcan), and is given the same name. Also the upper Huronian slate with which this iron-bearing formation is associated is similar to and continuous with the Michigamme ("Hanbury") slate of the Menominee district, and is therefore called by the same name.

The Michigamme slate over this great area is remarkably uniform in character, and it is difficult to tell at what horizon in the slate formation the ores occur in any particular locality. In the vicinity of Crystal Falls and Amasa the upper Huronian slate rests upon greenstones of the Hemlock formation, so that in this part of the district it is easy to determine the base of the upper Huronian, and the occurrence of the ore at a short though varying distance from the volcanic Hemlock formation shows that for this locality at least the iron-bearing rocks occur at a fairly persistent horizon near the base of the upper Huronian slate.

Most of the ore deposits of these districts are accompanied by black and pyritiferous slate walls, in places associated with greenstone, or they may be separated from such walls, especially the hanging wall, by a small amount of lean cherty iron-bearing rock. Along the trend of the iron-bearing member and in depth the iron-ore layers pass into lean cherty layers. The ore bodies throughout show a strong tendency to follow the steeply inclined and uniformly trending bedding of the iron-bearing member, having thus distinct linear shape and distribution at the surface and tabular or lens shape in three dimensions. In certain of the Crystal Falls deposits these characteristics are much more apparent than in others. For instance, the ores at the Hemlock mine at Amasa constitute a lens in a narrow band of iron-bearing rock, with considerable extent vertically and horizontally, parallel to the strike of the upper Huronian. The same is true of the ore deposits in the so-called "Mansfield slate." Though minor folds are present in both of these deposits, they are subordinate to the general tabular shape of the deposits.

Other ore bodies follow the axial lines of drag folds, thus pitching at various angles beneath the surface. Their shape, considered in three dimensions, tends to be linear rather than tabular. As few of these axial lines are uniform for long distances, offsets of the ore body are common. The ores of the Florence district seem to be in drag folds, with pitches to the northwest. Their distribution suggests sharp offsets by drag folding.

The iron-bearing rocks, and therefore the ore bodies, are usually not more than 300 feet thick, though locally the thickness may be much increased by buckling. It will be noted by figure 12 (p. 123) that folding of that type multiplies the thickness by 3. The depth to which mining has thus far extended is 1,000 feet, but exploration has shown ore to a greater depth. It can not yet be said what the maximum depth of the ores may be. At the Florence mine the formation becomes pyritiferous below this depth, although it is not demonstrated that the pyritiferous portion continues indefinitely.

The iron formations near the main area of the Hemlock formation in the Crystal Falls district and part of those in the Florence district are distinctly magnetic. Elsewhere in the Crystal Falls district and in the Iron River district the formations are weakly or not at all magnetic.

The structural relations of the ores of this group are less satisfactorily known than those of almost any other district in the Lake Superior region, partly because of the lack of sufficient development and partly because of the uniformity of the slate, making it difficult to find recognizable horizons as a basis for working out the structure. Because of the lack of continuity of the iron formation in this great slate area and the covering of a large part of the area by glacial drift, it seems altogether likely that there are still many deposits to be found through the slate. Magnetic work sometimes indicates places to begin exploration, but much of the exploration must begin blindly.

CHEMICAL COMPOSITION.

The ores of these districts, with the exception of the Mansfield deposit and the Amasa-Porter, south of Amasa, are non-Bessemer hydrated hematites of medium to low grade. The average composition and range for each constituent of the ores mined in these districts in 1907 and 1909 are as follows:

Average chemical composition of ores from cargo analyses for 1907 and 1909.

	Crystal Falls district.		Iron River district.		Florence district.	
	1907.	1909.	1907.	1909.	1907.	1909.
Moisture (loss on drying at 212°)	8.46	8.42	8.23	8.34	10.86	9.76
Analysis of ore dried at 212° F.:						
Iron	54.10	54.79	55.70	54.35	54.50	54.70
Phosphorus	.437	.495	.396	.404	.32	.319
Silica	6.27	7.71	8.62	8.77	6.72	6.89
Manganese	1.27	.799	.20	.30	.26	.08
Alumina	2.94	2.50	2.54	3.07	3.35	4.17
Lime	2.62	2.63	.92	1.31	1.51	1.80
Magnesia	2.15	2.16	.76	1.49	2.46	2.86
Sulphur	.056	.071	.057	.056	.132	.173
Loss on ignition	5.89	4.11	5.25	5.74	5.20	5.20

Range in percentage of each constituent in ores mined in 1909.

	Crystal Falls district.	Iron River district.	Florence district.
Moisture (loss on drying at 212°)	2.83 to 13.75	3.69 to 11.66	8.46 to 9.98
Analysis of ore dried at 212° F.:			
Iron	35.74 to 57.20	49.87 to 56.67	53.30 to 55.00
Phosphorus	.040 to 1.28	.709 to 3.13	.297 to .416
Silica	5.51 to 39.53	5.35 to 14.16	6.50 to 8.65
Manganese	.15 to 2.93	.18 to 2.10	.06 to .20
Alumina	1.20 to 3.41	.99 to 4.23	2.82 to 4.47
Lime	1.20 to 4.96	.40 to 2.74	1.61 to 2.63
Magnesia	.71 to 2.80	.20 to 2.40	2.74 to 2.88
Sulphur	.007 to .160	.009 to .088	.11 to 1.87
Loss on ignition	1.58 to 7.60	2.45 to 9.02	5.05 to 5.80

MINERAL COMPOSITION.

The ore of these districts is chiefly soft red hematite, though in places it is hydrated and graded as brown hematite (limonite). Goethite has been identified at Iron River. In addition, there are quartz and some kaolin, with small amounts of magnetite, calcium, and magnesium carbonates, and minute amounts of sulphides.

The average mineral composition of the ores of these districts, calculated from average analyses for 1909 given in the above table, is as follows:

Approximate mineralogical composition of ores, calculated from the average analyses for 1909.

	Crystal Falls district.	Iron River district.	Florence district.
Hematite	71.90	54.00	62.42
Limonite	7.50	27.80	18.10
Quartz	4.36	4.82	1.26
Kaolin	4.70	5.80	7.70
Chlorite and other ferromagnesian silicates	3.50	3.80	6.20
Dolomite	4.00	.45	2.85
Apatite (all phosphorus calculated as apatite)	2.60	2.12	1.65
Miscellaneous	1.44	1.21	....
	100.00	100.00	100.18

The above mineral compositions are necessarily only approximate, as ferrous and ferric iron are not separated, and the combined water, CO_2, and a possible small amount of organic material are included together under loss on ignition. All the phosphorus with proper amounts of limestone was calculated as apatite; the remaining lime with proper amounts of magnesia and water was calculated as dolomite. The remaining magnesia with alumina, silica, and water was calculated as chlorite. The alumina not used in the chlorite, together with sufficient silica and combined water, was taken as kaolin. Sufficient iron was combined with the remaining water to form limonite and the remaining iron figured as hematite. Hematite and limonite probably do not exist in the ores, but as a means of comparison and to show the degree of hydration the hydrated iron oxide is calculated in terms of these two minerals.

PHYSICAL CHARACTERISTICS.

The ore is very porous and shows many crystal-lined cavities. At places a hard steel hematite ore is found, which runs high in metallic iron. It breaks into a mixture of small blocks and soft ore similar to the ores of the Menominee district.

The average mineral density of the ores, calculated from the above analyses, is 4.38 for the Crystal Falls ores and 4.30 for the Iron River ores.

The porosity of the ores ranges from less than 5 per cent to over 40 per cent of their volume.

The cubic contents of the ores vary from 8.5 to 15 cubic feet to the ton, with an average of about 11 cubic feet. The volume composition of these ores, in comparison with those of the Menominee district, is represented in figure 50 (p. 352).

SECONDARY CONCENTRATION OF THE ORES OF THE CRYSTAL FALLS, IRON RIVER, AND FLORENCE DISTRICTS.

Structural conditions.—The ores of the Crystal Falls, Iron River, and Florence districts are enrichments of narrow beds and lenses of iron-bearing rocks, as a rule not more than 300 feet wide, usually between steeply inclined walls of slate, generally graphitic and pyritiferous near the contact, and commonly associated with greenstone. The iron-bearing member may trend in the same direction for considerable distances and yet be closely corrugated by minor folds of the drag type illustrated in figure 12 (p. 123). These steeply pitching drag folds furnish an impervious basement of slate along which the waters have followed the openings in the iron-bearing member in especial abundance and have effected the concentration of the ore. The iron-bearing rock is brittle, but the slate is not, the result being that breccias are common in such troughs, greatly favoring the flow of water. The folds are of various magnitudes and the concentration may follow either the minor or the major folds.

The circulation has been controlled by the fracture openings in the iron-bearing member and the bedding in it, and the confining strata have been foot-wall slates, hanging-wall slates, and iron-bearing member. The essential parallelism of the ores to the trend of the iron-bearing member shows the obvious tendency of the waters to follow that trend but to be deflected by the minor bends in it. This is especially well seen along the main belt of iron-bearing rocks along Iron River.

The depths to which the waters have acted is yet largely unknown. The deepest mines operate to a depth of 1,000 feet in the Crystal Falls district, 500 feet in the Iron River district, and 950 feet in the Florence district. In certain deposits the ore has apparently given out with depth. It is possible that in some mines it has been lost because of considerable offset by the folding. Deeper exploration is warranted.

The topographic relief of the region is so great that different parts of the iron-bearing member may differ as much as 300 feet in elevation. The ores are as a rule closely associated with the hills but seem to follow, indifferently, crests, slopes, and adjacent valleys. In the Iron River district the ores favor especially the valleys. These are discernible with difficulty through the thick drift, but are being found by drilling. The depth to which a head given by the observed topography would carry a vigorous circulation through the iron-bearing member can not be worked out theoretically because of the uncertainty of the factors involved. Certainly nothing is now known which would prevent exploration as deep as in other districts of the Lake Superior region, although here, as in other districts, many of the deposits have certainly been found to be only a few hundred feet deep.

Chemical and mineralogical changes.—The iron-bearing member was originally pyritiferous iron carbonate interbedded with more or less slate. The alteration to ore has occurred in two phases—first, the oxidation of the iron without removal of silica, producing ferruginous cherts; second, partly simultaneous and more local, the leaching of the silica, leaving the iron oxide concentrated as ore. The physical and chemical features of these alterations have not been worked out quantitatively as they have for other districts, but qualitatively they are known to be similar to those of other districts in all respects.

Time of concentration.—The ores were concentrated after the upper Huronian folding and before the Cambrian deposition, and since their concentration they have been little affected by further folding.

THE IRON ORES OF THE FELCH MOUNTAIN AND CALUMET DISTRICTS.

By the authors and W. J. Mead.

The Felch Mountain and Calumet districts are eastward branches of the Crystal Falls district. Except for low grade and low phosphorus, their ores are the same in horizon, relations, and mineralogical and physical character as the ores of the Crystal Falls and Menominee districts.

The shipment from these districts has been small.

FELCH MOUNTAIN DISTRICT.

Iron ores have been mined at two localities in the Felch Mountain district near Groveland and near Felch. In both these localities the iron-bearing Vulcan formation lies in a closely compressed syncline with basement of impervious slate or schist, called "Mansfield" schist by Smyth, but called Felch schist in this report. The lenses at the east end of the Felch Mountain trough are now largely worked out. At the Groveland mine dikes of granite cut the ore body.

The average composition of the ores mined in the Felch Mountain district in 1907 is as follows:

Average analysis of ore mined in the Felch Mountain district in 1907.

Moisture (loss on drying at 212°)	4.05
Analysis of ore dried at 212° F.:	
Iron	52.50
Phosphorus	.040
Silica	11.22
Manganese	1.10
Alumina	2.49
Lime	3.51
Magnesia	4.62
Sulphur	.008
Loss by ignition	5.29

The volume composition of these ores, in comparison with the Crystal Falls, Menominee, Iron River, and Florence ores, is given in figure 50 (p. 352).

CALUMET DISTRICT.

Ore is mined in the Calumet district only at the Calumet mine, a comparatively recent development, where there is a steeply southward-dipping succession beginning with Archean granite on the north, followed successively by Sturgeon quartzite, Randville dolomite, Felch schist, Vulcan formation (iron bearing), and Michigamme slate. The strike of the ore body is parallel to the bedding. The bedding trends east and west, but has minor folds with steep pitches parallel to the strike. The ore body with its associated iron-bearing formation is divided longitudinally into three parts by layers of slate, from north to south 60, 15, and 60 feet thick. The foot wall is slate, quartzite, and dolomite. The hanging wall is slate or iron-bearing formation. Along the strike the ore abuts irregularly against unaltered iron formation. The depth of mining operations to the date of writing is 200 feet. The possibilities of the extension of the deposits are discussed on page 324. The iron ore is banded cherty hematite and limonite and some magnetite. It is nonmagnetic in individual pieces, but collectively it exerts a powerful magnetic pull. The ore runs from 40 to 45 per cent of iron and is sold on the basis of 0.028 per cent of phosphorus. Its density is about 4 and its porosity 18 per cent; it averages about 10.5 cubic feet to the ton.

The average composition of the ores mined in the Calumet district in 1907 is as follows:

Average analysis of ore mined in the Calumet district in 1907.

Moisture (loss on drying at 212°)	5.00
Analysis of ore dried at 212° F.:	
Iron	42.82
Phosphorus	.028
Silica	32.27
Manganese	.20
Alumina	2.53
Lime	.74
Magnesia	1.06
Sulphur	.011
Loss by ignition	1.86

The volume composition of these ores, in comparison with Crystal Falls, Iron River, Florence, and Menominee ores, is given in figure 50 (p. 352).

SECONDARY CONCENTRATION OF THE FELCH MOUNTAIN AND CALUMET ORES.

Structural conditions.—The iron-bearing Vulcan formation of the Felch Mountain district is in closely compressed synclinal folds in the upper Huronian Felch schist. It stands out as erosion remnants forming the crests of the hills. The concentration has evidently been controlled by the impervious basements of slate, and also to some extent by the openings along fracture planes, especially north-south fracture planes crossing the axis of the trough. The granite dikes at the Groveland mine may also have been influential in controlling circulation.

In the Calumet district there is no essential difference in the structural relations governing the flow from those in the Crystal Falls and Iron River districts. The dip is steep and the formation has the usual drag type of corrugation.

Chemical and mineralogical changes.—The iron-bearing member was originally iron carbonate interbedded with more or less slate. The alteration to ore has occurred in two phases—first, the oxidation of the iron without removal of silica, producing ferruginous cherts; second, partly simultaneous and more local, the leaching of the silica, leaving the iron oxide concentrated as ore. The physical and chemical features of these alterations have not been worked out quantitatively as they have for other districts, but qualitatively they are known to be similar to those of other districts in all respects.

CHAPTER XIII. THE MENOMINEE IRON DISTRICT OF MICHIGAN.[a]

LOCATION AND EXTENT.

The portion of the Menominee district covered by the accompanying map (Pl. XXVI, in pocket) is bounded on the west by Menominee River, on the south by the same river and the south line of T. 39 N., on the north by the north line of T. 40 N., and on the east by the east line of secs. 10, 15, 22, 27, and 34, T. 39 N., R. 28 W. The area thus outlined constitutes a tongue of sedimentary deposits lying between a granite area to the north and a greenstone schist area to the south.

At about the line between Rs. 27 and 28 W. the characteristic rocks of the Menominee trough become so deeply buried under later sediments that they can be traced no farther by outcrop. Lines of magnetic attraction, however, have been obtained still farther east, and these are taken to mean that the Huronian deposits continue for a considerable distance beyond the places where they are last seen on the surface.

The area of sedimentary rocks belonging in the Menominee trough is about 125 square miles, entirely within the State of Michigan. This area is narrowest in the vicinity of Vulcan, where it measures about 4 miles in width from the contact with the granite on the north to the contact with the greenstone schist on Menominee River to the south. To the east the area widens gradually, until in the eastern portion of R. 28 W. its width measures about 7 miles. To the west it also widens gradually and finally loses its identity as a distinct trough at about the center line of R. 30 W., where it merges, with the Calumet trough, into the wide area of Huronian sediments on the west.

TOPOGRAPHY.

There are three important ridges in the district with axes parallel to its length, a northern one and two others, nearly parallel, near the central part of the district. The northern ridge is composed of Archean granite and the Sturgeon quartzite. The central ridges are composed of the Randville dolomite and the iron-bearing Vulcan formation, capped in much of the district by Cambrian sandstone. The higher points of these ridges range in altitude from about 1,000 feet to nearly 1,600 feet. The valleys between the ridges, as well as the valley to the south of the main central ridge sloping to Menominee River, are composed mainly of the Michigamme ("Hanbury") slate. The southern lowland area of the Michigamme slate continues into the area of the Quinnesec schist. The lower areas have altitudes varying for the most part from 800 to 1,000 feet.

The minor streams follow to a considerable extent the valleys of the Michigamme slate, and the same is true of the chief stream of the district, the Menominee, for a considerable part of the area, but this and a number of the other more important streams, such as Sturgeon River and Pine Creek and some of its branches, flow transverse to the ridges. Several of even the smaller branches break through either one or both of the iron ranges and the quartzite and granite range to the north. Sturgeon River crosses all the formations of the district.

SUCCESSION OF FORMATIONS.

The rocks of the Menominee district belong to the Archean, Algonkian, Cambrian, and Ordovician systems. The oldest rocks bordering the Menominee tongue are greenstone schists and granite. These are regarded as Archean. Resting unconformably upon the Archean rocks

[a] For further detailed description of the geology of this district see Mon. U. S. Geol. Survey, vol. 46, 1904, and references there given.

are Algonkian sediments, which belong to the Huronian series. These are divisible into lower Huronian, middle Huronian, and upper Huronian, and are separated by unconformities. The Paleozoic rocks comprise horizontal Cambrian sandstones and Cambro-Ordovician limestones. These occur in patches on the tops of the hills, capping the closely folded and truncated Huronian rocks. The Huronian series is divisible into a number of formations, each representing a time during which the conditions of deposition were approximately uniform. The following table gives the list of the formations arranged in descending order according to age. The members of the Vulcan formation are distinguished in the description but not on the map.

Cambro-Ordovician	Hermansville limestone.
Cambrian system	Lake Superior sandstone.
Unconformity.	
Algonkian system:	
Keweenawan series	Granite (?).
Huronian series:	
Upper Huronian (Animikie group)	Quinnesec schist and other green schists representing surface eruptions overlying and interbedded with Michigamme slate. Michigamme ("Hanbury") slate, including iron-bearing beds. Vulcan formation, subdivided into Curry iron-bearing member, Brier slate member, and Traders iron-bearing member.
Unconformity.	
Middle Huronian	Quartzite, not separated from Randville dolomite in mapping for most of the district.
Unconformity.	
Lower Huronian	Randville dolomite. Sturgeon quartzite.
Unconformity.	
Archean system:	
Laurentian series	Granites and gneisses, cut by granite and diabase dikes.
Keewatin series (not separated in mapping from Laurentian)	Green schists.

The Quinnesec schist is so named because the formation is typically developed at the Quinnesec Falls, on Menominee River. The Sturgeon quartzite is so called because this formation in the Menominee district has been traced almost continuously to a like formation in the Crystal Falls district which has been called the Sturgeon quartzite. The dolomite in the Menominee district is called the Randville dolomite because it has been practically connected with the Randville dolomite of the Crystal Falls district.

In the upper Huronian the Vulcan formation is so named because it occurs in typical development with full succession and fine exposures near the town of Vulcan. The "Hanbury" slate was thus named because in the vicinity of Lake Hanbury this formation is better exposed than anywhere else in the district. This slate, however, has been proved to be equivalent to and continuous with the Michigamme slate of the Marquette district, and the older name, Michigamme, is therefore used in this report.

ARCHEAN SYSTEM.

LAURENTIAN SERIES AND UNSEPARATED KEEWATIN.

The complex north of the Menominee district is composed largely of Laurentian rocks. They are principally gneissoid granites and finer-grained banded gneisses. In addition to these there are also present in subordinate quantity hornblende schists and certain feldspathic greenstone schists identical lithologically with some of the mashed eruptive rocks among the Quinnesec schist. These are intruded by Laurentian granites and are believed to represent the

Keewatin series. They have not been separated in mapping. Mica schists are found only in a few exposures in the interior of the Archean area north of the region shown on the map (Pl. XXVI, in pocket). The granites, gneisses, and schists are cut by small dikes and veins of granite, pegmatite, and aplite, by numerous quartz veins, and by coarse granite, massive basalt, diabase, and gabbro.

Some of the hornblende schists (Keewatin) and some of the gneisses appear to be older than most of the granites. Others of the schists are unquestionably mashed intrusive rocks that are younger than some of the granites. The aplites, pegmatites, and some of the basic intrusives are the youngest rocks belonging exclusively in the complex, but even these, as they are not known to cut through the Huronian deposits, are thought to have taken their present position before the sediments were deposited. The latest of all the intrusive rocks are certain coarse-grained massive diabases and gabbros. These rocks not only occur as members of the complex but are found also in the lower division of the Huronian series, overlying the Archean complex. There is no reason to believe that any of these rocks are metamorphosed sediments. Most of them are clearly of igneous origin.

The massive granites and the gneissoid granites differ from each other in no essential respect. The latter are merely schistose phases of the former. They both embrace medium-grained to fine-grained gray and pink rocks with a granitic texture that locally approaches in appearance the texture of some quartzites.

The banded gneisses consist of alternate bands of pink and gray material, each band having the look of granite. These bands, though appearing to be approximately parallel in the ledges, are found on close inspection to run parallel to one another for short distances only and then to anastomose or interlace. The red layers cut across the gray gneiss as if they were veins of granitic material. The only difference that can be discerned between the banded gneisses and the fine-grained gray gneisses cut by red granite veins is that the latter are irregularly injected by the granitic material, while in the former the injections are largely parallel.

The hornblende schists (Keewatin) are usually lustrous greenish-black schists with the normal characteristics of such rocks. They are cut by the granites in some places. In other places large blocks are found included in granite. Plainly they are older than the granites, and probably they are the oldest rocks in the northern complex. A second kind of hornblende schist exists in which the rocks are so related to the granites and gneisses that they must be regarded as dikes. In some places they appear as bands cutting across the banding of the gneisses, and in others as bands conforming in strike and dip with the lighter-colored bands of these rocks. These schists are therefore looked upon as mashed intrusive rocks.

ALGONKIAN SYSTEM.

GENERAL CHARACTER AND LIMITS.

The Algonkian rocks constituting the Menominee trough, though strongly metamorphosed, are recognized as mainly sediments. The greater mass of these sediments is mechanical, clastic textures being still plainly apparent. The iron-bearing formation is largely mechanical, but with the mechanical material an important amount of chemical and organic material was deposited, and some of the jaspers of the formation may be wholly chemical or organic. The limestones are chemical or organic sediments. The sedimentary rocks have been intruded by a few coarse-grained and some fine-grained igneous rocks. The latter are now usually schistose. The lowest formation of the Algonkian system has at its bottom basal conglomerates, which rest unconformably upon the Archean rocks of the northern complex. These conglomerates may be seen at a number of places along the border of the trough, and notably at the falls of Sturgeon River.

The formations of the Algonkian system are likewise separated from the overlying Cambrian sandstone by a profound unconformity. The Algonkian rocks are folded; the Cambrian sandstone is horizontal and thus lies across the truncated ends of the eroded folds. Its lower layer is formed largely of the débris of the more ancient rocks. Hence the Algonkian rocks formed a land surface for a vast period of time before the deposition of the Cambrian sandstone.

HURONIAN SERIES.

LOWER HURONIAN.

SUCCESSION AND DISTRIBUTION.

The lower Huronian is divided into two formations—the Sturgeon quartzite and the Randville dolomite, the former being the older. These formations are observed only in the center and on the north side of the Menominee trough. On the south side of the trough no evidence of their existence is obtainable. This may possibly be due to the thick covering of drift that blankets the rocks north of the southern area of Quinnesec schist; but it is thought to be more probable that these formations are not present at the rock surface in this portion of the district.

STURGEON QUARTZITE.

Distribution.—The Sturgeon quartzite forms a continuous border of bare hills on the south side of the northern complex. The formation lies between the Archean complex and the northern belt of dolomite. Prominent bluffs of the typical quartzite may be conveniently studied northeast of the Loretto mine.

Lithology.—At many places at the base of the Sturgeon quartzite there is a conglomerate made up of bowlders and fragments of granites, gneisses, and hornblende schists identical with the corresponding rocks in the adjacent Archean complex to the north. The matrix in which these are embedded is in some places a quartzite, in others an arkose composed of the fine-grained débris of granitic rocks. In many places this matrix is schistose and a large quantity of a micaceous mineral has been produced by alteration of the feldspar of the original sediment, so that the matrix is now lithologically a sericite schist.

The major portion of the formation consists of massive beds of a very compact, vitreous quartzite, usually white, but here and there tinted with some shade of pink or green. In its upper portion the cement between the quartz grains is locally calcareous. This calcareous constituent increases in quantity as the overlying dolomite is approached, until the rock becomes a calcareous quartzite and finally a quartzose dolomite. The change from the quartzite to the dolomite is thus a transition. This indicates a gradual deepening of the waters during the later part of the Sturgeon epoch.

Deformation.—The main belt of the Sturgeon quartzite is a nearly vertical southward-dipping monocline. The outcrop of this monocline varies in strike, thus indicating that cross folding has taken place to some extent. At the west end of the district the quartzite turns northward, wrapping around the Archean complex and then passing eastward into the area of the Calumet trough. On the turn to the north several small folds are developed, the synclines of which are now represented by embayments extending eastward into the Archean. The dips of the quartzite beds may vary a few degrees—25° in one place—from perpendicularity. There are almost as many northern dips toward the granite and gneiss complex as there are southern dips toward the center of the trough.

Relations to adjacent formations.—The Sturgeon quartzite rests unconformably upon the Archean rocks of the northern complex. This is shown by the character of the lower bed of the quartzite, which, as already said, is a basal conglomerate. This basal conglomerate contains almost every variety of fragment derivable from the rocks of the northern complex. Some of this material in its original position must have been formed at great depth in the earth. Therefore there was deep-seated denudation of the Archean before the deposition of the quartzite. Upward the Sturgeon quartzite grades into the Randville dolomite. The nature of the gradation is discussed in the section on that formation.

Thickness.—Two difficulties stand in the way of determining the thickness of the Sturgeon quartzite. The first is the impossibility of deciding how much of the apparent thickness of the many rock layers in a closely folded district, like the Menominee, is due to the duplication of beds in consequence of close folds. The other difficulty is the impossibility of fixing the upper limit of the formation. There is everywhere between the quartzites and the nearest ledges of the overlying dolomite a belt of country without exposures of any kind. If we assume that the southward-facing cliffs, which in so many places mark the southern limit of the quartzites, are cliffs of differential degradation, that the low ground at the base of the cliffs is underlain by the dolomite formation, and that the exposures are monoclinal, the maximum thickness of the formation is between 1,000 and 1,250 feet.

RANDVILLE DOLOMITE.

Distribution.—The Randville dolomite occupies three separate belts, whose positions and shapes are determined by the folding to which the formation has been subjected. These will be referred to as the northern, central, and southern belts of dolomite.

The northern belt is south of the belt of Sturgeon quartzite. Only a few exposures are found in this area, but they are so uniformly distributed that on the map (Pl. XXVI, in pocket) the whole belt has been colored for the formation. It is quite possible, however, that in some places erosion has carried away the dolomite and that the upper Huronian rests immediately upon the quartzite.

The central belt of dolomite borders the north side of Lake Antoine for a portion of its length, passes eastward between the Cuff and Indiana mines, and ends at the bluff known as Iron Hill in the E. ½ sec. 32, T. 40 N., R. 29 W. This belt is well marked by numerous and large exposures.

The southern belt of dolomite extends all the way from the west side of the sandstone bluff west of Iron Mountain to the village of Waucedah, at the east end of the district. Where not exposed the rock has been found in mines, test shafts, and pits, so that there is a reasonable certainty that it exists throughout this distance of 16 miles. Where there is any doubt of its existence at the surface this is due to a considerable thickness of overlying Cambrian sandstone. From Iron Mountain as far east as Sturgeon River the country underlain by the dolomite is a range of high hills, broken only at a few points by north-south gaps. On the southern slope of this ridge are the principal producing iron mines of the district.

Lithology.—The Randville dolomite is composed of a heterogeneous set of beds in which dolomite is dominant. With the pure dolomites are siliceous dolomites, calcareous quartzites, argillaceous rocks, and cherty quartz rocks. The Randville dolomite, lying upon the Sturgeon quartzite, grades downward into it. The intermediate rock is a calcareous quartzite.

The predominant rock of the Randville dolomite is an almost massive, apparently homogeneous, fine-grained white, pink, blue, or buff dolomite, occurring in beds from a few inches to many feet in thickness. This is interstratified with beds of siliceous dolomite in which are observable numerous grains of quartz. In many places on the weathered surfaces of the dolomites are thin projecting bands of vein quartz parallel to the bedding, which the microscope shows to be calcareous quartzite. In other places projecting bands anastomose or run irregularly over the weathered surfaces, here and there intersecting the bedding planes of the rock at acute angles. Their abundance proves clearly that the dolomites, in spite of their homogeneous appearance, have been extensively fractured and crushed. In many places the crushing has produced a breccia of dolomite fragments in a siliceous matrix. In a few localities the fragments are rounded, so that the rock is a pseudoconglomerate.

The greater part of the argillaceous rocks interstratified with the dolomite is soft light-gray or dark-gray slate. Another part is typical black slate, still plainly marked by bedding lines. Still other parts are purplish-pink schistose argillaceous dolomite. Many of the thin layers of the purplish-pink slatelike material between massive dolomite beds appear to be largely the selvage of the softer layers of dolomite, rendered schistose by the movement of accommodation between the stronger beds.

Deformation.—Structurally the northern belt of dolomite is a southward-dipping monocline. The central and southern belts are anticlines. The three belts are separated by two synclines.

In the anticlinal belts the beds at first sight appear to be isoclinal, but a close examination of the southern belt reveals the existence of a number of minor folds having almost vertical pitches. In the western part of the district the folds are overturned to the south, the axial planes dipping northward at high angles. In the central and eastern parts of the district, east of Quinnesec, the minor and major folds have their axial planes steeply inclined to the south. Although the minor folds are rather easily recognizable, it is only on the south side of the southern belt that they become prominent. Here the synclines open out, forming basins in which the ore bodies lie. The small folds, with a few exceptions, pitch west in the western portion of the range and east in the eastern portion.

The attitude of minor folds is, as is well known, an indication of the attitude of the major folds on which they are superimposed. By using this principle, it is concluded that the major anticlines in this district disappear to the east and to the west by plunging beneath the upper Huronian sediments.

From the above statements it is clear that, in addition to the major east-west anticlines and synclines that are so prominent in the district, the dolomite formation is also affected by a gentle but large cross anticlinorium whose axis runs approximately north and south. It is remarkable that erosion has nowhere exposed the Sturgeon quartzite in association with the central belts of dolomite.

Relations to adjacent formations.—The dolomite formation is nowhere seen in actual contact with the Sturgeon quartzite, nor are ledges of the two formations seen in close proximity. It is known, however, that the upper layers of the quartzite are calcareous and that the lower beds of the dolomite are quartzose. The inference seems to be safe that the two formations are conformable, and that they grade into each other through calcareous quartzites. The relations of the dolomite to the overlying formations are discussed in connection with the upper Huronian.

Thickness.—At no place within the area mapped is the dolomite known to be exposed from the bottom to the top of the formation. On the north side of the trough the formation is bordered by the Sturgeon quartzite on the north and the Vulcan formation on the south, but exposures between these limits are so few that it is not certain that the dolomite occupies the entire breadth, and on this account and because of the minor folds it is impossible to give anything like an exact estimate of the thickness of the formation. By making calculations so as to obtain a minimum figure, 1,000 feet or less could be obtained. If, on the other hand, calculations were made on the supposition that all of the isoclinal beds are different layers, the estimate might be as great as 5,000 feet. Probably the truth is much nearer the lower figure than the higher. The original thickness of the dolomite is probably somewhere between 1,000 and 1,500 feet.

MIDDLE HURONIAN.

The identified middle Huronian of the Menominee district consists entirely of cherty quartzite resting in a thin film, from a few feet to 70 feet thick, on the Randville dolomite near its contact with the upper Huronian (Animikie group), and it is included with the Randville dolomite on the general map of the district (Pl. XXVI, in pocket). These rocks were formerly regarded as a part of the dolomite formation, but recent work has shown them to be separable from the dolomite. The quartzite has been separated from the dolomite in the mapping for several small areas near Norway and the east end of Iron Hill. (See fig. 45.)

The cherty quartz rocks are fine grained, drusy in places, and white, light red, or dark purple. The darker colored kinds look very much like some varieties of jaspilite. Under the microscope the cherty quartz rocks seem to be composed almost exclusively of a fine-grained crystalline aggregate of quartz which incloses a few grains of hematite, magnetite, and other iron compounds. Here and there a fragmental quartz grain may be seen, but usually no trace of fragmental constituents can be discerned.

Pebbles in the conglomerate at the base of the upper Huronian are partly jasper and iron ore, obviously derived from some preexisting formation not now appearing. A reasonable inference is that these pebbles represent fragments of the Negaunee formation, which would normally lie above the middle Huronian quartzite. In the previous report on this district[a] several masses of iron-bearing rocks were doubtfully referred to the Negaunee. Subsequent work has demonstrated these to be upper Huronian.

The middle Huronian quartzite rests unconformably on the Randville dolomite, with discordance in bedding. The quartzite may be observed to fill fissures and depressions in the dolomite. At Norway Hill erosion cut off 100 feet or more of the dolomite before the quartzite was deposited. On the south side of Iron Hill there is a thin film of conglomerate, taken to represent the base of the middle Huronian quartzite, plastered against the dolomite escarpment. The quartzite is not shown directly above the conglomerate but appears a few hundred feet to the east, resting against the dolomite escarpment. (See Pl. XVII, *A*, of Monograph XLVI.) In fact, much of the middle Huronian quartzite itself on Iron Hill is conglomeratic and brecciated, and a considerable part of it may possibly represent a coarsely fragmental basal phase of the middle Huronian. The intricacy of the relations of the middle Huronian quartzite with the Randville dolomite on Iron Hill is represented in figure 45. The hill is a normal anticlinorium, of the type to be expected in competent formations of this type. It contrasts in every essential feature with the abnormal anticlinorium in the weak, incompetent beds of the Michigamme slate on Hanbury Hill.

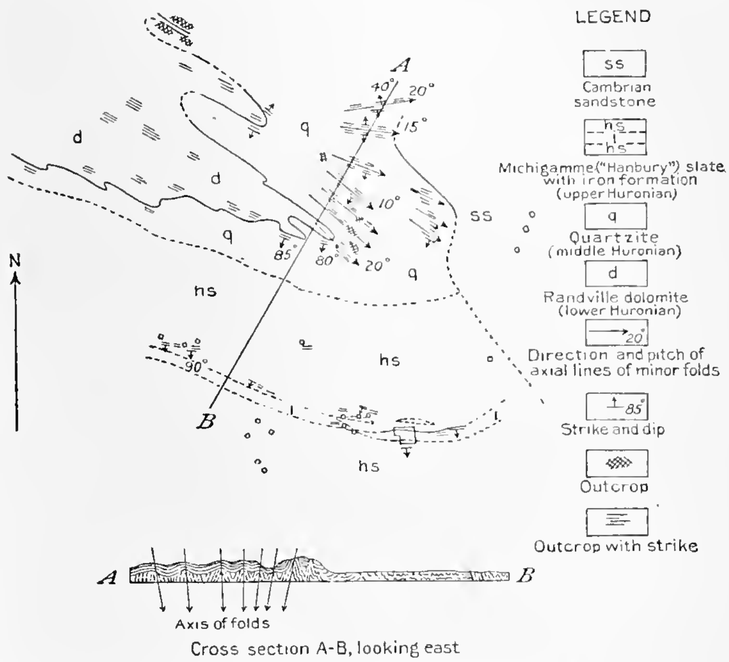


FIGURE 45.—Geologic map and cross section of Iron Hill, Menominee district, showing relations of lower and middle Huronian.

UPPER HURONIAN (ANIMIKIE GROUP).

All the formations between the Randville dolomite and the unconformity at the base of the Cambrian sandstone are placed in the upper Huronian. For the purpose of the present monograph the group may be divided into two formations; the lower, the Vulcan formation, includes all the known iron-bearing rocks of the district except the conglomerate beds at the base of the Cambrian; the upper, the Michigamme ("Hanbury") slate, comprises the great upper slate formation of the upper Huronian.

VULCAN FORMATION.

Subdivision into members.—The iron-bearing Vulcan formation embraces three members; these are, from the base up, the Traders iron-bearing member, the Brier slate member, and the Curry iron-bearing member. In this monograph the three members are mapped as a single formation because they are not so well exposed that they can everywhere be separately out-

[a] Mon. U. S. Geol. Survey, vol. 46, 1904, pp. 273-279.

lined. However, at several places the three members are known to exist, and can be separately mapped. The Traders iron-bearing member is so named because of its typical occurrence at the Traders mine, north of Iron Mountain. The Brier slate is so named because it is well exhibited at Brier Hill. The Curry member is so called because the Curry mine is located at its horizon.

Distribution.—From the position of the Vulcan formation immediately upon the lower and middle Huronian it would be natural to expect its distribution to be determined by the distribution of those rocks, and as a matter of fact, wherever the Vulcan formation occurs it lies immediately above the Randville dolomite or middle Huronian quartzite and below the Michigamme slate. But at some places within the district the dolomite or quartzite is in immediate contact with the Michigamme slate or is separated from exposures of it by intervals so narrow as to show that the Vulcan beds are lacking.

The principal area of the Vulcan formation extends as a belt from 900 to 1,300 feet wide along the south side of the southern belt of dolomite for nearly its entire extent. The belt follows the sinuosities of the southern border of the dolomite area rather closely, but it is much wider in the reentrants caused by the pitching synclines of the dolomite than elsewhere. The widening of the formation at these places is of course due to the repetition of beds in consequence of close folding. Along only one stretch, about a mile in length, is the iron-bearing formation known to be absent. This is in the W. ½ sec. 1 and the E. ½ sec. 2, T. 39 N., R. 30 W., where the Michigamme slate lies upon ledges of the typical dolomite.

On the north side of the southern dolomite belt, in the central or western part of the district, the iron-bearing formation has nowhere been found nor has any indication of its presence been detected. In the eastern part of the district the Vulcan formation appears at the Loretto mine in an eastward-pitching syncline. From this place it extends eastward along the north side of the dolomite, as shown by a line of magnetic attractions, to a point within a short distance of the east end of the area mapped, where the thick deposits of Paleozoic beds prevent further tracing.

The second important area of the Vulcan formation is that in which the Traders and Forest mines are situated. It stretches for about 5 miles along the south side of the central dolomite belt, running north of Lakes Antoine and Fumee and ending, so far as present information indicates, somewhere about the east line of R. 30 W. On the north side of this same dolomite belt the iron-bearing formation is known to extend for only a short distance on both sides of the Cuff mine, in the southern portion of sec. 22, T. 40 N., R. 30 W.

The third strip of country in which the iron-bearing beds are to be expected is that which borders the northern dolomite belt. This area, however, is in the valley of Pine Creek. The surface is thickly covered with sand. There is no indication of the character of the underlying rock anywhere west of the Loretto mine except that afforded by a group of pits near the center of sec. 14, T. 40 N., R. 30 W., at the western extremity of the belt. These pits have shown the presence of lean ore associated with cherts, jaspilites, and black slates. The cherts are filled with the "shots and bands" of ore characteristic of the cherts in the Michigamme slate and present to some extent in the jaspilites of the Curry iron-bearing member. The rocks in this locality are believed to belong to the Curry horizon.

From the foregoing account of the distribution of the Vulcan formation it will be noticed that the belts of iron-bearing rocks are not continuous. From the stratigraphic relations of the iron-bearing formation it would be expected to occur as continuous belts surrounding the dolomite anticlines, bordering the south side of the northern dolomite monocline. In several places, however, these relations do not exist. It is known that in parts of the district the iron-bearing formation is absent from the position it would naturally be expected to occupy, and that the Michigamme slate, which stratigraphically overlies the ore-bearing strata, is in immediate contact with the dolomite that underlies the Vulcan formation. It is probable that the larger parts of the belts mapped as doubtful—the areas in which the underlying rock is unknown—are underlain by the Michigamme slate rather than the Vulcan formation, but it is possible that the Vulcan formation underlies a portion of these areas.

Traders iron-bearing member.—The Traders iron-bearing member of the Vulcan formation consists of a comformable set of beds composed of ferruginous conglomerates, ferruginous quartzites, heavily ferruginous quartzose slates, and iron-ore deposits. The conglomerates and quartzites are usually at the base of the member, resting upon the Randville dolomite. These rocks vary in thickness from a few inches to 20 feet or more. They contain fragments, usually small but here and there large, of quartzite, jaspilite, white quartz, and rocks that make up the Archean complex. In many places, however, the conglomerate contains so much ore and jasper that it is an ore and jasper conglomerate or quartzite, of which some is so rich that it is mined. In these rocks the matrix is a mass of small grains of hematite, embedded in which are bowlders and pebbles of ore and of jaspilite. The conglomerates and quartzites of this kind are usually schistose. The ore and jaspilite fragments are mashed into lenticular bodies, and the matrix into a mass of thin scales like those characterizing the specular ores of the Marquette district. Typical occurrences of the ore-bearing quartzites and conglomerates may be seen at the open pits of the Traders mine and at the bottom and along the west side of pit No. 3 of the Penn Iron Company, in the SW. ¼ NE. ¼ sec. 9, T. 39 N., R. 29 W. In the vicinity of the Forest mine are heavy quartzites, some of them white and vitreous, interbedded with what is taken to be the Traders member. This is the largest mass of quartzite developed at this horizon in the district.

The conglomerates and quartzites pass upward into the ferruginous quartzose slates. These consist of alternating layers of heavily ferruginous quartzites, iron oxides, and in some cases jaspilites. The quartzose layers are dark red or purple jasper-like beds, from a fraction of an inch to 18 inches or 2 feet in thickness. Some of them on fresh fractures exhibit the quartzitic texture very plainly. The coarser of them approach ferruginous quartzites. Others, however, resemble very closely a typical jaspilite, which a number of them are believed to be. These varieties are in places mottled by red and purple blotches that appear to be due to the presence of red jaspilite grains in a ferruginous quartzose matrix. Some of these mottlings are secondary concretions and some are alterations of greenalite granules, more fully described in connection with the Curry iron-bearing member of the Vulcan formation. As a rule the mottling is in small elongated areas and the rock possesses an incipient schistosity in the direction of the longer axes of the areas. This phenomenon is the result of mashing, which flattened the jaspilite grains and the smaller components of the quartzose matrix, producing a parallel arrangement of the particles. It is difficult to determine with certainty the relative amounts of the detrital material and true jaspilite, which is nonfragmental, but apparently the former is more abundant and it may be dominant.

Brier slate member.—The Brier slate member lies immediately above the Traders iron-bearing member. The slates are heavy, black, ferruginous, and quartzose, presenting in many places a very even and fine banding, due either to the presence of layers richer than the average in iron oxides or merely to the presence of small quantities of pigments. On exposed surfaces the banding is emphasized by slight weathering. Where the weathering has progressed very far the slates are stained red. They open along the bedding planes and become very shaly. In this form they yield an abundant talus at the base of all cliff faces in which they are exposed.

Curry iron-bearing member.—The Curry iron-bearing member consists of interbedded jaspilites and ferruginous quartzose slates, with various mixtures of the two, and ore deposits. Many of the jaspilite bands are in the center of the quartzose slate layers, but a few are along one side; all are parallel to the bedding planes. Both the jaspilites and the ferruginous quartzose slates are dark red or purple. The two can usually, however, be distinguished. The jaspilites are homogeneous rocks, with a flinty fracture and luster. They consist as a rule of very finely crystalline quartz and hematite, with abundant concretionary and granular structures marked by varying combinations of iron oxide and chert. Some of the concretionary structures are similar to those figured by Van Hise and Irving for the Gogebic district.[a] Much more numerous granules have the same shape as the concretions but differ from them in lacking

[a] Mon. U. S. Geol. Survey, vol. 19, 1892.

radial or concentric structures. Such granules are identical in their characteristics with altered greenalite granules of the Mesabi district of Minnesota described by Leith [a] and of the Felch Mountain district of Michigan described by Smyth.[b]

It is concluded that the iron-bearing formation is essentially the result of alteration of greenalite rocks like those in the Mesabi district and of iron carbonates like those in the Gogebic district. None of the original greenalite or iron carbonate is now present, but pseudomorphs of both of them are abundant.

The ferruginous quartzose slates consist largely of plainly fragmental quartz. The coarser varieties approach quartzites. Between the grains of fragmental quartz there is finely crystalline quartz and iron oxide. What part of the matrix is truly detrital and what part, like the jaspilite, is nonfragmental in origin it is difficult to say. Between the bands which are plainly true jaspilites and nondetrital and those which are plainly detrital there are all gradations. It is difficult to ascertain whether the fragmental or the nonfragmental material is the more abundant in the Curry iron-bearing member as a whole, for it is poorly exposed. The ferruginous quartzose slates are believed to have been derived largely from the erosion of the lower Huronian. But mingled with this detrital material in many places was apparently a considerable amount of nonfragmental material. There are, therefore, in the Curry iron-bearing member all gradations between clastic and nonclastic sediment.

Deformation.—The Vulcan formation occupies a position on the upper sides of the dolomite anticlines. Its major folds, or folds of the first order, correspond exactly to the major folds of the Randville dolomite. The folds of the second order correspond also with those of the dolomite. The troughs on the south side of the southern dolomite area are occupied by the members of the iron-bearing formation. Moreover, within the Vulcan formation are numerous still smaller folds of the third order, which, because of the hardness of the rocks and the perfection of the banding, are well exhibited. These small folds may be observed at nearly every place where mining has progressed to any considerable extent and at many other places where only lean ores have been developed. The folds of the third order pitch in the same direction as those of the second order, upon which they are superimposed, but the strikes of their axes may diverge slightly.

Still smaller folds are superimposed on the folds of the third order in the same way in which the latter are superimposed on the folds of the second order. On exposed surfaces the folds of the higher orders appear as a series of crinklings or flutings, with heights ranging from one-quarter inch to 5 or 6 inches from trough to crest. Even in the troughs of these minute folds, under favorable circumstances, iron ore was deposited, especially where crushing and brecciating took place in connection with the folding.

Wherever folding is observed within the iron-bearing formation it is noticeable that the bedding is best preserved in the siliceous bands. The iron-ore layers between the siliceous layers, while yielding to the stresses that produced the folding, were mashed and sheared and became schistose. Where the compressing forces were very powerful a slaty cleavage developed in both the iron-ore and the siliceous layers.

In the western part of the south belt of the iron-bearing formation carrying the principal ore bodies the minor folds show considerable regularity of pitch to the west at angles approaching 30°. The ore bodies follow these axial lines. Not uncommonly these minor folds pass into overthrust faults. The distribution of the formation suggests that more overthrust faults are really present than have been found. In this area the rocks to the south have moved westward and upward with reference to the rocks to the north, developing drag or buckle folds and thrust faults in the relatively incompetent upper Huronian beds near the contact with the relatively competent lower Huronian. The eastern part of the south belt shows some eastward pitches.

Relations between the members of the Vulcan formation and the Michigamme slate.—Where the relations between the Traders iron-bearing member and the Brier slate member are normal

[a] Mon. U. S. Geol. Survey, vol. 43, 1903.

[b] Idem, vol. 36, 1899.

the Traders grades into the Brier by diminution of the amount of ferruginous material and by increase in the number and thickness of the quartzose beds. At the same time there is an increase in the proportion of slaty material. Where the ferruginous material is much reduced in quantity the Traders iron-bearing bed becomes the Brier slate member. This gradation occupies only a very short vertical range, so that the line between the iron-bearing member and the slate member is usually determinable within a few feet.

Where marked disturbances have occurred, as in the vicinity of Norway and for several miles to the east, the relations between the two members are very different. Wherever it can be seen the contact between the Traders and Brier members is sharp. In many places the contact seems to be slickensided and locally to be a plane of differential movement. At the open pits of the Norway mine and those north of the Curry mine and between this mine and the West Vulcan the Traders rocks are in places pseudoconglomeratic. The Brier slate member also may be brecciated. Moreover, the brecciation is not confined to these two members, but the underlying dolomite is at some places likewise brecciated for a short distance beneath its upper surface. The phenomena wherever studied appear to indicate that at the time of folding fault slipping occurred along the contact between the upper Huronian and the lower Huronian and between the Traders and Brier members. The dolomite was brecciated to some extent, the Traders detrital ores were crushed and brecciated, and in several places the lower portions of the Brier slate member were likewise included within the zone of movement and were fractured and brecciated. Later the breccias were enriched by the deposition of hematite and other iron compounds, and both the Traders member and the lower part of the brecciated Brier slate member became sufficiently ferruginous to warrant mining.

The Brier slate member passes upward into the Curry iron-bearing member by the diminution of argillaceous material and the introduction of ferruginous material, especially bands of jaspilite, the somewhat ferruginous quartzose Brier slate member thus becoming heavily ferruginous. At one place this transition is seen to occur laterally as well as vertically. No stratigraphic break has been discovered anywhere within the Vulcan formation.

The relations between the Vulcan formation and the overlying Michigamme slate are those of conformity. The contact is usually very sharp. No difficulty is experienced in defining the upper limit of the iron-bearing formation. The slates, however, are in places so very schistose on the upper side of the contact that their bedding planes can not be recognized, suggesting fault slipping. The bedding of the iron-bearing formation, on the other hand, is still almost perfectly preserved and is parallel to the contact.

The relations of the Vulcan formation with the lower and middle Huronian are discussed on pages 342–343.

Thickness.—A number of sections offer opportunities for determining the thickness of the separate members of the Vulcan formation, but in only a few can its total thickness be determined. All along the south side of the southern dolomite belt, from the Aragon mine eastward to Sturgeon River, the iron-bearing formation stretches as a narrow belt, which for much of the distance appears to be without important folds. At several places mining operations have afforded excellent sections from the base of the productive portion of the Traders iron-bearing member to the top of the Curry iron-bearing member, and at a few places the sections extend downward to the top of the Randville dolomite. At Brier Hill, where practically the whole formation can be seen on the surface, its thickness is about 600 feet. At the Curry shaft No. 2 it is 700 feet thick and at the Aragon mine about 675 feet.

At a number of sections the thickness of the individual members comprising the formation is easily measured. The Brier slate member has been measured at seven places, yielding results between 100 and 360 feet. Five of these measurements fall between 320 and 360 feet. Eight measurements of the Curry member have given results varying between 100 and 225 feet. Six of these fall between 160 and 225 feet. Measurements of the Traders iron-bearing member have yielded no such concordant results. In the first place, its thickness probably varies widely, as should be expected of a formation composed largely of detrital deposits.

Moreover, only a few sections reach as low as the dolomite; hence the exact position of the contact between this rock and the iron-bearing formation must be guessed at. Only three measurements have been made from the known top of the dolomite to the known top of the Traders member. These give 170 feet, 85 feet, and 155 feet.

An interesting feature of these figures appears when the estimated thickness of the Brier and Curry members is compared with the total thickness of the two. In almost every section where the estimated thickness of either of these members falls below the average of all the measurements for that member the thickness of the other member exceeds the average, and the total of the two is fairly constant. Thus, whereas seven estimates of the thickness of the Brier slate member vary between 240 and 360 feet, and eight estimates for the Curry iron-bearing member vary between 112 and 225 feet, measurements of the total thickness of the two vary only between 400 and 530 feet. The apparent greater variation in thickness of the two members separately than in that of the two combined may be partly explained as due to the gradation between the two and the consequent difficulty of fixing the exact place at which one ends and the other begins.

From a careful consideration of the figures given above and a few others that are not here recorded, it is estimated that the average thickness of the Vulcan formation is approximately 650 feet, divided as follows: Traders iron-bearing member, 150 feet; Brier slate member, 330 feet; Curry iron-bearing member, 170 feet—that is, the two ore-bearing members combined about equal in thickness the intervening slates. It is conceded, however, that the Traders member departs considerably from this average and that the total thickness of the ormation varies accordingly.

MICHIGAMME ("HANBURY") SLATE.

Distribution.—The Michigamme slate occurs mainly in three large belts constituting valleys which correspond with synclines between the older rocks. It occupies nearly all the low ground in the Menominee trough, forming a plain broken only by heaps of glacial material deposited upon it, by the protrusions of a few hillocks composed of the harder slates, or by equally resistant greenstones. The slate areas are narrowest at the east and gradually widen toward the west. The northern belt is divided into two portions by the western area of Quinnesec schist. The northern part turns northwest and leaves the Menominee district at the northern limit of the mapped area; the southern portion coalesces with the middle belt and crosses Menominee River into Wisconsin. East of Iron Hill the two northern belts again coalesce and extend as a single belt to Sturgeon River. Near the longitude of Waucedah all the slates disappear to the east beneath the Paleozoic beds.

Name.—In previous reports on this district this slate has been called the Hanbury slate, but the formation has been proved to be equivalent to and continuous with the Michigamme slate of the Marquette district, and the older name, Michigamme, is therefore used in this report.

Lithology.—The formation is dominantly a pelite. It comprises black and gray clay slates, gray calcareous slates, graphite slates, graywackes, thin beds of quartzite, local beds of ferruginous dolomite and siderite, and rarer bodies of ferruginous chert and iron oxide. The formation is cut by dikes of schistose greenstones, and in one or two places sheets of the same rock have been intruded between the sedimentary beds. The predominant rocks of the formation are gray clay slates and calcareous slates. The latter are more abundant in the lower portions of the formation and the former in the upper portions. The exact vertical relations of the two rocks have not been made out, because of the scarcity of exposures and the very intricate folding to which they have been subjected. The clay slates are normal argillaceous slates, in which there is always more or less ferruginous matter. Those exposed to the weather are light in color and have a shaly character. Muscovite then becomes prominent. Their iron components are decomposed to red ocherous compounds. Where most altered the rocks are light-red sericite slates or shales. The weathering of the slates that contain small quantities of calcareous components is somewhat different. They tend to bleach to a very pale-green or white color and to become porous through the loss of their calcareous cement. The ferruginous components oxidize, forming red ocher, and this lies in an irregular pattern on the light-colored background. The result of these changes is a red and white or pale-green mottled friable slate, known locally as "calico slate."

By the addition of carbonates the argillaceous slates pass into the carbonate slates. These in places contain as much as 50 per cent of carbonate as a cement. With an increase in the carbonate the slates lose their slaty character, become more massive, and finally pass into beds of ferrodolomite and siderite measuring from a few inches to 20 feet in thickness. On many of the weathered surfaces both the dolomite and the calcareous slates are coated with a skin of brown ocherous limonite, which on some of the massive dolomites reaches a thickness of an inch or more. Much of the limonite is pseudomorphous after the carbonate siderite.

The ferruginous cherts and iron oxides are not known to be present in the Michigamme slate in large quantity. Indeed, they are as a rule only locally developed in association with the sideritic dolomites and calcareous slates where these have been severely crushed or folded. The source of the iron oxides is clearly iron-bearing carbonate in the calcareous slates and the dolomites. The cherts are white or yellow massive rocks with finely granular texture. They occur as thin seams and veins traversing the slates and dolomites, and as thin beds interlaminated with the thicker beds of the last-named rocks.

Wherever the cherts occur there is usually found also a greater or less quantity of some iron oxide. This occurs as small veins of pure hematite cutting through the cherts, as coatings of hematite on the walls of cracks traversing the slates, as small vugs inclosed in shattered cherts, as druses covering the walls of the cavities in an extremely porous chert, in distinct bands interlaminated with bands of graywacke or quartzite, and in the form of a mixture of oxides and hydroxides impregnating slaty material. In short, the iron oxides occur in all forms characteristic of deposits precipitated from percolating waters. The slates impregnated with ferruginous matter are naturally dark red. Those that are but slightly ferruginous still plainly exhibit their true character. In those containing a large proportion of the iron oxides, however, but few traces of the original slate remain and the rock resembles a slaty ocher.

The graphite slates are black, very fissile, thinly laminated rocks. They appear to be limited to the lower portions of the Michigamme slate. At any rate, they have been seen only in association with the underlying Curry iron-bearing member and at horizons a few hundred feet above the base of the slate formation, but they do not everywhere occur at the base of the formation. Their association with iron-bearing beds at many places in this and other districts probably has some significance as to the origin of the ore. (See p. 502.) The graphite slates appear to grade laterally into the normal gray slates, of which they seem to be local modifications. The graywackes and quartzites of the Michigamme slate are normal rocks of their kind, requiring no special description. They both occur in comparatively thin beds, more commonly in the lower part of the formation than in the upper part. The quartzites are more abundant than the graywackes, but neither are common.

Deformation.—The major folding of the Michigamme slate seems to correspond with that of the underlying formations, and the slate therefore lies in three major synclines. This structure is inferred from areal relations to older rocks rather than from structures seen in the slates themselves, which are poorly exposed, lack easily identifiable horizons, and have their bedding much obscured by cleavage.

Many of the folds are of the abnormal type characteristic of incompetent strata. The limbs are thinned and the crests thickened, as would be expected in folds of this type, contrasting in every essential detail with folds in the competent quartzites and dolomites, as, for instance, in Iron Hill. (See fig. 45, p. 335.)

The strong north-south compression of the slate beds, producing the close east-west folds, also produced in all the weaker members of the formation a perfect slaty cleavage with a nearly east-west strike and a dip that varies but a few degrees on either side of the vertical. There is also a set of fracture planes or joints at right angles to the cleavage. These joints intersect the rocks at approximately equal intervals of several inches. In some places they are bordered by narrow shear zones in which the total displacement of the slate beds is an inch or more. On some flat horizontal surfaces two sets of these joints are seen cutting each other at acute angles, and about each slight faulting has occurred. Extensive thrust faults are suggested by the close folding of cleavage, but these have not been identified.

Thickness.—No even approximately correct estimate of the thickness of the Michigamme slate can at present be made. The similarity of the beds and their reduplication in consequence of the close folding render it impossible to determine what proportion of the apparent thickness of the formation is due to folding and what proportion is due to successive deposits. There is no doubt that the Michigamme slate is little thicker than any of the other formations in the district.

RELATIONS OF UPPER HURONIAN TO UNDERLYING ROCKS.

Relations between Vulcan formation and the lower Huronian.—The iron-bearing Vulcan formation, except in very small areas, rests upon the Randville dolomite or middle Huronian quartzite. If the Vulcan formation exists in the doubtful areas adjacent to the Quinnesec schist, it there rests against that schist. Where the Vulcan formation rests upon the middle Huronian quartzite or Randville dolomite the lower layers of the younger formation appear to lie conformably upon the older one, with an extremely sharp line of definition between them. In places the contact rock is a talc schist derived from the dolomite or cherty quartzite. The basal member of the Vulcan formation is either a quartzite which in places contains ore and jaspilite fragments, or an ore and jasper conglomerate containing large and small pebbles of ore, or a breccia containing fragments of all the adjacent rocks. The relative abundance of autoclastic rocks and true water-deposited conglomerates is uncertain. The Traders iron-bearing member appears to be nearly conformable in attitude with the underlying dolomite, but detailed work discloses distinct though slight discordance.

Contacts between the Randville dolomite or middle Huronian quartzite and the overlying formation are found in many of the mines, but they are nowhere discoverable on the surface. In the little ravine just east of the old Brier Hill mine the dolomite and the lower members of the iron-bearing formation are very close together, but their actual contact is covered. The space between the ledges of the two formations is filled with loose fragments, and among these fragments are large pieces of quartzite holding pebbles of jaspilite, quartzite, granite, and other members of the Archean.

In many of the mines and the open pits a similar conglomerate or a coarse quartzite is found lying upon the dolomite or quartzite.

The dolomite near the contact is usually schistose, so much so that in most places it is a pure talc schist. The calcium of the dolomite has been removed and much of it has been deposited in the ore bodies as calcite, while the magnesium has remained in the talc. A surprisingly similar schist has been formed from the middle Huronian quartzite, though on the whole it is more siliceous and less talcose. This talc schist serves as an impervious lining to many of the folds in which the ore deposits lie, and afforded better conditions for the concentration of the ore material than were afforded by the massive and shattered dolomite underlying the ore formation at many places. The schist was probably formed in connection with movement along the contact plane after the upper Huronian deposits were laid down, contemporaneously with the folding and metamorphism that affected both the lower Huronian and upper Huronian. The contact between the schist and the superjacent quartzite is extremely sharp, and in many places the plane of contact is slickensided.

In those places where the basal member of the iron-bearing formation is not a coarse quartzite, it is usually a bedded red slate, or more nearly a schist composed of small grains of quartz, considerable dolomite, and locally talc. Alternate bands are composed of layers in which dolomite and talc are predominant and those in which siliceous material predominates. The contacts between the schist and the rocks on both sides of it are usually covered. There is in some localities an apparent gradation between these underlying rocks and the rocks lying above them, but in others the line of division between them is well defined.

In earlier reports certain dense jaspilites were discriminated from the fragmental and micaceous jaspilites of the Vulcan formation above them and were regarded as belonging to the middle Huronian, unconformably below the Vulcan formation. The principal evidence of the existence of such a formation is the presence of fragments of jaspilite in the conglomerate at the base of the Vulcan formation.

In general, then, there is a slight structural discordance between the beds of the Vulcan formation and the middle and lower Huronian, and schistosity and autoclastic rocks seem to indicate that this has been a plane of considerable faulting. Also the fragmental phases of the Vulcan formation point to a preceding erosion interval, though evidence of great differential erosion is lacking, and so far as these fragmental phases are autoclastic this evidence is weakened. The general significance of the unconformity will be discussed in the chapter on general correlation (pp. 597 et seq.).

Relations between Michigamme ("Hanbury") slate and the middle or lower Huronian.—The Michigamme slate rests upon the Vulcan formation conformably. Where the Vulcan formation is absent the slate rests directly upon the Randville dolomite or the middle Huronian quartzite. This relation is seen for a short distance in the central part of the southern belt of the slate, and it is the relation which prevails generally in the two northern belts, for in this part of the district the Vulcan formation occurs only locally. Contacts are not exposed.

At Iron Hill, in sec. 32, T. 40 N., R. 29 W., there is at the top of the middle Huronian quartzite a conglomerate the débris of which is derived largely from that formation and which may be a basal conglomerate of the Michigamme slate. At other localities also there is a breccia which appears to be a brecciated conglomerate.

The absence of the Vulcan formation east of Quinnesec could be explained by the hypothesis that the Michigamme slate had been thrust over the lower formation of the upper Huronian so as to rest upon the Randville dolomite. The absence of the Vulcan formation between the Michigamme slate and the middle Huronian quartzite at Iron Hill might be similarly explained, only here it would be necessary to believe that folding accompanied the faulting, else the manner in which the slate wraps around the east end of the central belt of dolomite would be inexplicable. There are undoubted minor faults in the Menominee district, but most of them are extremely small, that in the Pewabic mine being the only one of sufficient magnitude to be mapped on the mine plats. It is clear that certain crushed zones of the Traders and Brier members near Vulcan are due to faulting. Further, there have been marked movements of accommodation between the different formations at their contacts, which might be called faulting. All these faults are local, and in none of them is the displacement of the faulted beds known to be great.

On the other hand the existence of overthrust folds grading into faults, so clearly indicated in the distribution of the southern belt of the iron-bearing formation, is the best of evidence of the extensive relative displacement of the upper and lower Huronian beds, a displacement brought about largely by the close deformation of the lower beds of the upper Huronian as they are crowded against the competent beds of the lower Huronian. It is entirely likely that more faults are present than have been found, and there is little difficulty in believing that overthrust faulting may have been a large factor in this deformation and may have thrust the slate locally over the iron-bearing formation against the dolomite, or, on the farther side of the fold, may have carried the dolomite up and over the slate.

Although faulting is doubtless a factor in determining the distribution of the Vulcan formation, from present evidence faulting is inadequate to explain the uniform absence of the formation through such long belts of country where it might be supposed to exist.

The presence of doubtful conglomerates at the base of the Michigamme slate where it rests upon the middle or lower Huronian suggests unconformable overlap of the Michigamme. It is possible also that the iron-bearing formation was originally deposited in discontinuous lenses, with intervening slate, resting directly upon the lower or middle Huronian.

IGNEOUS ROCKS IN THE ALGONKIAN.

QUINNESEC SCHIST.

The Quinnesec schist lies along and adjacent to Menominee River, from the sharp northward bend in the river due west of Iron Mountain to the eastern limit of the area mapped. The river is bordered by schistose greenstones and various rocks that cut them, except at a few places where rock ledges are absent. The Quinnesec Falls and Sturgeon Falls are on some of the harder ledges of these rocks. South of the river, in Wisconsin, at a distance ranging from half a mile to 2 miles, is the north side of a large area of granite. This granite sends apophyses into the greenstone schists, and consequently is of later age. For the most part the schists are arranged in belts striking a little north of west at Sturgeon Falls, but trending more toward the north as they pass up the river, until at the Upper Quinnesec Falls they strike about northwest. Their schistosity is, as a rule, nearly vertical.

The Quinnesec schist is composed of schists of two classes, basic and acidic. The basic schists comprise greenstone schists, chlorite schists, and amphibolites. Ellipsoidal and other extrusive structures are common. The acidic schists comprise gneissoid granites, porphyritic gneisses, felsite schists, and sericite schists. Associated with the schists are both basic and acidic massive rocks. The basic rocks include gabbro, diorites, diabases, and basalts. The acidic rocks include granite and granite porphyry. The greenstones and the basic schists are closely allied, as are also the granites and granite porphyries and the acidic schists.

A microscopic study [a] of the basic schists shows that they comprise schistose gabbros, diorites, diabases, basalts, and basalt tuffs. Where the schistosity is not strongly developed the original structures of the massive eruptive rocks may be recognized, so that there is no doubt that the greenstone schists, chlorite schists, and amphibolites are merely altered phases of the greenstones. The amphibolites are limited in their distribution to the neighborhood of the great granite mass of Wisconsin, and nearly all of them occur directly in contact with this granite. It is clear that the schistosity in these rocks has developed in connection with the folding of the district and that the extreme phase of metamorphism represented by the amphibolites has taken place in connection with the intrusion of the great batholithic granite of Wisconsin.

The acidic schists are limited principally to the neighborhood of Horserace Rapids and Big Quinnesec. The sericite schists in many places grade into the felsite schists. They occur mainly in bands parallel to the trend of the bands of basic schists. The coarser-grained gneissoid granites and porphyritic rocks clearly represent metamorphosed phases of the great granite mass to the south in Wisconsin, but some of the felsite schists and the sericite schists may represent acidic lavas contemporaneous with the basic igneous rocks.

From the field relations and microscopic study of the Quinnesec schist and associated rocks it must be concluded that all are of igneous origin. Many of them were lava flows; some were beds of volcanic ashes, or tuffs; others were dikes cutting through the bedded deposits.

A few small dikes cutting the schists are normal diabases and basalts, identical in composition with some of the rocks cutting through the iron-bearing beds.

Within the Menominee district itself there are no contacts between the Quinnesec schist and the Huronian sediments. A sand plane covers the area of contact. Exposures and explorations indicate that upper Huronian slates are the rocks nearest to the Quinnesec schist, and these have not been found nearer than 200 yards.

In earlier reports on the Menominee district [b] the Quinnesec schist was provisionally correlated with the Keewatin series of the Archean because of its relatively high degree of metamorphism and similarity to certain schists in the known Archean on the north side of the district. The apparent absence of the Vulcan formation at the base of the upper Huronian was explained by overlap, and later it was suggested that faulting might play a part. During the summer

[a] Williams, G. H., The greenstone schist areas of the Menominee and Marquette regions of Michigan: Bull. U. S. Geol. Survey No. 62, 1890.
[b] Mon. U. S. Geol. Survey, vol. 46, 1904; Menominee special folio (No. 62), Geol. Atlas U. S., U. S. Geol. Survey, 1900.

of 1910 the Wisconsin Geological and Natural History Survey, under direction of W. O. Hotchkiss, mapped what is probably the continuation of the Quinnesec schist to the northwest along the south side of the Florence district of Wisconsin, and determined the green schists there clearly to overlie the upper Huronian sediments to the north of them and to be locally interbedded with upper Huronian sediments. However, it is yet possible that the Quinnesec schist in the Menominee district may be really pre-Huronian, for continuous exposures do not connect the two areas, and green schists of this type are known in at least three different horizons in the pre-Cambrian of Michigan.

GREEN SCHISTS AT FOURFOOT FALLS.

Another area of igneous rocks of Algonkian age occupies about 5 square miles, extending from about the center of sec. 15, T. 40 N., R. 30 W., to Menominee River. The Fourfoot Falls are on the south side of the area, and the old village of Badwater at its northern edge. The rocks of this area are mainly schists, but they are cut by altered diabase dikes.

The schists are grayish-green fine-grained greenstones, in which schistosity is nearly everywhere noticeable. In some places the rocks are well-defined schists, with a cleavage almost as perfect as that in slates; in other places they are nearly massive. On many of the exposures a typical ellipsoidal structure is discernible. The ellipsoids vary in diameter from a few inches to 3 or 4 feet. There is no striking contrast between the material of the ellipsoids and that of the matrix between them. In both the rock is a dense grayish greenstone without any distinct textural features. The matrix is usually slightly more schistose than the ellipsoids, but otherwise it is like them. At the Fourfoot Falls the exposures consist of alternating beds of massive, schistose, and slaty rocks, striking about N. 80° W., almost at right angles to the course of the river, and yet these rocks are mostly schistose on the Wisconsin side of the river and mostly massive on the Michigan side.

The microscopic examination of thin sections shows that some of the rocks in the western area are altered dolerites still preserving their characteristic textures. Others are so much changed that their original nature can only be inferred from the character of their alteration products. Some of these appear to have been fine-grained dolerites and others perhaps glassy basalts. A few others were originally basic tuffs. All are now aggregates of actinolite, uralite, zoisite, epidote, quartz, and other well-known decomposition products of basic igneous rocks.

This area of schists, at the time the Menominee monograph was written, was supposed to be equivalent in age with the Quinnesec schist of Menominee River, then regarded as Archean. Later work by G. W. Corey and C. F. Bowen [a] has shown that they are really intrusive and extrusive in the upper Huronian or in part contemporaneous flows. That these igneous rocks antedate the chief folding of the district is shown by the fact that they are so extensively transformed to schists.

The only other large masses of igneous rocks which have been found in the Huronian series are in the Michigamme slate and the Sturgeon quartzite. In each of these formations in a number of places are found greenstones, locally in the form of dikes, in other places as sills, and in others as interbedded eruptives. In the Michigamme slate the form of the igneous bodies is known in but few places. In their present condition they are much-altered diabases or basalts composed of uralitized augite or hornblende, decomposed plagioclase, and a considerable quantity of quartz that is probably entirely secondary.

PALEOZOIC ROCKS.

Small areas of Paleozoic sediments in horizontal sheets lie on the eroded edges of the Huronian and Archean rocks. The Paleozoic rocks are represented by two formations, one of Cambrian age and the other of Cambro-Ordovician age. The lower formation consists mainly of red sandstone, and is known as the Lake Superior sandstone. The upper formation is a porous arenaceous limestone, identified by Rominger as corresponding to the Chazy and "Calciferous" of the Eastern States, and designated the Hermansville limestone. The sandstones

[a] Unpublished field notes, 1905.

and limestones were at one time spread continuously over the entire Menominee district. To the east of the district they still cover all the older rocks. West of Waucedah, however, they have been generally eroded from the valleys, leaving remnants as isolated patches on the tops of the higher hills.

CAMBRIAN SYSTEM.

LAKE SUPERIOR SANDSTONE.

Lithology.—The Lake Superior sandstone consists of a lower portion partly cemented by an iron oxide and consequently red in color and an upper portion in which the cement is partly calcareous and the color white. The total thickness is estimated by Rominger[a] at 300 feet. Several pieces of the sandstone have been obtained, which according to reliable authority came from the ledge through which one of the Pewabic mine shafts, near Iron Mountain, was driven. These contain numerous fragments of fossils, some of which were determined by Walcott as "the heads of small trilobites, probably *Dicellocephalus misa;* also fragments of a large species of *Dicellocephalus.*" According to Walcott, "These indicate the Upper Cambrian horizon of the Mississippi Valley section."

Relations to adjacent formations.—The relations of the sandstone to the underlying formations are everywhere practically the same. Whether on the tops of hills or in the depressions between the hills, the horizontal beds of the younger rock rest unconformably upon the upturned and truncated layers of the older series. Moreover, the basal layers of the sandstone contain a great deal of material derived from the immediately subjacent formations. Where the underlying rocks belong to the Vulcan formation the basal member of the sandstone is an ore and jasper conglomerate, composed of huge rounded bowlders of ore and large sharp-edged fragments of ferruginous quartzose slate and jasper in a matrix consisting of quartzose sand, numerous small pebbles and fragments of ore-formation materials, quartzite, and a few pebbles of white quartz, of granite, or of other Archean rocks. In a few places their proportion of ferruginous material is so great that they have been utilized as sources of iron ore.

CAMBRO-ORDOVICIAN.

HERMANSVILLE LIMESTONE.

The general character of the Hermansville limestone "is that of a coarse-grained sandstone, with abundant calcareous cement, in alternation with pure dolomite or sometimes oolitic beds." The limestone may be seen near the top of the hill east of Iron Mountain, on the bluff northeast of Norway, and at several places on the hills north of Waucedah. Its maximum thickness, according to Rominger,[b] is about 100 feet, but this maximum is rarely reached in the Menominee district. Only a few fossils have been reported from it. Rominger states that it has yielded a few fragments of molluscan shells. To these may now be added a broken *Orthoceras*, a fragment resembling a piece of a *Cyrtoceras*, a gastropod, and several other fragmentary forms found in the top layer on the bluff northeast of Norway.

THE IRON ORES OF THE MENOMINEE DISTRICT.

By the authors and W. J. MEAD.

DISTRIBUTION, STRUCTURE, AND RELATIONS.

The ore deposits of the Menominee district occur in the two iron-bearing members of the Vulcan formation known as the Traders iron-bearing member and the Curry iron-bearing member. These are separated by the Brier slate member. Much the larger tonnage of ore mined has come from the Traders member, lying south of the southern dolomite belt. The ores may occur at any horizon within these members, but other conditions being equal they are more likely to occur at low and high horizons than at middle horizons. A number of the

[a] Rominger, Carl, Paleozoic rocks: Geol. Survey Michigan, vol. 1, pt. 3, 1873, p. 81.

[b] Idem, p. 71.

VERTICAL NORTH-SOUTH CROSS SECTIONS THROUGH THE NORWAY-ARAGON AREA, MENOMINEE DISTRICT, MICH., ILLUSTRATING GEOLOGIC STRUCTURE.

After Bayley. See page 347

large ore bodies extend entirely across the members in which they occur. The deposits of large size rest upon relatively impervious formations, which are in such positions as to constitute pitching troughs. A pitching trough may be made (*a*) by the Randville dolomite or middle Huronian, underlying the Traders iron-bearing member of the Vulcan formation; (*b*) by a slate constituting the lower part of the Traders member; or (*c*) by the Brier slate member, between the Traders and Curry iron-bearing members. (See Pl. XXVII; figs. 46, 47, 48.) The dolomite or quartzite formation is especially likely to furnish an impervious basement where its upper portion has been transformed into a talc schist, as a consequence of folding and shearing between the formations.

These pitching troughs are minor folds of the drag type. In the western and central parts of the south belt of Vulcan formation carrying the principal ore bodies there is consider-

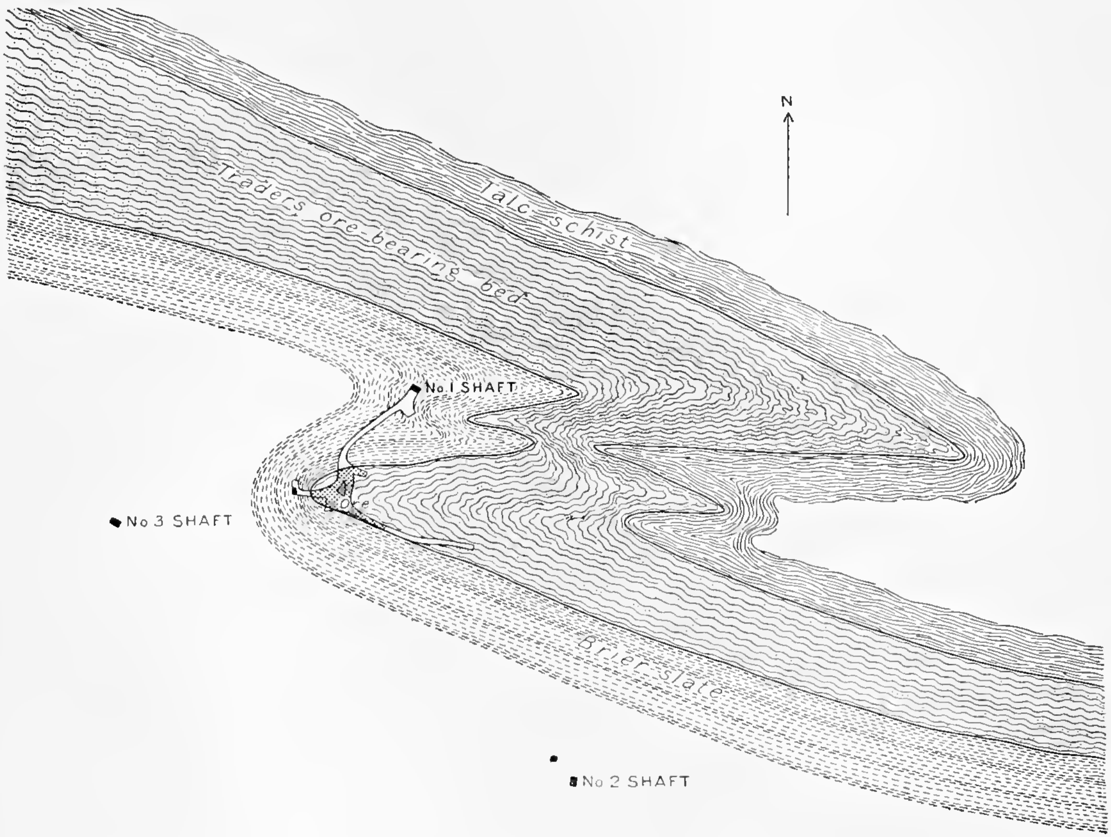


FIGURE 46.—Horizontal section of the Aragon mine at the first level, Menominee district, Michigan. Scale, 1 inch = 250 feet. After Bayley.

able uniformity of pitch to the west, resulting from the westward and upward shearing of the southerly beds with reference to the northerly beds. At the east end of the district some of the pitches are eastward. Any portion of the iron-bearing member may have yielded to the shearing by a series of these drag folds. The ore bodies following the axial lines may thus be in a series of parallel shoots, one pitching below the other along the strike. This is well illustrated in the Chapin and Millie mines.

In these folds the strike of the shoots at the surface is at a slight angle from the strike of the bedding, as shown in figure 49 (p. 350).

The wall rocks of the ore bodies may be unaltered phases of the iron-bearing member, especially the ferruginous cherts, or any of the rocks forming the impervious basement. The beds in the ore body, when followed along the strike and dip, usually pass into ferruginous cherts or iron carbonates.

At first sight the forms of the ore deposits might be thought to be exceedingly irregular, but when the above relations are understood they appear to have orderly forms. A main mass of ore is likely to be at the bottom of a trough, but from this main mass a considerable belt of ore may extend along the limbs of the trough to a much higher altitude than in the center of the trough. Many of the ore bodies in cross sections thus constitute a U, which is very thick at the bottom, the center of the U being occupied by the iron-bearing rocks which have not been transformed to ore. If the fold is very much compressed the limbs of the U may unite at the center and produce a pitching lens, with its lower extremity rounded to conform with the shape of the trough of the fold and its upper end, where not at the surface, more or less irregular in shape in consequence of the gradual passage of the ore into jaspilite. The deposits at Chapin are good illustrations of such lenses.

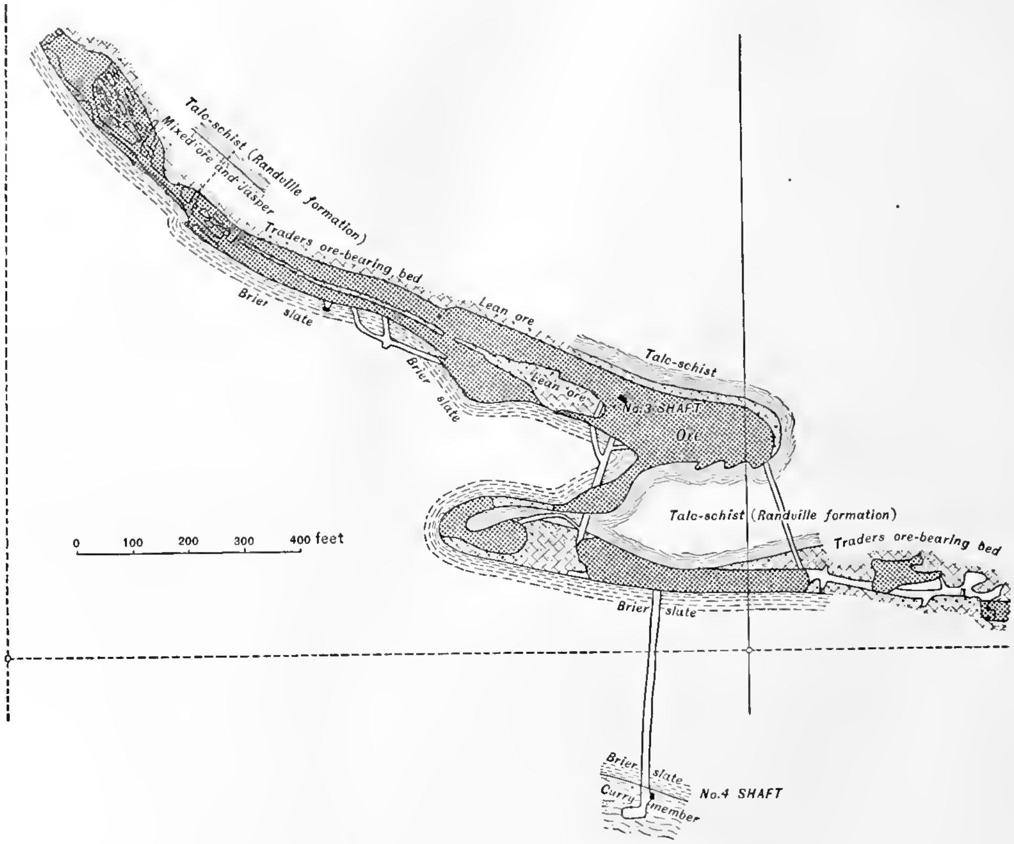


FIGURE 47.—Horizontal section of the Aragon mine at the eighth level, Menominee district, Michigan. After Bayley.

Though all the largest iron-ore bodies are confined to the pitching troughs with impervious basements of dolomite, quartzite, or talc schist, smaller ore deposits occur at contacts between the different members and at places within the iron-bearing members where severe brecciation has occurred. The deposits formed at contacts are usually much more irregular than those formed in troughs. In general, they are broad and thin sheetlike masses with irregular boundaries on all sides. Their lower surfaces are the more even and the better defined, but even these are undulatory. For the most part they remain near the contact of the iron-bearing formation with the underlying rocks, but at many places they leave this contact, rise into the iron-bearing beds, and thus become separated from the base of the formation by considerable thicknesses of jaspilites. The upper surfaces are much more uneven than the lower ones. Not only are they undulatory to a greater degree, but ore projections extend upward into the overlying jaspilites and, ramifying through these in an extremely irregular manner, in places coalesce and inclose lenses of jaspilite and then continue their separate courses until the contact with the overlying

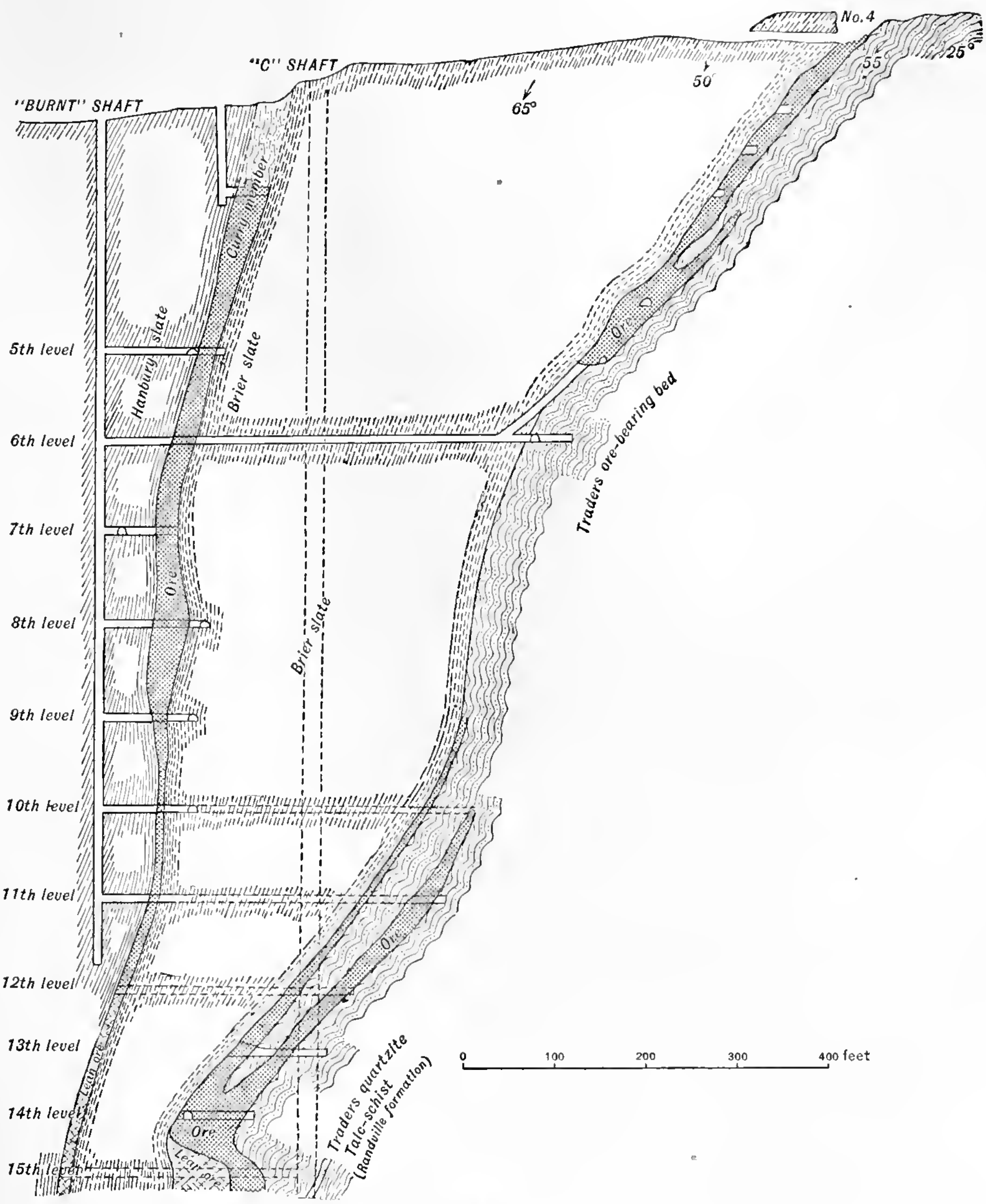


FIGURE 48.—Vertical north-south cross section through Burnt shaft, West Vulcan mine, Menominee district, Michigan. After Bayley.

slates is reached, where they again coalesce, spread out, and form a second sheetlike body, which, however, is usually much thinner and much less extensive than the deposit at the lower contact. Deposits of this kind occur principally in the straight portions of the member, where folding is absent and where the dip is not overturned. A portion of the deposits of the West Vulcan and Verona mines are of this class.

The Menominee ores rest for the most part on the middle slopes of the ridges formed by the Randville dolomite and middle Huronian quartzite, but they also go beneath the lower ground.

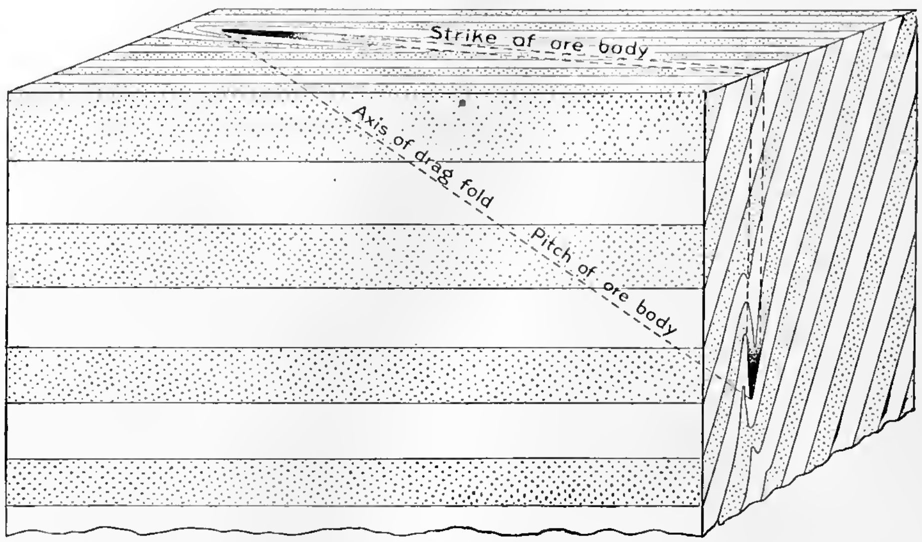


FIGURE 49.—Sketch to show pitch of a drag fold in a monoclinal succession. The ores in some places follow the axis of the fold. It will be noted that the strike of the ore body, measured at the surface, is at a slight angle to the strike of the bedding, notwithstanding the fact that the ore body follows throughout a single bed or set of beds.

CHEMICAL COMPOSITION OF THE ORES.

The averages of the cargo analyses of ore shipped from the district in 1907 and 1909, with the range for each constituent, are as follows:

Average chemical composition of ores from cargo analyses for 1907 and 1909, with range for each constituent.

	Average.		Range.	
	1907.	1909.	1907.	1909.
Moisture (loss on drying at 212° F.)	5.92	6.67	2.16 to 7.92	1.07 to 8.77
Analysis of ore dried at 212° F:				
Iron	50.70	52.23	39.00 to 59.90	38.46 to 61.26
Phosphorus	.038	.074	.010 to .084	.008 to .620
Alumina	1.54	1.41	.80 to 2.73	.86 to 2.28
Silica	21.15	16.77	5.70 to 41.53	4.25 to 39.34
Manganese	.17	.19	.03 to .47	.07 to 1.27
Lime	.28	1.31	.35 to 1.70	.63 to 2.90
Magnesia	2.12	2.70	.14 to 3.71	.70 to 3.98
Sulphur	.013	.012	.005 to .022	.006 to .041
Loss on ignition	1.92	2.52	.60 to 3.50	.90 to 4.30

Comparison of analyses of all the ores of the district shows the rich ores to consist principally of slightly hydrated hematite, with additional varying amounts of magnetite, silica, alumina, lime, magnesia, carbon dioxide, phosphorus pentoxide, and water. Most of the ores contain also manganese, potash, and soda, and a few of them titanium and carbon.

Following are three complete analyses of high-grade Menominee ore.

Complete analyses of Menominee ores.[a]

	1.	2.	3.
Fe	60.54	65.63	57.03
Fe_2O_3	85.44	91.51	80.15
FeO	.47	1.97	1.10
Al_2O_3	1.33	1.53	3.88
Mn_2O_3	.76		
CaO	1.26	.36	.17
MgO	3.02	.21	.48
K_2O	.064	.57	2.29
Na_2O	.066	.03	.30
SiO_2	4.53	3.03	10.72
P_2O_5	.15	.021	.074
S	.002	.099	.146
CO_2		.38	.08
H_2O (above 100°)	2.75	.27	.56
	99.842	99.980	99.950

[a] Mon. U. S. Geol. Survey, vol. 46, 1904, p. 383.

1. Chapin ore; analysis furnished by E. E. Brewster.
2. "Soft specular" Quinnesec ore.
3. "Soft specular blue ore" from Cornell mine.

AVERAGE IRON CONTENT OF THE IRON-BEARING FORMATION.

An average of 1,681 analyses, representing 5,287 feet of drilling from the district away from the available ores, gives 37.93 per cent of iron. Ores of this class are so much more abundant than the "available" ores that the average of the entire formation, including ores, is not much higher than this figure. The composition of the lean, unaltered jaspers where not altered to ore has not been averaged, but presumably the iron content is about 25 per cent, as in other districts.

MINERAL COMPOSITION OF THE ORES.

The approximate mineral composition of the average ores of the Menominee district, calculated from the preceding average chemical analysis, follows:

Approximate mineral composition of average Menominee ore, calculated from average chemical analysis.

	1906.	1909.
Hematite (including a small amount of magnetite)	68.00	74.70 (Hematite and Limonite together)
Limonite	5.98	
Quartz	15.35	14.49
Kaolin	3.90	1.10
Serpentine and talc	6.05	5.25
Dolomite	.[illegible]2	3.60
Miscellaneous		.86
	100.20	100.00

The richer ores are usually bluish black, porous, fine-grained aggregates of crystallized hematite. These rich ores grade into leaner phases containing more or less hydrated hematite, with varying amounts of quartz, serpentine, talc, clay, and carbonates of calcium and magnesium, ranging in color from the bluish black of the richer ores through various shades of red and brown to yellow.

All the minerals occurring as constituents of the ores are found also as visible masses either in veins cutting the ore bodies or in vugs or pores within them. Dolomite, calcite, and pyrite occur locally in excellent crystals, and serpentine as large, white, almost pure masses. Talc also occurs in thick seams of almost ideal purity, and chalcopyrite in small crystals associated with pyrite. The carbonates and sulphides are found near watercourses and the silicates mainly in the lower portions of the ore bodies.

The ores when exposed to the action of the atmosphere become coated with a white efflorescence, consisting of a mixture of the sulphates of sodium, magnesium, and calcium, in which the sodium sulphate is greatly in excess.

PHYSICAL CHARACTERISTICS OF THE ORES.

The lean ores differ very little in appearance from the jaspilites, of which they are essentially a part. They are banded, brecciated, and in places specular. The brecciated ores may consist of jasper fragments in a mass of hematite, or of hematite fragments in a mass of dolomite, or fragments of ore, jasper, and slate in a mass consisting largely of slate débris that has been strongly ferruginized.

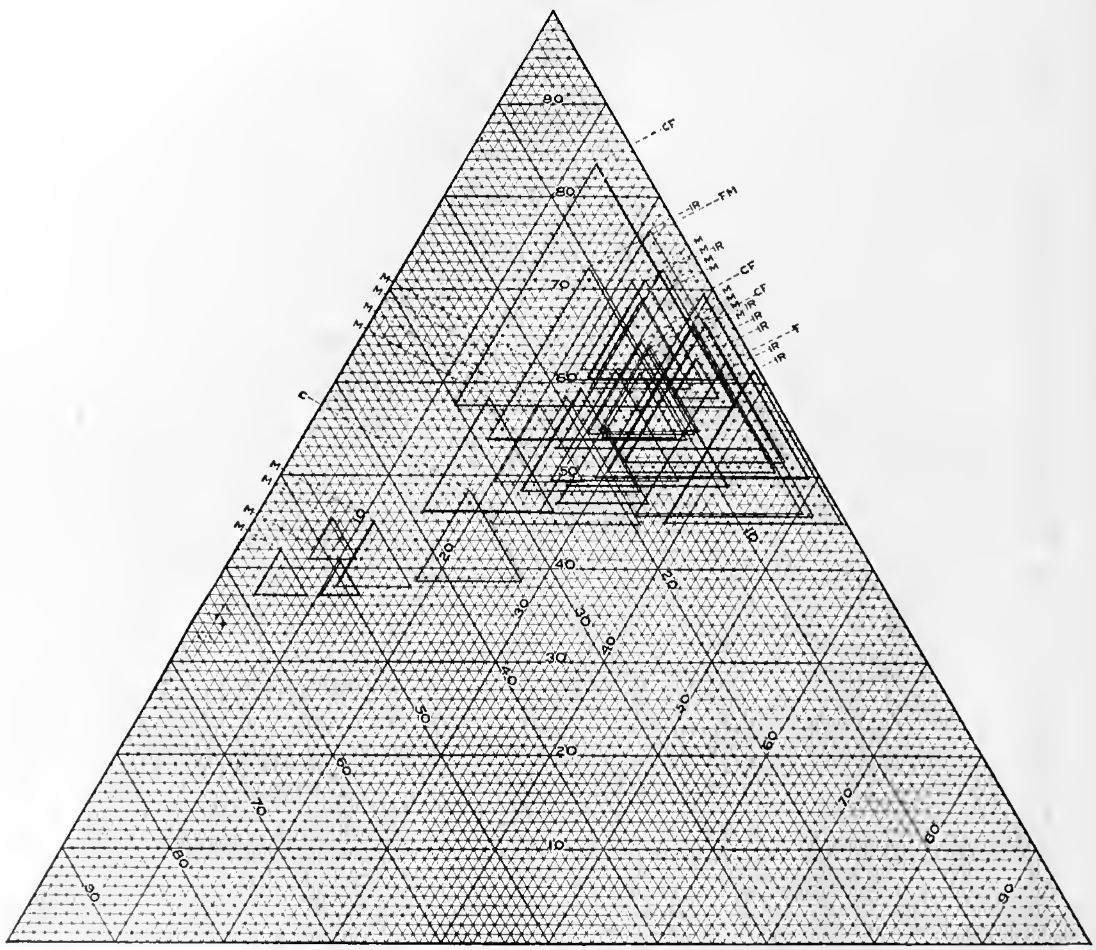


FIGURE 50.—Triangular diagram representing the volume composition of the various grades of ore mined in the Menominee, Crystal Falls, and neighboring districts in 1907. M, Menominee; CF, Crystal Falls; IR, Iron River; F, Florence; FM, Felch Mountain; C, Calumet. The pore space for each grade was calculated from the average moisture content, and hence represents the true pore space only when the moisture in a particular grade was at a maximum. The true porosity of the various grades of ore would therefore be slightly greater than is shown. For description of the method of platting on triangular diagram, see page 189.

The average texture of the Menominee ores is shown by the following table of screening tests, made by the Oliver Iron Mining Company on six typical grades of ore representing a total of 1,033,491 tons. Each test was made on a sample of 100 pounds, representative of the entire year's output of that grade. A comparison of the textures of the ores of the several ranges is shown in figure 72 (p. 481).

Textures of Menominee ores as shown by screening tests.

	Per cent.
Held on ½-inch sieve	39.44
⅛-inch sieve	30.63
No. 20 sieve	11.56
No. 40 sieve	4.73
No. 60 sieve	1.31
No. 80 sieve	1.19
No. 100 sieve	1.35
Passed through No. 100 sieve	9.67

The mineral density of the ores varies with the iron content. The average mineral density of the ores calculated from the average of the cargo analyses for 1907, by computing the mineral composition and properly combining the densities of the component minerals, is 4.28.

To test the accuracy of this method of computing mineral density, pycnometer determinations were made on the average pulp samples [a] of Ajax and Chapin grade for 1907, with the following results:

Mineral density of Menominee ores.

	Ajax grade.	Chapin grade.
Determined by means of pycnometer	4.21	4.601
Calculated from chemical analysis	4.34	4.607

The porosity of the ores ranges from 1 per cent or less in some of the lean jaspilite ores to as much as 45 per cent in some of the richer hematites and especially in the limonitic ores.

The cubic contents of the ores vary greatly. The bulk of the ores, however, lies between 9 and 14 cubic feet to the ton.

Volume comparisons of the Menominee ores with each other and with ores of the Crystal Falls, Iron River, Florence, Felch Mountain, and Calumet districts are made in figure 50.

IRON ORE AT BASE OF CAMBRIAN SANDSTONE.

The basal conglomerate of the Cambrian sandstone where it rests upon the iron-bearing formation contains abundant fragments of that formation. In a few places the proportion of ferruginous material is so great that the conglomerates have been utilized as sources of iron ore. A deposit of this kind was formerly worked by the operators of the Quinnesec mine, and another has recently been worked by the Pewabic company. The latter was reached by the open pit in the SE. ¼ sec. 32, T. 40 N., R. 30 W., known as the Pewabic pit. Although at this place the rock immediately underlying is dolomite, the amount of iron ore in the conglomerate is so great that the company operating the pit felt warranted in erecting concentrating works on the property for the separation of the ore from the sandstone.

SECONDARY CONCENTRATION OF THE MENOMINEE ORES.

Structural conditions.—The ore deposits in the Menominee district rest upon steeply dipping impervious basements of sheared dolomite or slate. The hanging wall may be of slate or iron-bearing formation. The greater dimensions of the deposits are parallel to the bedding. Folding, of the type illustrated in figure 12 (p. 123), develops minor corrugations in the foot wall and other rocks, with pitches parallel to the main strike of the formation. In these pitching folds the ore deposits are likely to be larger and better concentrated than elsewhere. It is obvious that the flow of water concentrating the ore has been principally parallel to the bedding, that it has been especially strong where the bedding has been folded into pitching troughs, and that the fracturing of the brittle iron-bearing rocks during this folding has aided greatly in the circulation of waters in pitching troughs and elsewhere in the formation. The ores are associated with marked topographic relief, affording abundant head for the waters. The larger number

[a] Kindly furnished by Mr. J. H. Hitchens, chief chemist for the Oliver Iron Mining Company at Iron Mountain.

of them are on the upper or middle slopes of the rock elevations, though some of them extend beneath the depressions.

Mineralogical and chemical changes.—The iron-bearing formation was originally iron carbonate and greenalite interbedded with more or less slate and containing much detrital ferric oxide at the base of the formation. The alteration of the cherty iron carbonate and greenalite to ore has been accomplished in the general manner already described as typical for the region—(1) oxidation and hydration of the iron minerals in place, (2) leaching of silica, and (3) introduction of secondary iron oxide and iron carbonate from other parts of the formation. These changes may start simultaneously, but 1 is usually far advanced or complete before 2 and 3 are conspicuous. The early products of alteration therefore are ferruginous cherts—that is, rocks in which the iron is oxidized and hydrated and the silica not removed. The later removal of silica is necessary to produce the ore.

SEQUENCE OF ORE CONCENTRATION IN THE MENOMINEE DISTRICT.

The first considerable concentration of ore in the district which is now mined did not take place until the erosion period following upper Huronian time. As indicated in the general discussion, the process was well advanced before Cambrian time and has practically continued to the present.

CHAPTER XIV. NORTH-CENTRAL WISCONSIN AND OUTLYING PRE-CAMBRIAN AREAS OF CENTRAL WISCONSIN.

NORTHERN WISCONSIN IN GENERAL.

The only work done by the United States Geological Survey in northern Wisconsin is in the Florence district; the southern extension of the Menominee district, in the northeastern part of the State; the Penokee range, in the northern part of the State; and the Keweenawan belt crossing the northwest corner of the State. These districts are described on other pages. Other areas in northern Wisconsin have been examined in reconnaissance work by members of the Survey, but no detailed mapping has been done. Outside of the areas named, the distribution of the rocks of northern Wisconsin shown on the general map (Pl. I) is taken from the Wisconsin Geological Survey reports, particularly that of Weidman [a] for north-central Wisconsin. The recent map of Douglas County made by Grant [b] for the Wisconsin Geological Survey is used in place of the earlier map by Irving.

Granites and gneisses, with subordinate amounts of sedimentary rocks and basic igneous rocks, constitute a highland in the northern part of the State, roughly oval in its outline, extending from the vicinity of Grand Rapids and Stevens Point, on the south, to the State boundary, on the north, and from Barron County eastward to the Michigan boundary. The area is bounded on the northwest by the Keweenawan rocks described in Chapter XV, and on the north and northeast by the Huronian formations of Michigan; on the southeast, south, and southwest it is overlapped on the lower ground by Paleozoic sediments which outcrop in wide belts surrounding the pre-Cambrian core. The predominating granites and gneisses were called Laurentian and the sedimentary rocks Huronian by the geologists of the first Wisconsin Geological Survey (1882). The highlands as a whole have been often referred to as a "Laurentian highland." The drift cover is heavy, exposures are few, except in certain localities, and much of it has been difficult of access even to the present time. The only published detailed work is that of Weidman,[a] which is summarized below.

WAUSAU DISTRICT.

LOCATION, AREA, AND GENERAL GEOLOGIC SUCCESSION.

The pre-Cambrian area in north-central Wisconsin mapped and described by Weidman includes the counties of Marathon, Portage, Wood, Clark, Taylor, Lincoln, and adjacent parts of Rusk, Price, and Langlade, containing in all about 7,200 square miles. From 90 to 95 per cent of the pre-Cambrian rocks of this area are of igneous origin.

The following table is compiled from the succession worked out by Weidman. The rocks he classes doubtfully as lower and middle Huronian we classify doubtfully as middle and upper Huronian, respectively. The names of the formations are those used by Weidman.

Quaternary system:

Pleistocene series	Wisconsin drift. Third drift. Second drift. First drift. Alluvial deposits (contemporaneous with drift).

[a] Weidman, Samuel, The geology of north-central Wisconsin; Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907.

[b] Grant, U. S., Preliminary report on the copper-bearing rocks of Douglas County, Wisconsin; Bull. Wisconsin Geol. and Nat. Hist. Survey No. 6, 2d ed., 1901.

Unconformity.	
Cambrian system	Upper Cambrian or Potsdam sandstone.
Unconformity.	
Algonkian system:	
Huronian series:	
Upper Huronian? ("Middle Huronian?" or "Upper sedimentary group," of Weidman). (Stratigraphic relations unknown; formations presumably contemporaneous.)	North Mound conglomerate and quartzite. Arpin conglomerate and quartzite. Mosinee conglomerate. Marshall Hill conglomerate. Marathon conglomerate.
Unconformity.	
Intrusive igneous rocks. (In order of intrusion)	3. Granite and nepheline syenite series. 2. Gabbro and diorite series. 1. Rhyolite series.
Middle Huronian? ("Lower Huronian?" or "Lower sedimentary group," of Weidman). (Stratigraphic relations unknown.)	Rib Hill quartzite. Powers Bluff quartzite. Hamburg slate. Wausau graywacke.
Unconformity.	
Archean system (?)	Gneiss and schists.

ARCHEAN (?) SYSTEM.

The basal rocks, believed to be the oldest and to belong to the Archean system, consist of a complex mixture of rocks, such as contorted and crumpled granite gneiss, diorite gneiss, granite schist, syenite schist, and diorite schist. The gneisses and schists form a belt which can be fairly well outlined, extending from the vicinity of Stevens Point and Grand Rapids in a northwesterly direction through Neillsville. The rocks are closely intermingled with one another, and have been subjected to extensive folding and metamorphism. The zone in which they are largely comprised lies between areas of later igneous and sedimentary rock to the north and to the south, and hence appears to have the position of the arch of an anticline. These basal rocks are intruded by later formations of rhyolite, diorite, and granite. Sedimentary rocks have not been found in contact with the basal rocks.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

MIDDLE HURONIAN (?).

The rocks next succeeding are of sedimentary origin, and consist of quartzite, slate, and graywacke. They include the quartzite of Rib Hill and vicinity, the quartzite of Powers Bluff and in the vicinity of Junction and Rudolph, a wide belt of slate in northwestern Marathon County, and graywackes in the vicinity of Wausau. These rocks are almost entirely of fragmental origin, and only rarely contain phases of carbonaceous, calcareous, and ferruginous deposits. The basement upon which these sediments were deposited can not be definitely determined, for all the observed contacts with associated rocks are those either of later intrusive igneous rocks or of later overlying conglomerate. The quartzites are throughout extremely metamorphosed and to all appearances completely recrystallized. The slates and graywackes do not reveal as much metamorphism as the quartzite, although in places rocks presumably belonging with the slate have been changed to schists bearing staurolite, cordierite, and garnet. These sedimentary rocks appear to bear the relation of great fragmentary masses intersected and surrounded by later igneous intrusive rocks. They constitute the lowest and oldest sedimentary rocks of this area.

ROCKS INTRUSIVE IN MIDDLE HURONIAN (?) AND ARCHEAN (?).

The next younger rocks are of igneous origin. They form about 75 per cent of the rocks of the area, and in the order of their intrusion are (1) rhyolite; (2) a basic series of diorite, gabbro, and peridotite; (3) a series consisting of granite, quartz syenite, nepheline syenite, and related rocks. Of these the last-named series is the most abundant, the granite alone forming about 50 per cent of the surface rocks of the area. The three series are intrusive in the Archean(?) of the area and also in the middle Huronian (?). They are in turn overlain by later Algonkian sediments. The period involved in the intrusion of the igneous formations must have been a very long one, and evidently constituted an important portion of the pre-Cambrian era, for the granite and syenite series itself represents a complex magma of varying though related rocks, intruded at different dates. In the stratigraphy of this area, therefore, these igneous intrusives play an important part and occupy a well-defined position between the upper Huronian (?) and the middle Huronian (?) sediments.

UPPER HURONIAN (?).

The latest Algonkian rocks of the area consist mainly of conglomerate and quartzite overlying all the other rocks above referred to. North of Wausau, at Arpin, and at North Mound they are represented by conglomerate and quartzite, and at Marathon City and Mosinee by conglomerate.

CAMBRIAN SYSTEM.

In the north-central area the pre-Cambrian was worn down to base-level by subaerial erosion before the much later Upper Cambrian or Potsdam sandstone [a] was deposited upon it.[b]

BARRON, RUSK, AND SAWYER COUNTIES.

In Barron, Rusk, and Sawyer counties the pre-Cambrian rocks are largely of igneous origin. The most prominent sedimentary areas are the prominent ridge of quartzite at the junction of Flambeau and Chippewa rivers and the numerous quartzite ridges along the divide of Chippewa and Red Cedar rivers. In general, these quartzites dip westward, away from the crystalline and schistose area, with strongly marked eastward escarpments overlooking the nearly flat plain of older rocks. Although no final conclusion has been reached concerning the relative age of these quartzites, Weidman is of the opinion that there are here represented at least two and probably three series. The quartzite in the small outcrops along the railroad about 3 miles east of Weyerhauser is greatly metamorphosed and is correlated with the Rib Hill quartzite at Wausau. The prominent ridge of quartzite at the junction of the Flambeau and the Chippewa is correlated with the upper sedimentary series in north-central Wisconsin and the Baraboo quartzite. The prominent ridges of quartzite in eastern Barron County and in the adjacent parts of Rusk and Sawyer counties are but slightly metamorphosed, the bedding is in general nearly flat-lying, and the formation has a much younger aspect than the other two quartzite formations in the region and may be Keweenawan.

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[a] The term Potsdam sandstone is here used in a quotational sense from the Wisconsin Geological Survey.

[b] Weidman, Samuel, The pre-Potsdam peneplain of the pre-Cambrian of north-central Wisconsin: Jour. Geology, vol. 11, 1903, pp. 289-313.

VICINITY OF LAKEWOOD.

Quartzites are known in the vicinity of Lakewood, indicating the presence of Huronian rocks in this district. Practically all that is known concerning the distribution and structure of these quartzites is shown on the accompanying sketch (fig. 51). They stand up as monad-

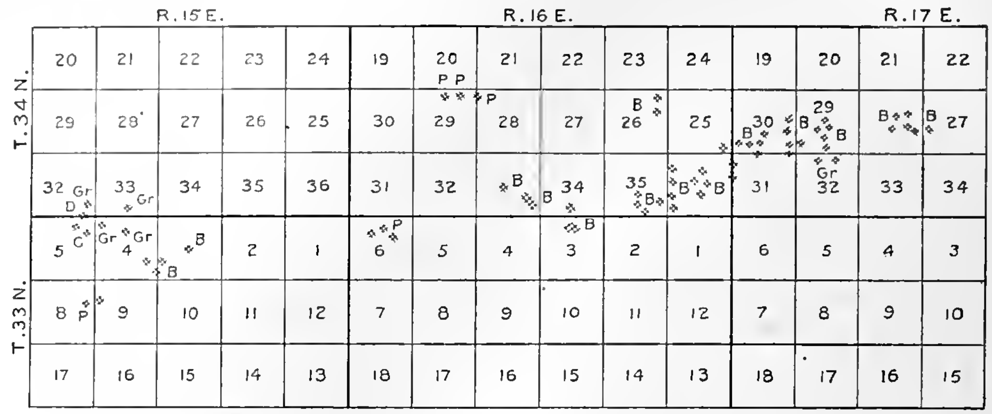

FIGURE 51.—Sketch map showing occurrence of quartzites of Huronian age in Tps. 33 and 34 N., Rs. 15, 16, and 17 E., Wisconsin. B, Quartzite and quartzite breccia; C, conglomerate; D, diabase; Gr, granite; P, porphyry.

nocks above the surrounding drift-covered surface. Associated with them are granite, porphyry, and diabase in isolated exposures.

NECEDAH, NORTH BLUFF, AND BLACK RIVER AREAS.

At Necedah, in Juneau County (see figs. 52 and 53), and at North Bluff, in Wood County, are quartzite exposures projecting through the Cambrian.

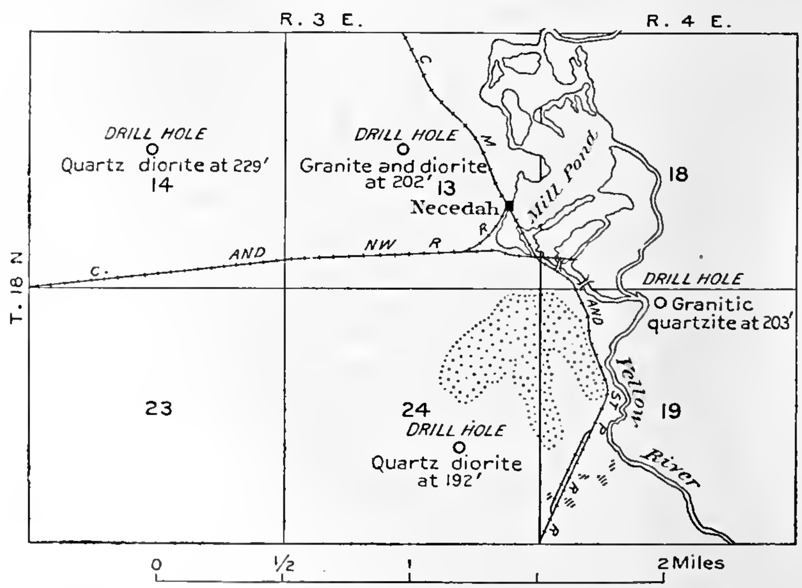

FIGURE 52.—Sketch map showing occurrence of Huronian quartzite near Necedah, Wis.

Drilling at Necedah has disclosed the presence of granite, probably intrusive into quartzite. The quartzite is highly metamorphosed and is lithologically similar to the Huronian rocks.

In the Black River valley, north of Black River Falls, are exposures of gneiss, granite, hornblende schist, magnesian schist, and ferruginous quartz schist, mapped by Irving [a] in 1873 and by Hancock [b] in 1901. The relation of these rocks to one another is not definitely known. All are pre-Cambrian.

BARABOO IRON DISTRICT.[c]

LOCATION AND GENERAL GEOLOGIC SUCCESSION.

The Baraboo district constitutes an outlier in the Paleozoic rocks and centers in the town of Baraboo, in the south-central part of Wisconsin. (See fig. 53.) It is south of the area

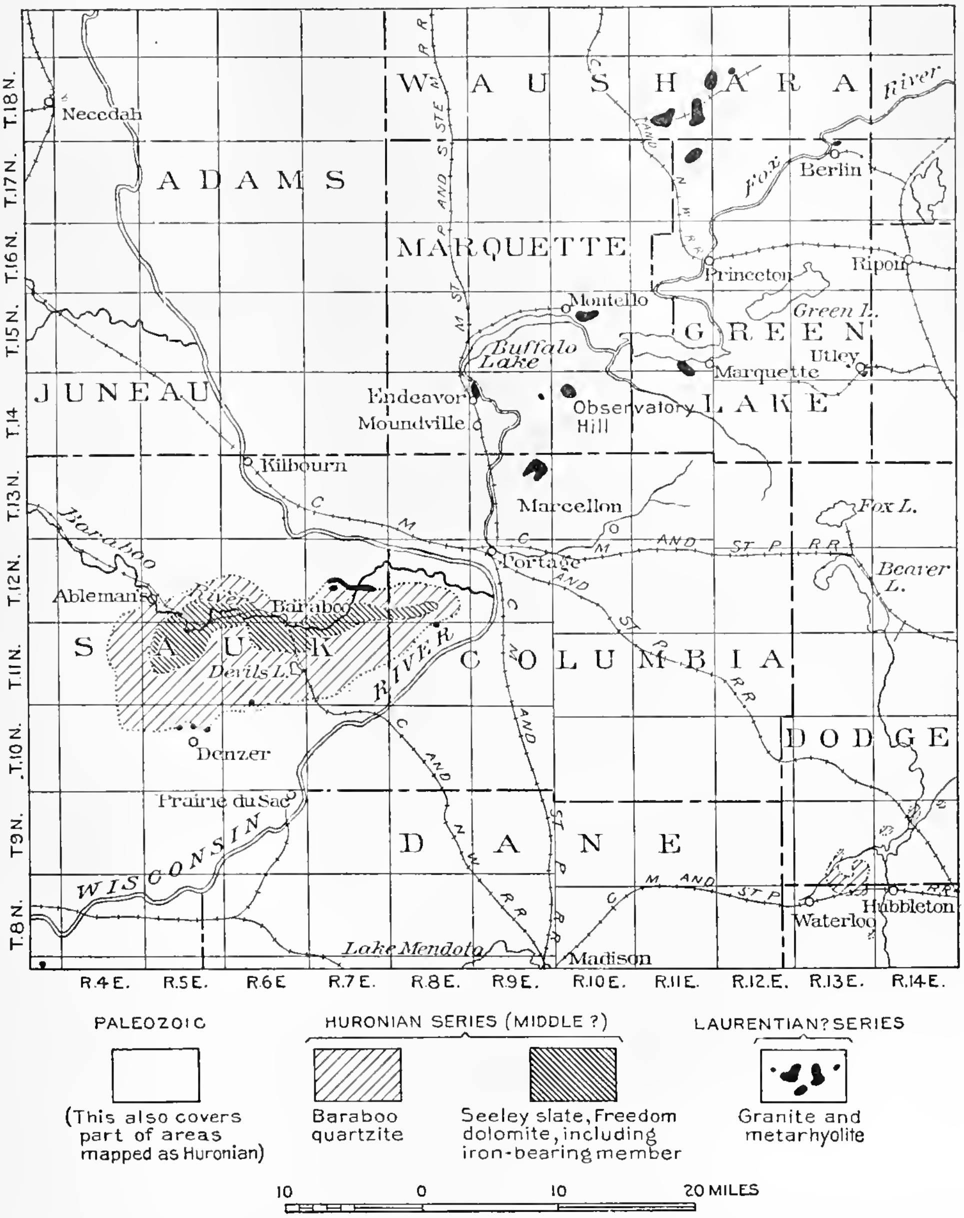

FIGURE 53.—Sketch map showing Baraboo, Fox River valley, Necedah, Waushara, and Waterloo pre-Cambrian areas of south-central Wisconsin.

shown on the general Lake Superior map (Pl. I), but a brief description is here given because the district is producing iron ore and is similar lithologically and structurally to the iron-producing area of the Lake Superior region.

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[a] Irving, R. D., The Necedah quartzite: Geology of Wisconsin, vol. 2, 1873–1877, pp. 523–524.

[b] Hancock, E. T., The geology of the area at Black River Falls, Wisconsin: Unpublished thesis, Geol. Dept. Univ. Wisconsin, 1901.

[c] See Weidman, Samuel, The Baraboo iron-bearing district of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 13, 1904.

The area is elliptical in outline, extending 20 miles east and west and ranging in width from 2 to 12 miles. It is essentially a quartzite syncline.

The succession is as follows:

Quaternary system............Pleistocene deposits.
Ordovician system............Trenton limestone.[a] / St. Peter sandstone. / "Lower Magnesian" limestone.
Cambrian system ....Potsdam sandstone.[a]
Unconformity.
Algonkian system:
  Huronian series:
    Upper Huronian (?)...Quartzite.
    Unconformity.
    Middle Huronian (?)..Granite, intrusive into lower formations. / Freedom dolomite, mainly dolomite, including an iron-bearing member in its lower part. / Seeley slate, 500 to 800 feet. / Baraboo quartzite, 3,000 to 5,000 feet.
Unconformity.
Archean system:
  Laurentian (?) series ......Granites, rhyolites, tuffs, etc.

The principal structural feature is an east-west synclinorium of middle Huronian (?) rocks resting on the Archean basement, carrying in the trough unconformable upper Huronian (?) quartzite and Paleozoic sediments, and surrounded by Paleozoic sediments. The edges of the basin, composed of hard, resisting middle Huronian (?) quartzite, form ridges known as the north and south Baraboo ranges, standing 700 to 800 feet above the surrounding country and the intervening valley. (See fig. 54.)

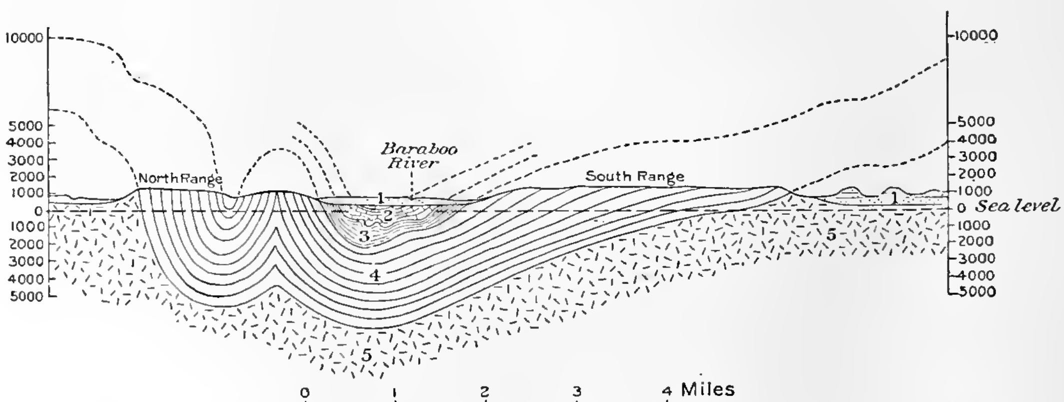

FIGURE 54.—Generalized cross section extending north and south across the Baraboo district. 1, Potsdam sandstone; 2-4, Huronian (2, Freedom dolomite; 3, Seeley slate; 4, Baraboo quartzite); 5, rhyolite and granite (Laurentian?). After Weidman.

ARCHEAN SYSTEM.

LAURENTIAN SERIES.

The Laurentian rocks outcrop in isolated areas bordering the outside of the Baraboo syncline. The surface volcanic phases are best exposed west of the Lower Narrows of Baraboo River on the northeast side and near the town of Alloa on the southeast side. They are similar to the surface volcanic rocks of the Fox River valley. Granitic rocks appear in isolated areas on the south side of the belt. Some of these rocks, previously considered as Archean, have recently been found to be intrusive into the middle Huronian (?).

[a] Used in a quotational sense from the Wisconsin Geological Survey.

ALGONKIAN SYSTEM.

HURONIAN SERIES.

MIDDLE HURONIAN (?).

BARABOO QUARTZITE.

The Baraboo quartzite is a massive though well-bedded formation, considerably jointed, faulted, and brecciated, but showing no cleavage as evidence of rock flowage except along certain thin slate beds in which readjustment has been concentrated during folding. Cross-bedding, ripple marks, and thin conglomeratic layers are numerous. In the north range the beds stand nearly vertical; in the south range they dip gently toward the south. Isolated exposures in the north-central side of the trough are thought to be brought up by minor folds. There is, however, a possibility that faulting has been a factor.

SEELEY SLATE.

The Baraboo quartzite passes up into the Seeley slate, a soft, gray, finely banded chlorite slate, known principally by drilling along the south limb of the syncline. The cleavage is somewhat steeper than the bedding, corresponding to the normal development of cleavage in such relation to a syncline.

FREEDOM DOLOMITE.

The Freedom formation consists principally of dolomite but contains near its base slate, chert, and iron ore and all gradational phases between these kinds of rocks. The lowest member is a ferruginous kaolinitic slate, well exposed in the Illinois mine, representing a ferruginated gradation phase of the Seeley slate into the Freedom dolomite. The next overlying member of the Freedom dolomite is banded ferruginous chert and iron ore, known principally along the south limb of the syncline, but occurring also in the east end of the basin and in several explored areas on the north side. Interbedded with the chert, especially near its upper parts, are calcite, siderite, kaolin, and dolomitic slates. Minor folding and brecciation are conspicuous in this member, part of it at least resulting from secondary chemical changes, causing slump in the formation.

The cherty dolomite making up the upper member and by far the greatest part of the Freedom formation is a fine-grained banded rock similar in some of its phases to the ferruginous cherts but usually softer. It grades locally into ferrodolomite.

UPPER HURONIAN (?).

Upper Huronian (?) quartzite has been found only by drilling in the deeper parts of the east end of the trough. Only recently has it been discriminated from the Cambrian sandstone above it or the middle Huronian (?) quartzite below. When the drill penetrated the Cambrian sandstone and conglomerate and reached quartzite below it was usually assumed that this was the middle Huronian (?) quartzite and the drilling was stopped. When this quartzite was penetrated by the drill, however, it was found to overlap the edges of all the middle Huronian (?) rocks and to have conglomerate at its base. The thickness of this quartzite, as shown by the drilling, is not more than 50 feet. Its attitude is not definitely known, but from the way it lies over all the earlier formations it is believed to be not much tilted. No exposures of the formation are recognized as such. It seems to remain simply as a residual patch in the deeper part of the trough where protected from erosion. However, some of the quartzite on the so-called Baraboo ridges may be upper Huronian (?) rather than middle Huronian (?). Still more recently red slate has been found above this upper Huronian (?) quartzite.

PALEOZOIC SEDIMENTS.

The Paleozoic rocks consist, from the base upward, of the Potsdam sandstone, the "Lower Magnesian" limestone, the St. Peter sandstone, and the Trenton limestone. The Potsdam sandstone occurs on the lower flanks of the quartzite ranges and in the valley bottom; the succeeding formations lie at higher elevations. The Paleozoic beds rest horizontally upon the more or less folded Huronian beds, a conspicuous basal conglomerate marking the great unconformity.

QUATERNARY DEPOSITS.

Pleistocene deposits cover about the northeast half of the district. (See Chapter XVI, pp. 427–459.)

THE IRON ORES OF THE BARABOO DISTRICT.

By the authors and W. J. Mead.

OCCURRENCE.

The iron-bearing beds, which are a part of the Freedom dolomite, have been productive thus far on the south limb of the basin. They dip northward at angles ranging from 50° to 70°. The foot wall is Seeley slate; the hanging wall is cherty dolomite, with small amounts of slate and iron carbonate. The iron-bearing member itself consists of ferruginous chert, iron carbonate, ferruginous slate, and iron ore. There is a gradation from this member into both hanging and foot walls. It is thin, for the most part not more than 200 feet thick, and the productive ore bodies are still thinner, 20 to 30 feet. The ores stand as lenses arranged end for end or overlapping parallel to the layers of chert. These have been found by drilling at a maximum depth of 1,500 feet, but mining operations do not yet go beyond 500 feet. Their lateral extent has been found to be at least 2,000 feet. Deep drilling down the dip discloses minor folds. Also to the south of the main outcrop the ore may be repeated by an additional minor fold.

The iron-bearing member has been found also on the north side of the basin, where it stands almost vertical or dips south, but so far it is nonproductive here.

Only one mine has operated to the present time, the Illinois mine (see fig. 55), although three other shafts are now being sunk.

CHEMICAL COMPOSITION.

The following is a complete analysis of the Baraboo ore:[a]

Chemical composition of the Baraboo ore.

Ferric oxide (Fe_2O_3)	88.62
Ferrous oxide (FeO)	.92
Alumina (Al_2O_3)	.68
Manganese monoxide (MnO)	.265
Silica (SiO_2)	8.06
Lime (CaO)	.12
Magnesia (MgO)	None.
Titanium oxide (TiO_2)	None.
Sulphur (S)	Trace.
Chromium oxide (Cr_2O_3)	None.
Water at 110°	.21
Water at red heat	.55
Carbon in carbonaceous matter	.04
Carbon dioxide (CO_2)	.51
Phosphoric oxide (P_2O_5)	.004
	99.979
Total iron	62.75

[a] Weidman, Samuel, The Baraboo iron-bearing district of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 13, 1904, p. 128.

A commercial analysis showing the average grade shipped for 1907 is as follows:

Partial analysis showing average grade of ore shipped for 1907.

[Sample dried at 212° F.]

Fe	53.47
P	.043
SiO_2	18.51
Mn	.22
Moisture	11.36

An average of 1,517 analyses, representing 4,814 feet of drilling in the iron-bearing member away from the available ores, gives 36.40 per cent of iron. This includes both the lean jaspers and the partly altered jaspers but not the ores. Because of their great mass compared with the ores, they represent nearly the general average composition of the entire iron-bearing member.

MINERALOGICAL CHARACTER.[a]

The Baraboo iron ore is mainly red hematite with a small amount of hydrated hematite. There are also small amounts of iron carbonate in isomorphous combination with varying amounts of manganese, calcium, and magnesium carbonate. Next to hematite in abundance is quartz or chert, which occurs either in bands in the ore or somewhat uniformly distributed throughout the ore. Chlorite, mica, and kaolin also occur in the ore in varying but usually small quantities.

The vein material in the ore is to a very large extent quartz, to a small extent calcite or ferrodolomite, and to a very small extent iron sulphide and iron oxide. The quartz of the veins has the usual interlocking granitic texture of vein quartz and is generally very much coarser than the finely granular cherty quartz in the ore and in the banded ferruginous chert. The carbonate of the veins is also much coarser than the carbonate of the beds.

PHYSICAL CHARACTER.[b]

The common phases of the Baraboo ore are soft granular ore, hard banded ore, and hard blue ore. The soft granular phases generally carry the highest percentage of iron, the banded and hard blue ore containing usually a larger amount of silica. The ore in its prevailing aspects is more like the hard varieties of ore of the old ranges of the Lake Superior district than the soft, hydrated hematite ore of the Mesabi district.

SECONDARY CONCENTRATION.

Structural conditions.—The circulation of waters in this district is controlled by the impervious foot-wall slate on the one hand and the impervious dolomite on the other. The zone between is a narrow one. The shaft of the Illinois mine (see fig. 55) goes down in the foot-wall slate. In walking from the shaft in the drift toward the ore body one notes the conspicuous dryness of the slate as contrasted with the extreme wetness of the drift where it passes through the iron-bearing member. Water is circulating at the present time through the iron-bearing member with great rapidity. The point of escape of the waters is not known; neither is it possible to tell what the depth of circulation has been. Ores have been found to a depth of 1,500 feet, but the deep ores were not so rich as those at the surface. The Baraboo quartzite ridges control the major circulation. The ores, however, are a considerable distance from the foot wall of these ridges on a comparatively flat area, although the hanging walls are usually in still lower ground.

Original character of the iron-bearing member.—The iron-bearing member was at least in larger part iron carbonate, as shown by the residual iron carbonate into which the member grades below, but it may have consisted also in part of banded ferric hydrate and chert.

[a] Weidman, Samuel, op. cit., pp. 127-128.

[b] Idem, p. 127.

Mineralogical and chemical changes.—The alterations of the iron carbonate have been accomplished through the usual processes as described on earlier pages. All stages of alteration are to be observed and all criteria for determining these alterations are known to be present. Weidman believes that the iron ore of the Baraboo district was originally a deposit of ferric hydrate, or limonite, formed in comparatively stagnant shallow water under conditions similar to those existing where bog or lake ores are being formed to-day, and that through subsequent changes long after the iron was deposited as limonite, while the member was deeply buried below the surface and subjected to heat and pressure, the original limonite became to a large extent dehydrated and changed to hematite, and that therefore its structural relations are not primarily controlled by the necessity of later water circulation.

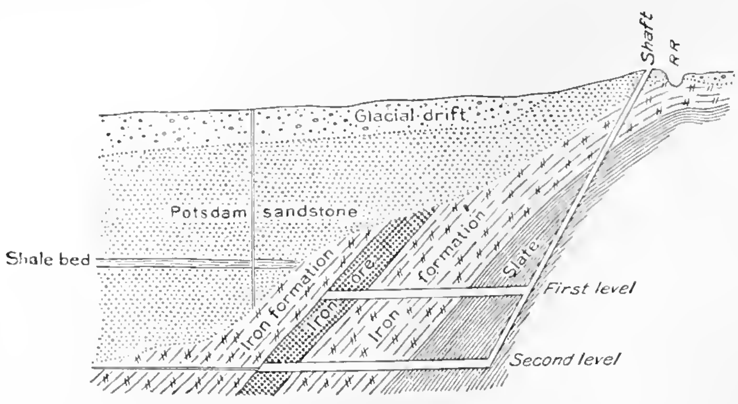

FIGURE 55.—Vertical section of Illinois mine. (After Weidman, Bull. Wisconsin Geol. and Nat. Hist. Survey No. 13, 1904, fig. 1, pl. 15.)

Though this district is widely separated from the principal Lake Superior ranges and may have the different origin outlined by Weidman, its close similarity in lithology and structure to the Lake Superior ranges is believed to be a priori evidence of similarity in origin. The theory of origin of the Lake Superior ores adequately explains the origin of the Baraboo ores and is combated by no facts yet shown in the Baraboo district. Moreover, recent deep drilling has shown an abundance of original iron carbonate. Certainly development work has not been nearly sufficient in the Baraboo district to warrant any conclusions at variance with those for the older Lake Superior ranges at the present time.

WATERLOO QUARTZITE AREA.

The mapping of the Waterloo quartzite at Portland, Hubbleton, Mudlake, and Lake Mills (see fig. 53) by Buell [a] and subsequently by J. H. Warner [b] shows that the outcrops of this quartzite have a distribution and structure such as to suggest that they represent part of a great eastward-pitching syncline of quartzite. The quartzite is lithologically almost identical with the Baraboo quartzite and its synclinal axis has the same direction as the axis of the Baraboo syncline. There is little reason to doubt that the Baraboo and Waterloo quartzites are of the same age. If this is the case, one would expect to find slate and ferruginous dolomite formations within the Waterloo quartzite syncline, as in the Baraboo syncline, but drilling has thus far failed to locate them. Like the Baraboo quartzite, the Waterloo quartzite is referred to the Huronian, and its similarity with the middle Huronian is emphasized. Well drilling outside of the Waterloo syncline shows the presence of a granite basement.

[a] Buell, I. M., Geology of the Waterloo quartzite area: Trans. Wisconsin Acad. Sci., vol. 9, 1893, pp. 255-274.
[b] Warner, J. H., The Waterloo quartzite area of Wisconsin: Unpublished bachelor's thesis, Dept. Geology Univ. Wisconsin, 1904.

FOX RIVER VALLEY.[a]

Several small isolated outcrops of pre-Cambrian crystalline rocks project through the Paleozoic sediments in the Fox River valley at Berlin, Utley, Waushara, Marquette, Montello, Observatory Hill, Marcellon, and Endeavor. (See fig. 53, p. 359.) The rocks are mainly acidic extrusives: metarhyolites, showing gradation into rocks of more deep-seated origin; rhyolite gneiss; quartz rhyolite; and granite, all of them cut by basic dikes. The characteristic feature in the metarhyolites is the presence of abundant and well-preserved surface volcanic textures, such as fluxion, perlitic, spherulitic, and brecciated textures. The lithologic similarities of the rocks, the presence of the surface textures, and their composition, as shown by analysis, indicate clearly their consanguinity with one another and with certain of the igneous rocks on the north and south sides of the Baraboo range. In the Baraboo district these rocks have been found by Weidman [b] to lie unconformably below the sedimentary rocks, and hence the volcanic rocks of Fox River may be supposed to be pre-Huronian.

[a] Hobbs, W. H., and Leith, C. K., The pre-Cambrian volcanic rocks of the Fox River valley, Wisconsin: Bull. Univ. Wisconsin No. 158 (Sci. ser., vol. 3, No. 6), 1907, pp. 247–278.

[b] Weidman, Samuel, The Baraboo iron-bearing district of Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 13, 1904, p. 21.

CHAPTER XV. THE KEWEENAWAN SERIES.[a]

GENERAL CHARACTERISTICS.

The Keweenawan is the upper series of the Algonkian system in the Lake Superior region. Its most characteristic feature is that its abundant effusive rocks are as widespread as the series itself. Indeed, they probably compose from a third to a half of the series. The Keweenawan contrasts with the Huronian in that in the latter series the effusive rocks are largely concentrated in a number of localities, although in these areas they may be of very great thickness. In short, the Keweenawan was a period of regional volcanic activity and the Huronian was a period of local volcanism. It results from these facts that in the earliest studies of the Keweenawan the igneous rocks were noted and described. In the Huronian, on the other hand, the sediments were more conspicuous and were especially studied in the early years, and it is only recently that the extent and magnitude of the igneous rocks of that period have been appreciated.

In the following discussion of the Keweenawan no attempt will be made to give detailed petrographic descriptions. The most salient petrographic features will be mentioned, and a review of the petrography and chemistry, with reference to nomenclature, will be presented by A. N. Winchell. In order to give a somewhat more definite impression of the series, the more important districts will be briefly described.

DISTRIBUTION.

The Keweenawan rocks border the major part of the shore of the western half of Lake Superior, occupy islands in the eastern half, and are found on the mainland at the extreme east end of the lake. They extend to a maximum distance of 120 miles northwest of Lake Superior. To the southwest Keweenawan rocks have been penetrated by drills at Stillwater, and still farther southwest, at St. Paul and vicinity, certain red sandstones have been drilled which may be Keweenawan. On the south side of the lake they occur mainly within 12 miles of the shore. Sandstones, Keweenawan or Cambrian, are known also at the east end of the Felch Mountain trough. This distribution shows that this series once occupied the greater portion of the Lake Superior basin and from it extended for varying distances. In much of the basin at present the Keweenawan rocks are overlain by Cambrian sandstone.

The total present exposed area of the Keweenawan rocks is approximately 15,000 square miles. To obtain the original area there must be added a very large but unknown portion of the Lake Superior basin. Further, there must be added the numerous masses, large and small, of the rocks of Keweenawan age intrusive into the Huronian and Archean of the Lake Superior region. Irving[b] estimated the area of the Keweenawan, aside from the rocks intrusive in older series, at 41,000 square miles.

It is thus evident that Lake Superior in Keweenawan time was an area of regional activity extending east and west for more than 400 miles and north and south for scarcely a less distance.

SUCCESSION.

A broad study of the several Keweenawan districts leads to the conclusion that a threefold division of the series as a whole may be made, beginning at the bottom, as follows: (1) Lower Keweenawan, comprising conglomerates, sandstones, dolomitic sandstones, shales, and marls;

[a] For further detailed description of the Keweenawan rocks of the Lake Superior region see Mon. U. S. Geol. Survey, vol. 5, and references there given. In the descriptions of the several districts accounts of local features of the Keweenawan are given.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, p. 27.

(2) middle Keweenawan, comprising extrusive and intrusive igneous rocks with important amounts of interstratified sandstones and conglomerates and subordinate amounts of shale; and (3) upper Keweenawan, comprising conglomerates, sandstones, and shales, represented in northern Wisconsin and Michigan. In only one district, northern Wisconsin and Michigan, is the full succession found. In the area of Black and Nipigon bays and Lake Nipigon, in Minnesota, and at the east end of Lake Superior the lower and middle Keweenawan appear. On Isle Royal the upper and middle Keweenawan occur, and on Michipicoten Island only the middle Keweenawan is found.

BLACK AND NIPIGON BAYS AND LAKE NIPIGON.

LOWER KEWEENAWAN.

The rocks belonging to the lower Keweenawan occupy the peninsula between Thunder and Black bays and the neck between Nipigon and Black bays from the northwest corner of Nipigon Bay to a point 20 miles west of Black Sturgeon River. They consist of quartzose sandstones, dolomitic sandstones, and red marls. According to Logan[a] their thickness is from 800 to 900 feet. Bell, however, estimated it from 1,300 to 1,400 feet. Bell's section[b] is as follows:

Section of lower Keweenawan rocks near Black and Nipigon bays.

	Feet.
Alternating red and white dolomitic sandstone, with a red conglomerate layer at the bottom, occurring on Wood's location, Thunder Cape[c]	40
Light-gray dolomitic sandstone, with occasional red layers and spots and patches of the same color. These sandstones occur along the southwest side of Thunder Bay and on Wood's location[d]	200
Red sandstones and shales, interstratified with white or light-gray sandstone beds, frequently exhibiting ripple-marked surfaces, and also with conglomerate layers composed of pebbles and bowlders of coarse red jasper in a matrix of white, red, or greenish sand	500
Compact light-reddish limestones (some of them fit for burning into quicklime), interstratified with shales and sandstones of the same color	80
Indurated red and yellowish-gray marl, usually containing a large proportion of the carbonates of lime and magnesia.[e] This division runs through the center of the peninsula between Thunder Bay and Black Bay, and may, in this region, have a thickness of 350 feet or more	350
Red and white sandstones, with conglomerate layers, the red sandstones being often very argillaceous and variegated with green spots and streaks, and having many of their surfaces ripple-marked. These rocks are found all along the northwest side of Black Bay as far up as the township of McTavish	200

There are no lavas interstratified with the Black Bay and Nipigon Bay rocks, but at numerous places they are cut by diabase dikes similar to those which cut the upper Huronian (Animikie group).

The lower Keweenawan occurs on the shore of the southwestern part of Lake Nipigon in relatively small areas and inland from Lake Nipigon in a large area of which Black Sturgeon Lake is the center. This division is called the Nipigon formation by Wilson.[f] It comprises basal conglomerates which rest unconformably upon the Archean, sandstones, shales, and dolomites—green, ferruginous, and white. For this area Wilson gives the succession, in descending order, as follows:

Section of lower Keweenawan rocks in Nipigon basin.

	Feet.
Dolomites and dolomitic shales	400
Grits and sandstones	150
Basal conglomerate	4–6

[a] Logan, W. E., Report of progress to 1863, Geol. Survey Canada, 1863, p. 70.

[b] Bell, Robert, Report of progress from 1866 to 1869, Geol. Survey Canada, 1870, p. 319.

[c] Macfarlane finds the red sandstone to contain 12.5 per cent of carbonate of lime and 11 per cent of carbonate of magnesia.

[d] Macfarlane found them to contain 13 per cent of carbonate of lime and 12 per cent of carbonate of magnesia.

[e] The amount varying, in the specimens analyzed by Macfarlane, from 21 to 34.5 per cent of the carbonate of lime, and from 7.5 to 13.5 per cent of the carbonate of magnesia.

[f] Wilson, A. W. G., Geology of the Nipigon basin, Ontario: Canada Dept. Mines, Geol. Survey Branch, Memoir No. 1, 1910, pp. 69–70.

Nothing is said by Wilson as to the dips of the lower Keweenawan rocks, but it is apparent from his descriptions that they are relatively flat.

The district above described is of interest as being the only district in which the accumulation of detrital material before the outbreak of the Keweenawan lavas covers any considerable area. It is believed that these rocks really represent the first deposits of the transgressing Keweenawan sea and antedate the igneous epoch of the Keweenawan altogether. The absence of material derived from the Keweenawan lavas led some of the earlier geologists—for instance, Macfarlane [a] and Hunt [b]—to question whether these rocks really belong with the Keweenawan. These lower Keweenawan rocks pass under the middle Keweenawan diabases and amygdaloids, which form the southern half of the peninsula southwest of Black Bay. On the north they are overlain, according to Bell, [c] by columnar trap.

MIDDLE KEWEENAWAN.

Aside from the area occupied by the lower Keweenawan sediments the remainder of the Black and Nipigon bays and Lake Nipigon district is occupied by the middle Keweenawan, consisting of basic igneous rocks with subordinate amounts of interstratified clastic material. These igneous rocks are partly flows and partly intrusions.

BLACK AND NIPIGON BAYS AND ADJACENT ISLANDS.

Black and Nipigon bays are noted for their conspicuous and interesting topography, which has originated in essentially the same way as the topography of Thunder Bay. In both localities the sediments are interleaved with great sills of diabase, sedimentary and igneous rocks alike being in nearly horizontal attitude.

The rocks of the middle Keweenawan constitute the shores of the outer parts of Black and Nipigon bays and of the adjacent islands, including those from the size of St. Ignace to small rocks, and from the shore they extend considerable but varying distances inland. Over large areas these rocks present facies which are similar to those of the Beaver Bay area of the Minnesota coast, described on pages 371–374. Locally they show spheroidal weathering, as at Fluor Island. They are cut by red rock, which metamorphoses the diabase to an orthoclase gabbro, just as on the Minnesota coast. The sediments are subordinate. In places the diabase clearly intrudes the sediments and locally the latter are somewhat modified at the contact, the color changing toward the intrusive rock from red to gray or white.

For the most part the dip of the rocks of the areas of Black and Nipigon bays is very gentle, here in one direction and there in another, but near the shore of Lake Superior there is the usual gentle and persistent lakeward slant of 8° to 10°. Locally, however, the dips go up to 20° or 30°, to 60° or 70°, or even to the vertical. These steep dips occur at places where the diabases intrude the sediments or the amygdaloids, and thus disturb their normal attitudes.

LAKE NIPIGON.

The middle Keweenawan igneous rocks extend throughout the Lake Nipigon district, except in the areas of the lower Keweenawan already mentioned. They occupy about half of the shore line on the east and north sides of Lake Nipigon, where they mainly constitute the peninsulas and headlands. North of the lake they extend 40 miles or more to the Hudson Bay divide. They occupy all the hundreds of islands of the lake, varying in size from those which are several miles long and wide to those which are mere rocks.

The middle Keweenawan of Lake Nipigon consists mainly of great masses of diabase, which Wilson says are in sheets and dikes, and with these are later acidic dikes. English Bay is an area of granite porphyry, which Wilson places with the Archean, but which, it may be suggested from the association, may belong with the Keweenawan.

[a] Macfarlane, Thomas, Canadian Naturalist, new ser., vol. 3, 1868, p. 252; vol. 4, 1869, p. 38.

[b] Hunt, T. S., Special report on the trap dikes and Azoic rocks of southern Pennsylvania, pt. 1: Rept. E, Second Geol. Survey Pennsylvania, 1878, p. 241.

[c] Bell, Robert, Report of progress from 1866 to 1869, Geol. Survey Canada, 1870, p. 338.

There has been much discussion as to whether the great diabase sheets are intrusive or extrusive rocks. Wilson[a] summarizes the evidence in favor of extrusion as follows:

1. The very widespread occurrence of unconformities between diabase sheets and underlying formations.

2. The occurrence of bowlders of granite and gneiss and schist in diabase, the latter resting on similar rocks in situ in localities where there is direct evidence that before the advent of the trap the underlying rocks were buried beneath the sediments similar to those now present, near by, under the same diabase sheet.

3. The occurrence of old soils in situ at the bases and on the sides of sedimentary ridges, the whole being covered in places with a diabase cap.

4. The nicety of the adjustment by which the diabase sheets have fitted themselves to the underlying topography. While the upper surfaces of the residuals of the capping sheets are everywhere fairly uniform in height, the base of the sheet has adjusted itself to a topography where the relief was at times as much as 300 feet.

5. The mechanical problem which arises in explaining the numerous unconformities, especially those on the embossed Archean surface, by the theory of intrusion vanishes completely on the theory of surface erosion prior to surface extrusion.

6. The features characteristic of the upper surface of sills—the occurrence of overlying beds or fragments thereof, aphanitic structures, included fragments of an old cover in the upper parts of sheets—are not found.

7. The medium to coarse texture, which characterizes the sheets, would be found at the base of thick surface flows as well as in sills, being dependent not on the nature and thickness of the cover so much as on the rate of cooling.

8. A glassy matrix, amygdaloidal or porous structure, basaltic texture, flow structure, and associated volcanics would not be characteristic features of the under parts of surface flows, and the upper parts of these sheets are unquestionably removed, without a single exception.

In favor of intrusive sills are:

1. Entire absence of any of those features that are usually associated with the upper parts of a surface flow—glassy matrix; amygdaloidal, porous, or basaltic texture; flow structure; associated volcanic rocks, either lava breccias or pyroclastic rocks.

2. A medium to coarse crystalline texture, usually indicative of a slow rate of cooling, such as would normally take place only at some considerable distance below the surface.

From the evidence presented Wilson draws the following conclusions:[b]

It seems that we have no data relative to the actual character of the upper surface of the trap "caps;" such negative evidence as is available is equally applicable to both theories. With regard to the texture of the residual basal portions of the sheets there are no recorded differences which would indicate that it belonged to a flow and not to a sheet. On the other hand, numerous unconformities exist, and the diabases are known to rest successively upon Laurentian, Keewatin, Huronian (possibly middle, certainly lower, and Animikie), and Keweenawan (lower, middle, and upper beds), and these unconformities are very widely distributed. Owing to the mechanical difficulties involved by any other interpretation it seems to the writer that the balance of evidence available is distinctly in favor of considering these capping sheets as the basal residuals of a once very extensive flow or series of flows of a very fluid diabase over the well-dissected topography of a previous cycle.

It may be suggested in this case, as in so many others, that the diabases of the Keweenawan sheets are not exclusively intrusive or extrusive.

It has heretofore been the prevailing view that the capping diabases, so characteristic of the step topography of the Animikie area and of the Keweenawan area on the northwest side of Lake Superior, are sills down to which erosion has worked. Wilson has held that some are not sills but are flows upon an old erosion surface. His conclusion that the flows are as late as Cretaceous rests on very slender evidence—that is, on the identification of the plane on which the flows rest as of post-Cretaceous age. He presents no evidence to show that the flows are not Keweenawan or some of them even Animikie. The view that they are Keweenawan is favored by their petrologic, areal, and structural relations with known Keweenawan rocks of the northwest and south sides of the Lake Superior basin.

RELATIONS OF THE KEWEENAWAN OF BLACK AND NIPIGON BAYS TO OTHER ROCKS.

As the sediments of Black and Nipigon bays are at the bottom of the Keweenawan series their relations to the underlying rocks are important. At the very base of the series occur conglomerates the débris of which is derived from the underlying Huronian series, including the

[a] Wilson, A. W. G., Geology of the Nipigon basin, Ontario: Canada Dept. Mines, Geol. Survey Branch, Memoir No. 1, 1910, pp. 94-95.
[b] Idem, pp. 95-96.

Animikie group, showing that there is an unconformity between the normal sediments making up the earliest Keweenawan and the latest Huronian. One of the best exposures of this unconformity is at a cliff adjacent to Surprise Lake, a short distance from Silver Islet village. Here in actual contact with the slates of the Animikie group is a conglomerate about 6 feet in thickness, which is largely composed of angular fragments of slates from the Animikie with, however, detritus from granites, mica schists, vein quartz, etc., but no fragments of any of the Keweenawan lavas. The contact between the conglomerate and slate is knifelike in sharpness. Locally the matrix of the conglomerate is limestone. The conglomerate grades upward into white quartzite interstratified with slaty layers, over which are bands of red and white dolomite. Here, as is common between the Keweenawan and Animikie, the discordance is shown mainly by the conglomerate and not by an important difference in dip, but in a number of places the conglomerate cuts across the slate bands in a minor way.

Other very satisfactory contacts between the Keweenawan and Animikie are those in a cut of the Canadian Pacific Railway about a mile west of Loon Lake and at the south shore of Deception Lake. Here the conglomerate of the Keweenawan resting upon the Animikie contains bowlders as much as 2 feet in diameter. At the railway cut the phenomena are very similar to those at Surprise Lake, but at Deception Lake the Animikie rocks have been somewhat sharply folded, and the conglomerate rests horizontally upon the truncated beds of the Animikie.

The débris of the Keweenawan conglomerate at these localities includes the slates from the underlying Animikie, material from the iron-bearing formation of the Animikie, and granites and schists from the lower Huronian or Archean. At all these localities the completely indurated pebbles of the Animikie as compared with the much less cemented Keweenawan are notable. This, combined with actual discordance, would indicate an important time break between the two series, an inference which is confirmed by the relations of the two in the Penokee-Gogebic district.

According to Wilson, in the Nipigon basin diabases rest unconformably on the Keweenawan, Animikie, and Archean rocks.

NORTHERN MINNESOTA.

THE KEWEENAWAN AREA.

The Keweenawan rocks of northern Minnesota lie in a great crescent-shaped area, opening lakeward, extending from Fond du Lac, on St. Louis River, at the southwest to Grand Portage Bay at the northeast. Both the lower and the middle Keweenawan are represented.

This area of Keweenawan rocks is undoubtedly the largest continuous area of the series. It covers approximately 4,500 square miles.[a] As yet this great region has been too insufficiently studied to permit a satisfactory account of it, and many points remain doubtful. Granites and diabases intrusive into the Animikie of the Cuyuna and St. Louis River areas are probably of Keweenawan age.

LOWER KEWEENAWAN.

The lower Keweenawan is represented by the Puckwunge conglomerate. According to Winchell,[b] this conglomerate is seen in various localities at the top of the Animikie group from Grand Portage Island, in Grand Portage Bay, as far west as the middle of R. 3 E., a distance of about 20 miles. He states that the basal rock of the Keweenawan is a conglomerate which grades up into sandstone. The thickness of the conglomerate is not determined, but this formation is just what one would expect between the Animikie group and the Keweenawan series from the character of the lower division of the Keweenawan about Black and Nipigon bays. Winchell[c] also states that a quartzite conglomerate which he regards as Puckwunge occurs in

[a] Elftman, A. H., The geology of the Keweenawan area in northeastern Minnesota: Am. Geologist, vol. 21, 1898, p. 175.
[b] Winchell, N. H., The geology of Minnesota, vol. 4, 1899, pp. 307, 327, 517-519; vol. 5, 1900, pp. 50-52.
[c] Idem, vol. 4, p. 13.

sec. 1, T. 48 N., R. 16 W., on St. Louis River, and that its total thickness is nearly 100 feet. There are, however, rare pebbles of Keweenawan rocks in this formation. It is conformable below the younger beds. The pebbles of this conglomerate are largely derived from the quartz veins of the slates of the underlying Animikie, and the conglomerate therefore lies unconformably on the Animikie. The formation grades into a white sandstone and then into a shale. Thus the sedimentary formation is seen at the base of the Minnesota Keweenawan at both the northeast and the southwest ends. In the intervening stretch of more than 100 miles the exact base of the sedimentary or volcanic Keweenawan has not been traced because of lack of exposures and because of the intrusion of the great Duluth gabbro to be mentioned later.

MIDDLE KEWEENAWAN.

The middle Keweenawan rocks comprise all of the Keweenawan in Minnesota except the relatively insignificant Puckwunge conglomerate. They represent the volcanic epoch of the Keweenawan. Broadly the middle Keweenawan of northeastern Minnesota may be divided into two great divisions—(1) the effusive rocks and the associated sediments and (2) the intrusive rocks.

EFFUSIVE ROCKS.

The effusive rocks occupy the larger part of the Minnesota coast and extend for varying distances inland. The Minnesota coast line, looked at as a whole, presents a flat crescentic shape, with the concavity toward the lake. The same is true of the courses of the effusive rocks, but the crescents formed by them have a smaller radius and hence intersect that formed by the coast line, trending more to the north at the Duluth end and more to the east at the Grand Portage end. In following the coast, then, from Duluth to Grand Portage, we ascend in geologic horizon to a point near Two Islands River and descend from a point just east of Temperance River to Grand Portage.

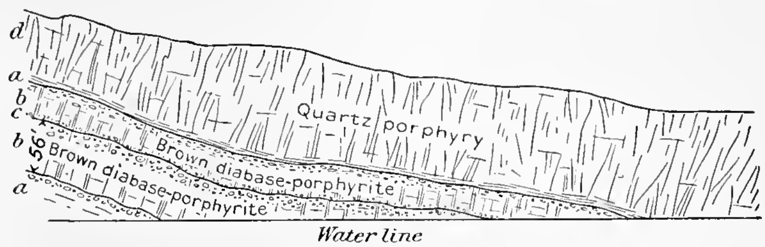

FIGURE 56.—Section on south cliff of Great Palisades, Minnesota coast. (After Irving.) *a*, Amygdaloid; *b*, columnar diabase-porphyrite; *c*, mingled amygdaloid and detrital matter; *d*, quartz porphyry.

These rocks consist dominantly of a well-stratified series of volcanic flows having a gentle lakeward dip, which commonly is from 8° to 10° but locally is as low as 5° or 6° and as high as 25° or 30°, or rarely even 45° or 60°. Numerous minor bowings and corrugations may be seen in the individual layers and sets of layers, which may be followed for some miles. These may be seen rising into arches, locally of short span, and sinking into synclines to reappear as anticlines a short distance away.

The lavas are diabases which are commonly amygdaloidal. Many of these amygdaloids are very scoriaceous. These rocks are softer than the intrusive rocks and are especially likely to constitute the bays. There are subordinate masses of intermediate rocks, which usually have not been separated on the maps from the basic flows. At one place, east of Kadonces Bay, this intermediate rock has a peculiar spheroidal weathering similar to that of the Ely greenstone, a structure which has been regarded as evidence of subaqueous extrusion.

Associated with the basic lavas are masses of acidic lavas represented by quartz porphyrites and felsites. One of the more notable localities for these rocks is the great Palisades (fig. 56).

The conglomerates and sandstones interstratified with the lavas are subordinate in amount. In the lower part of the series they are either absent altogether or are represented by very thin beds. In the upper part of the series, especially the portion to which Irving [a] has given the

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 323-329.

name Temperance River group, the sandstone and conglomerate beds are numerous. Most of these beds are only a few inches to a few feet in thickness, but there are some beds which are 100 feet thick, and according to Elftman[a] one which is 250 feet thick. Lawson[b] estimates that the sandstones and conglomerates occupy less than 0.5 per cent of the coast line.

INTRUSIVE ROCKS.

The intrusive rocks comprise both basic and acidic types.

BASIC ROCKS.

The basic rocks include the Duluth laccolith, the Beaver Bay and similar laccoliths and sills, the anorthosites, and the dike rocks.

DULUTH LACCOLITH.

Area and character.—The Duluth laccolith is a gabbro. It extends from St. Louis River to the northeast, gradually widening until in the center of the belt it is 30 miles wide. From this maximum breadth it narrows toward the east until it makes a point at the Minnesota coast.

It is not our purpose here to give anything more than a most general petrographic account of the Duluth gabbro. It is, for the most part, normal gabbro, but it has many facies. Mineralogically it ranges from a very magnetitic gabbro through olivine gabbro in which the feldspar is subordinate and ordinary olivine gabbro to olivine-free gabbro, or ordinary gabbro, and finally to a rock in which feldspar is the dominant mineral, the rock being a labradorite or an anorthosite. The anorthosite masses vary from those a few feet across to those hundreds of feet in diameter. The anorthosite appears to be but a differentiation phase of the gabbro, there being every gradation between it and both coarse and fine grained phases of the main mass of the rock. These relations are particularly well seen at Little Saganaga Lake, where, according to Clements,[c] the anorthosite unquestionably shows gradations into the surrounding basic masses. Nowhere is there a sharp line of contact between the two rocks. In these respects the occurrences are in sharp contrast with the anorthosite and the diabase of the Minnesota coast, to be later described.

Structurally the gabbro is ordinarily massive. However, at many places, especially near its borders, it has a sheeted structure. Some of the sheets are very thin and strongly resemble bedded rocks. This variety may be very well seen in the north bay of Bashitanequeb Lake. In addition to this sheeted structure there is a banded structure, due to the parallel arrangement of the mineral constituents.

Texturally the gabbro varies from a rock of very coarse grain to one that is almost aphanitic. All varieties, coarse and fine, are granulitic.

Relations to other formations.—The structural relations of the Duluth gabbro are very interesting. On the north, in passing from St. Louis River to Grand Portage, the gabbro is in contact for a long way with the upper Huronian, then for many miles with the several members of the lower Huronian and the Archean, and finally for many miles again with the upper Huronian. It thus cuts diagonally across the upper Huronian in its northern and southern parts and in passing toward the center of the area goes through the lower Huronian and deep into the Archean.

Evidence of its intrusive character is afforded by its coarse crystallization; by the presence of numerous subordinate bosses and dikes, offshoots of the gabbro mass, in the Huronian series; by the inclusion of isolated masses of upper Huronian near its margin and the profound metamorphic effects of the gabbro, the rocks being changed to schists or gneisses or even to completely granular crystalline rocks for distances up to half a mile or a mile from the main gabbro mass, an effect not to be expected from a rapidly cooling extrusive; and finally by the higher density of the gabbro than of the intruded rocks.

[a] Elftman, A. H., The geology of the Keweenawan area in northeastern Minnesota: Am. Geologist, vol. 21, 1898, p. 185.

[b] Lawson, A. C., Sketch of the coastal topography of the north side of Lake Superior: Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, p. 190.

[c] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, pp. 402–403.

The relations of the gabbro to the lavas of the coast have not been satisfactorily determined. Their contact is mainly in the plateau of the interior, is very poorly exposed, and has not been sufficiently studied. However, it is believed that when these relations are worked out it will be found that the gabbro is intrusive and has produced profound metamorphic effects.

If this inferred intrusive relation is confirmed, the Duluth gabbro is a great laccolith, which has as a basement the Huronian and Archean and as a roof the Keweenawan lava flows. The relations of the Duluth gabbro to the Puckwunge conglomerate at the base of the Keweenawan and to the earlier Keweenawan lavas have not been established. Until this is done it is impossible to gain any definite conception as to how far Keweenawan time had advanced before the appearance of the gabbro. If the Duluth gabbro is interpreted as a laccolith it surpasses in magnitude any other yet described. With a maximum diameter of 100 miles, if its thickness has approximately the ratio shown in the typical laccoliths of the Henry Mountains,[a] the thickness would be 75,000 feet. If an average dip of 10° for 50 miles on the north shore is assumed the thickness would figure 45,000 feet.

The intrusion of so vast a mass of material must have required a long time. The parts earlier intruded were doubtless solidified long before magma ceased to enter. Thus, offshoots of these later parts would be found as dikes in the earlier solidified parts. There would be great variation in its coarseness of crystallization. Ample time would be afforded for differentiation by fractional crystallization, separation by gravity, and other processes, and thus is explained the structural complexity of the gabbro and its great variation in mineral and chemica character.

THE BEAVER BAY AND OTHER LACCOLITHS AND SILLS.

Intruded in the lavas of the Minnesota coast are a great many laccoliths or sills of diabase. These intrusive rocks are especially prevalent in the lower part of the lavas, and particularly in the part below the Temperance River group. In texture these rocks vary from diabases to gabbros and include the so-called black gabbros of Irving.[b] The diabases in many places show a remarkable luster mottling due to the inclusion of numerous individuals of plagioclase in large individuals of augite. Not uncommonly the augites are several inches in diameter and include hundreds of lath-shaped feldspars.

Many of these laccoliths and sills were supposed by the earlier geologists to be lava flows, but when examined closely they are found to cut the lava beds by passing gradually across their edges and by sending out dike offshoots. In not a few places they show a distinct columnar structure at right angles to their borders.

The local steep dips of the lava beds mentioned in the previous section are apparently all due to the influence of the intrusive masses and thus their exceptional character is explained.

A typical illustration of these laccoliths is seen at Beaver Bay. The center of this laccolith extends from a point near Beaver Bay to a point near Two Harbors Bay. In this distance it occupies the entire coast. Neither its top nor its bottom is seen. In this part it is not luster mottled but is the coarse black gabbro of Irving.[b] Its central part is sheeted and in general has a coarse or imperfect columnar structure at right angles to the horizon or nearly so. Where it is found in association with the lavas farther east and west, as at Split Rock and Beaver Bay, its structure corresponds with the bedding of the amygdaloids, so that it was natural for Irving to regard it as a bedded flow, although even he recognized that at some places it cut the amygdaloids in a curious way. Indeed, locally it cuts the amygdaloids in a most intricate fashion, following the joints, winding around the blocks, intruding itself as films between the plating of the amygdaloid, but always with sharp contacts. It is a significant fact that near the lavas the laccolith is luster mottled. Very close to the amygdaloid it is locally fine grained. In places it retains its coarse texture, even in narrow stringers. The laccoliths and sills, being resistant rocks, usually make the major headlands of the coast, just as the lavas usually constitute the bays.

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[a] Gilbert, G. K., The geology of the Henry Mountains, 2d ed.: U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880, p. 55.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 267-268.

The Logan sills and capping rocks in the Animikie and Keweenawan of northeastern Minnesota should be particularly mentioned. These are doubtless to be correlated with the great gabbro mass. In fact, in the Gunflint Lake district they seem to be directly connected. To these sills are due the step topography of this region. Wilson [a] has concluded that farther to the east in the Nipigon basin some of the capping steps instead of being sills are really flows. It is possible that this conclusion may be applied to part of the capping rocks in northeastern Minnesota.

ANORTHOSITES.

The anorthosites of the Minnesota coast early attracted attention because of their brilliant light color. They may be well seen at Split Rock, Beaver Bay, and Carlton Peak. At these places a large portion of them are inclusions in the basic laccoliths and sills, such as the Beaver Bay laccolith. Indeed, at many places they form a stucco in this diabase laccolith. In size the inclusions range from those which are minute, being no more than individual crystals of feldspars, to great masses 50 or 60 feet in diameter. In addition to these masses, which are plainly inclusions, there are other masses which are so large that they can not be asserted to be inclusions. These are mantled by the Beaver Bay laccolith, as described by Lawson,[b] the relations at the bottom, however, not being exposed. Some of these masses on the Minnesota coast are as large as a cathedral, and the largest masses are found at Carlton Peak, the different points of which are composed entirely of anorthosite. The anorthosite inclusions are not contained in the central part of the Beaver Bay laccolith, but in its upper part, where it is in contact with or near the amygdaloids.

The relations above described conclusively show that the anorthosite, as a rock, antedated the including rocks. Lawson [c] has interpreted this to mean that the anorthosite marked a pre-Keweenawan terrane, but from our point of view the anorthosite is but a facies of the great Duluth gabbro mass which had been segregated before the diabase intrusions (see p. 372), and therefore has been included in the diabase, as above described.

It is conjectured that the very abundant diabase laccoliths and sills at Beaver Bay and other localities are but later offshoots of the original reservoir of magma from which the Duluth gabbro was also derived. The alliance between the diabase intrusives of the coast and the Duluth gabbro is shown by their chemical and mineralogical likeness.

BASIC DIKES.

Diabase dikes cut the lavas and sills at numerous places. As a rule they are nearly vertical. Many of them lie approximately at right angles to the coast, and are likely to make projections into the water. Others run approximately parallel to the coast. These dikes conform to the sets of strike and dip fractures which were produced by the deformation. Commonly these diabase dikes are less than 50 or 60 feet across. At some places they have a columnar structure at right angles to the walls, parallel to the bedding of the lavas, and consequently at right angles also to the columnar structure of the laccoliths.

ACIDIC ROCKS.

Along the northwest shore of Lake Superior and back from the coast are many areas of acidic rocks, collectively mapped as red rock, because of their prevailing red color.[d] The red rock consists of intrusives, mainly granite and augite syenite, and their equivalent effusives, quartz porphyry. These are later than the associated basic extrusive and intrusive rocks, succeeding the Duluth gabbro and the diabase of the Beaver Bay laccolith. The red rocks range in size from considerable masses to minute stringers. In many places the intrusives intricately cut the basic rocks. This is well illustrated at Beaver Bay, where both the amygdaloidal lavas and the diabase are intruded. Dikes of the red rock, great and small, cut the diabase

[a] Wilson, A. W. G., Geology of the Nipigon basin: Canada Dept. Mines, Geol. Survey Branch, Memoir No. 1, 1910, pp. 95-96.
[b] Lawson, A. C., The anorthosites of the Minnesota coast of Lake Superior: Bull. Geol. and Nat. Hist. Survey Minnesota No. 8, 1893, p. 16.
[c] Idem, p. 19.
[d] Elftman, A. H., The geology of the Keweenawan area in northeastern Minnesota: Am. Geologist, vol. 22, 1898, pl. 7.

through and through, and have produced an important exomorphic effect. Where thus altered the diabase grades into a rock of a somewhat more acidic aspect and becomes the orthoclase gabbro of Irving.[a] Wherever we have seen this rock it is but a facies of the diabase, produced through the minute penetration of the acidic magma of the red rock. It is clear that the chemical composition of the diabase has been affected by minute penetration of the acidic magma and its emanations.

KEWEENAWAN ROCKS IN THE CUYUNA DISTRICT OF NORTH-CENTRAL MINNESOTA.

Granite, diabase, and gabbro cut the slates of the Animikie in the great north-central area of Minnesota, including the Carlton, Cloquet, Cuyuna, and Little Falls areas. Being later than the Animikie, they are probably to be correlated with the Keweenawan intrusive rocks of northeastern Minnesota. They are probably to be regarded as the plutonic equivalents of the Keweenawan flows. In the Cuyuna district there is also a thin layer of amygdaloidal acidic rock, 15 feet thick, resting upon the eroded edges of the slates and iron-bearing formation of the Animikie group. Drilling in this district discloses many masses of basic and acidic rock intricately associated with the slates of the Animikie, but the relations are not yet determined.

THICKNESS OF THE KEWEENAWAN OF MINNESOTA.

Irving,[b] in his monograph on the copper-bearing rocks of Lake Superior, makes a formal division of the Keweenawan of the Minnesota coast into six groups, for which he estimates thicknesses as follows, from the top down:

	Feet.
Temperance River group	2,500–3,000
Beaver Bay group	4,000–6,000
Agate Bay group	1,500
Lester River group	2,600
Duluth group	5,000
St. Louis gabbro [now called Duluth gabbro]	Thickness uncertain.

Excluding the gabbro, Irving[c] estimates the total thickness to be between 17,000 and 18,000 feet. It is to be remembered that these estimates of thickness include large masses of intrusive rocks, as, for instance, the Duluth gabbro and the diabase of Beaver Bay. Also it is far from certain that the lavas on the Minnesota coast have the regularity of superposition supposed by Irving. Finally, it is uncertain what part of the present dip of the lavas is initial.

Elftman, the one other geologist who has made an extensive study of the Keweenawan of the Minnesota coast, gives the following order:[d]

1. Later diabase member.
2. Temperance River member.
3. Red Rock member.
4. Beaver Bay diabase member.
5. Gabbro member.

This is the structural order. It is clear that the order is only partly one of age, for before the gabbro and other laccoliths and sills could be intruded in the Keweenawan a certain amount of sediments and lavas must have been built up. This succession, as well as that of Irving,[b] ignores the Puckwunge conglomerate.

Elftman supposed that between the "Temperance River member" and the "Red Rock" member there is a considerable unconformity, because at the bottom of the "Temperance River member" is a conglomerate 100 feet thick. This conglomerate contains fragments of diabase similar to the diabase of Beaver Bay, and also many fragments of red rock, indicating

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 50 et seq.
[b] Idem, pp. 266–268.
[c] Idem, p. 266.
[d] Elftman, A. H., The geology of the Keweenawan area in northeastern Minnesota: Am. Geologist, vol. 21, 1898, pp. 183–185.

that these lavas were formed before the deposition of the "Temperance River member." As the "Temperance River member" is cut by other diabase dikes and by red rocks, however, there is no reason to believe that the supposed unconformity is different from that marked elsewhere in the Keneenawan by the appearance of considerable beds of sediments. The volcanic epoch had not ceased.

In view of the great uncertainty as to the exact succession, relations, initial dips, and faulting of the Minnesota rocks, it is almost impossible to give any estimate of their thickness. Probably if the lavas and sediments only were considered, the thickness would be very much less than the amount that Irving[a] mentioned, but if the thickness of the intrusive rocks, including the Duluth gabbro, were computed, and this added to the thickness of the extrusives, an amount vastly in excess of 20,000 feet would be obtained.

NORTHERN WISCONSIN AND EXTENSION INTO MINNESOTA.

DISTRIBUTION.

The Keweenawan rocks of northwestern Wisconsin and their extension into Minnesota include an area estimated at over 5,000 square miles. The greater extent of the area is in a northeast-southwest direction. At the southwest end the Paleozoic strata make a deep embayment, thus partly dividing the area into two belts crossing St. Croix River. Farther to the southwest the Keweenawan has been found by deep drilling at Stillwater, and it is not impossible that the red sandstone found at St. Paul and to the southwest may belong to the same division. Granites of probable Keweenawan age occupy a considerable area in the Florence district of northeastern Wisconsin.

STRUCTURE.

The Keweenawan area of northeastern Wisconsin is a synclinorium, the axis of which extends southwest from Chequamegon Bay and at its southwest end bends more to the south. On the northeast, in the vicinity of Ashland and Clinton Point, the work of Thwaites[b] in 1910 has disclosed minor folding and possibly faulting in this synclinorium, the steeper dips of the minor folds being to the north. On the southwest end of the district in Minnesota, along St. Croix River, the work of Grout[c] has disclosed similar complexity of structure.

The synclinorium is bordered for its entire length on the north by a fault against which the Cambrian is faulted down. The fault plane dips 38° to 45° S. It dies out in Bayfield County. The Lake Superior sandstone beds are buckled along the contact. It is not known to what extent the movement has been vertical or horizontal, although striations in at least one place point to a vertical movement. The net result in any case has been to bring the traps up over the Cambrian or Lake Superior sandstone. Minor dip faults have been noted in northern Iron County similar to those on Black River in Michigan.

The dip of the upper as well as the lower divisions of the Keweenawan is as high as 90°, but averages about 70° to 80° at the east end of the southern part of this area. In the bottom of the synclinorium, as has been noted, a series of minor rolls show dips up to 90° on the north limbs and as low as 25° on the south sides, while in the Apostle Islands to the north the overlying quartz sandstone (Lake Superior) dips about 1° to 5° SE. To the west, along the syncline, the dips become less until inclinations of only 15° occur, but in Minnesota much higher ones are recorded. On the north limb in Douglas County are found dips of 30° to 70° S.

LOWER KEWEENAWAN.

At only one place in northern Wisconsin is the lower Keweenawan known to be exposed. This is in the southeastern portion of secs. 11 and 12, T. 45 N., R. 1 W., west of a small lake. At this point there is a considerable mass of coarse conglomerate, the pebbles of which are mostly

[a] Irvin, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, p. 266.
[b] Thwaites, F. T., unpublished field notes for Wisconsin Geol. and Nat. Hist. Survey, 1910.
[c] Grout, F. F., Contribution to the petrography of the Keweenawan: Jour. Geology, vol. 18, 1910, pp. 633–657.

white quartz, some of them being 8 or 10 inches in diameter. Flint and black hornstone pebbles are also plentiful. This conglomerate grades up into a coarse quartzite, and this into a fine-grained compact quartzite. Immediately to the north of the latter formation are the basic flows of the middle Keweenawan, and 400 or 500 feet south of the conglomerate are upper Huronian micaceous graywackes. The thickness of the conglomerate and quartzite exposed is probably from 300 to 400 feet.

The quartzites adjacent to the Keweenawan in Barron County, Wis., may be in part Keweenawan. There are here at least two series of pre-Cambrian quartzites, the upper of which is reddish, feldspathic, and not strongly consolidated, and has comparatively low dips. These facts, together with the position of the quartzites on the southeast side of the Keweenawan syncline, have suggested to Weidman[a] the possibility that they represent lower Keweenawan sediments, but this has not been proved.

MIDDLE KEWEENAWAN.

The general characters of the middle Keweenawan in this region are substantially the same as those of northeastern Minnesota. The igneous rocks comprise both plutonic and volcanic masses. The volcanic series covers a much greater area than the plutonic rocks. At the sections which have been studied, Potato River, Tylers Fork, and Bad River, the igneous rocks, according to Irving,[b] consist dominantly of beds of diabases, diabase amygdaloids, and melaphyres. With the basic igneous rocks are subordinate masses of felsite and quartz porphyry. Interstratified with the lavas are subordinate beds of conglomerate and sandstone. Along the north side of the Keweenawan of Wisconsin, in Douglas County, the lower part of the series is composed wholly of igneous rocks, but at higher horizons in the southeastern part of the district conglomerates are interstratified with lava flows. On the whole the interbedded detrital rocks of this area are apparently less abundant than on Keweenaw Point but more abundant than in Minnesota. The lithology of the interstratified conglomerates and sandstones is in no respect peculiar.

So far as we know, there has been no approximately accurate determination of the entire thickness of the lava flows and interstratified sediments of the middle Keweenawan in Wisconsin. Berkey[c] has estimated the thickness of the Keweenawan eruptive rocks exposed along the St. Croix Dalles as 4,000 feet. Hall[d] estimates a thickness of 20,000 feet on Snake and Kettle rivers in Minnesota.

On the south side of the syncline at the base of the Keweenawan in Wisconsin is a great basal gabbro, which in every respect is equivalent to the Duluth gabbro described on pages 372–373. This gabbro has been traced from Black River in Michigan as far west as R. 7 W., but how much farther it extends is unknown. Thus it has an extent northeast and southwest of 60 miles or more. For most of the distance the belt is from 2 to 5 miles broad. The rocks of the underlying upper Huronian along most of this gabbro belt dip about 75° N. If the thickness of the gabbro mass were calculated at right angles to the dip of the underlying Huronian rocks, this would give a thickness of 9,500 to 25,000 feet.

It has been explained in connection with the Penokee-Gogebic district that this gabbro cuts diagonally across all the formations of the Huronian series and down into the Archean; also that adjacent to the contact the upper Huronian rocks are profoundly metamorphosed, the Tyler slate into mica slates and mica schists, the iron-bearing Ironwood formation into actinolite-magnetite schists, the Bad River limestone into a coarsely crystalline tremolitic limestone. Further, within the Huronian and the Archean are smaller masses of intrusive gabbro which doubtless are offshoots or necks of the main mass. Thus in every respect the relations of this basal gabbro to the underlying rocks are the same as in northern Minnesota.

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[a] Personal communication.
[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 230–231.
[c] Berkey, C. P., Geology of the St. Croix Dalles: Am. Geologist, vol. 20, 1897, p. 382.
[d] Hall, C. W., Keweenawan area of eastern Minnesota: Bull. Geol. Soc. America, vol. 12, 1901, p. 331.

Unfortunately the relations between the gabbro mass and the lavas of the Keweenawan have not been closely studied. Irving[a] represents this gabbro as feathering out into a series of points to the east, suggesting very strongly its intrusive character. However, his descriptions scarcely correspond to that distribution. He says:[a]

The coarse gray gabbros so largely developed in the Bad River country of Wisconsin, at the base of the series, present the appearance of a certain sort of unconformity with the overlying beds. These gabbros, which lie immediately upon the Huronian slates, form a belt which tapers out rapidly at both ends and seems to lie right in the course of the diabase belts to the east and west, since these belts, both westward toward Lake Numakagon and eastward toward the Montreal River, lie directly against the older rocks, without any of the coarse gabbros intervening.

The coarseness of grain, the perfection of the crystallization, the abrupt terminations of the belts, the complete lack of structure, and the presence of intersecting areas of crystalline granitoid rocks led Irving[b] to the belief that these rocks were not ordinary lavas, but had solidified at a great depth.

The acidic rocks cutting these coarse gabbros are clearly intrusive.

The gabbro in Wisconsin, like the Duluth gabbro, is believed to be a great laccolith, which was intruded in Keweenawan time after a considerable thickness of Keweenawan lava beds had been built up, and, as in Minnesota, it roughly followed the contact at the base of the Keweenawan and penetrated diagonally across the lower formations as well as irregularly across the Keweenawan beds themselves. It has since been turned up at angles of 75° or 80° and truncated by erosion.

Gabbro on the north side of the Keweenawan trough in Douglas County, Wis., is described by Grant,[c] but its extent has not been determined. It dips to the south and its relations to the lavas are similar to those of the gabbro on the south side of the Douglas County syncline. It is faulted on the north against the Cambrian rocks, which are on the downthrown side. It dips in the same direction as the Duluth gabbro, and the displacement of the fault is in such a direction as to show that it may have been originally continuous with the Duluth gabbro.

UPPER KEWEENAWAN.

The upper division of the Keweenawan in this area consists of red sandstones, shales, and conglomerates, divided, in the eastern part of the district, into several distinct members. Beginning at the base are found conglomerate 300 to 1,200 feet in thickness, black shales up to 400 feet, about 19,000 feet of red arkose sandstone, grading up to more siliceous sandstone, red and green shales, and coarse arkose. Above this is quartz sandstone, somewhat feldspathic at the base, nearly 4,000 feet thick, here called the Lake Superior sandstone. These beds appear to thin rapidly toward the west. These figures make no allowance for initial dip.

RELATIONS OF THE KEWEENAWAN TO OTHER SERIES.

The only places at which the relations between the Keweenawan and lower series are shown are in Wisconsin. Here, as has been seen, the lowest formation of the Keweenawan is made up of conglomerate and coarse sandstone and is overlain by the lava flows of the middle Keweenawan. The coarse conglomerate of Potato River is evidence of the erosion interval between the Keweenawan and the upper Huronian, but the magnitude of the unconformity is realized only by a study of the relations of the two along the strike, which gives evidence of a large amount of erosion of the Huronian series before Keweenawan time. The details proving the greatness of this unconformity are given in the chapter on the Penokee-Gogebic district (pp. 234–235).

As to the relations of the middle Keweenawan with the Upper Cambrian sandstone along St. Croix, Kettle, and Copper rivers (of Minnesota), there is no difference of opinion. The Upper Cambrian sandstone, in horizontal attitude, rests upon the steeply tilted and eroded

[a] Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 155–156.
[b] Idem, p. 141.
[c] Grant, U. S., Preliminary report on the copper-bearing rocks of Douglas County, Wis.: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 6 (2d ed.), 1901, pp. 31-32.

edges of the middle Keweenawan rocks and bears abundant detritus from them. It is therefore perfectly clear that before the sandstone was laid down the middle Keweenawan had been placed at its present angles and had been profoundly eroded. The relation is very well illustrated at Taylors Falls on St. Croix River, where the Cambrian sandstone is fossiliferous and has been certainly determined as of Upper or Middle Cambrian age. The relations between the diabases and the Cambrian here are shown by figure 57.

The relation of the upper Keweenawan feldspathic sandstone and the quartz sandstones, here called the Lake Superior sandstone, has long been a subject of dispute, but the discovery by Thwaites in 1910 of outcrops on Fish Creek near Ashland has thrown new light on the question. At this point the layers are steeply inclined to the north, exposing about 1,400 feet of strata and disclosing a transition between the red shales, arkose sandstones, and conglomerates of the upper Keweenawan and the Lake Superior sandstone. A deep well at Ashland passes into these red shales at a depth of 2,670 feet.

A reexamination of Middle River in Douglas County north of the great fault showed that the sandstone beds are inverted.[a] About 3,100 feet of strata have been turned up by the faulting, exposing mud-cracked and ripple-marked green and red shales and arkose sandstones of the usual Keweenawan aspect, grading above into the Lake Superior sandstone such as is found in horizontal attitude along the shore of the lake. On St. Louis River, Minnesota,[b] a similar transition occurs between red shales and brown sandstones. Clinton Point, where somewhat quartzose sandstones are found, does not belong to the Lake Superior sandstone but is the crest of a minor anticline in the lower beds. Nearly 2,000 feet of similar rocks lie some distance beneath the red shales on Fish Creek.

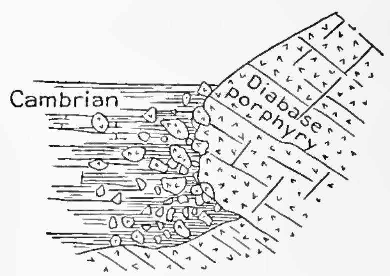

FIGURE 57.—Sketch showing unconformable contact between Keweenawan diabase porphyry and Cambrian sandstone at Taylors Falls, Minn. (After Strong.)

The contact with the flat-lying quartz sandstones (Lake Superior sandstone) along the north side of the area of middle Keweenawan in Douglas County has long been known to be a fault. The best exposures are on Black, Copper, Amicon, and Middle rivers. That on Middle River has been described above. At all other points the sandstone is turned up sharply for a short distance to the north of the fault, which dips, where exposed, 38° to 45° S. At all places the trap is intensely brecciated, but the sandstone is much less affected. On Black and Amicon rivers the sandstone is conglomeratic for a few feet from the contact. The pebbles are usually small and are not matched in the neighboring igneous rocks.

Within the trap breccias are found large blocks of sandstone. The view in the past has been that this contact was an unconformable one along a fault scarp, and that movement had taken place along the fault since the deposition of the sandstone, thus complicating the simple unconformable relations. An alternative view, supported by considerable evidence, is that the conglomerate has been faulted up by parallel faults from conglomerate found at lower horizons in the sandstone, and in part dragged up along the fault plane. The displacement must be at least equal to the thickness of the beds turned up at Middle River—3,100 feet.

The significance of the relations of the Keweenawan to the Lake Superior sandstone is discussed on pages 415–416.

KEWEENAWAN GRANITES OF FLORENCE COUNTY, NORTHEASTERN WISCONSIN.

The granite along the south side of the Florence district of northeastern Wisconsin is intrusive into green schists which are interbedded with upper Huronian slates. These granites are probably part of the same mass that intrudes the Quinnesec schist of the Menominee district, where the relations are similar. These granites of northeastern Wisconsin, therefore,

[a] Grant, U. S., Junction of Lake Superior sandstone and Keweenawan traps in Wisconsin: Bull. Geol. Soc. America, vol. 13, 1902, pp. 6–9.
[b] Winchell, N. H., A rational view of the Keweenawan: Am. Geologist, vol. 16, 1895, p. 150; Geology of Minnesota, vol. 4, 1899, p. 15.

like those south of the Cuyuna district in central Minnesota, are to be regarded as the plutonic equivalents of igneous flows. In both areas these plutonic masses have greatly metamorphosed the invaded strata.

NORTHERN MICHIGAN.

DISTRIBUTION.

The Keweenawan rocks of northern Michigan occupy a broad belt running continuously from Montreal River, the boundary between Michigan and Wisconsin, along the lake shore to the outer extremity of Keweenaw Point and including Manitou Island and Stannard Rock. This belt ranges in breadth from 15 or 20 miles west of Lake Gogebic to about 6 miles at the outer part of Keweenaw Point. Approximately one-half of Keweenaw Point is occupied by rocks of the Keweenawan series. The general strike roughly follows the coast. In passing from the southwest the strikes gradually change from about N. 45° E. to east-west, and at the extreme outer part of the point the rocks swing south of east, here having a northwesterly strike. This curved outer area of the end of Keweenaw Point beyond Portage Lake corresponds almost exactly with the strike of the rocks. Except in one fold in the Porcupine Mountains the dips are always to the north or northwest.

The dips of the middle and lower divisions are in general lower toward the east end of Keweenaw Point, the steepest dips ranging from nearly vertical on the Gogebic Range to 27° at the end of the point. There is a somewhat regular decrease in the dip of each of the sections in passing from lower to higher horizons. The best illustration of this is furnished by the section at Black River in Michigan, which shows a continuous succession from the base of the series to and including a part of the upper sandstone. According to Gordon,[a] at the base of the series the dips are from 75° to 78° N., whereas the highest strata show a dip of about 20° N. The change in dip in passing from the lower to the higher members is gradual. Further illustrations are furnished by the sections on Keweenaw Point; for instance, at the Portage Lake section the dips of the lower beds are as high as 55°, whereas in the lower part of the upper series they have dropped as low as 7°. At the outer part of Keweenaw Point the dips of the lowest part of the series there exposed are from 51° to 57°, but according to Hubbard,[b] the dips of the higher beds constituting the outer front of the point do not average more than 23°.

In this region, as in northern Wisconsin, the lower, middle, and upper Keweenawan are all represented. The general characterization which has been made for these divisions (see pp. 376–379) applies to the northern Michigan area.

The Keweenawan of Michigan will be more specifically discussed below.

KEWEENAW POINT.

SUCCESSION AND CORRELATION.

On account of the occurrence of great and valuable deposits of copper on Keweenaw Point, more detailed studies have been made of this than of any other of the Keweenawan districts, with the possible exception of Isle Royal. Areas which have been studied with considerable detail are the outer part of Keweenaw Point, especially Eagle River, by Marvine [c] and Hubbard;[d] Mount Bohemia, by Wright;[e] and the Portage Lake area, where the important deposits of copper occur, by Pumpelly[f] and Hubbard.[d] Studies of intermediate areas have been less detailed but still sufficient for Irving,[g] Seaman,[h] and others to attempt to correlate the different formations for Keweenaw Point. (See Pl. XXVIII.)

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[a] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Michigan Geol. Survey for 1906, 1907, p. 463.

[b] Michigan Geol. Survey, vol. 6, pt. 2, 1898, p. 53.

[c] Marvine, A. R., Geol. Survey Michigan, 1869–1873, vol. 1, pt. 2, 1873, pp. 47–61, 95–140.

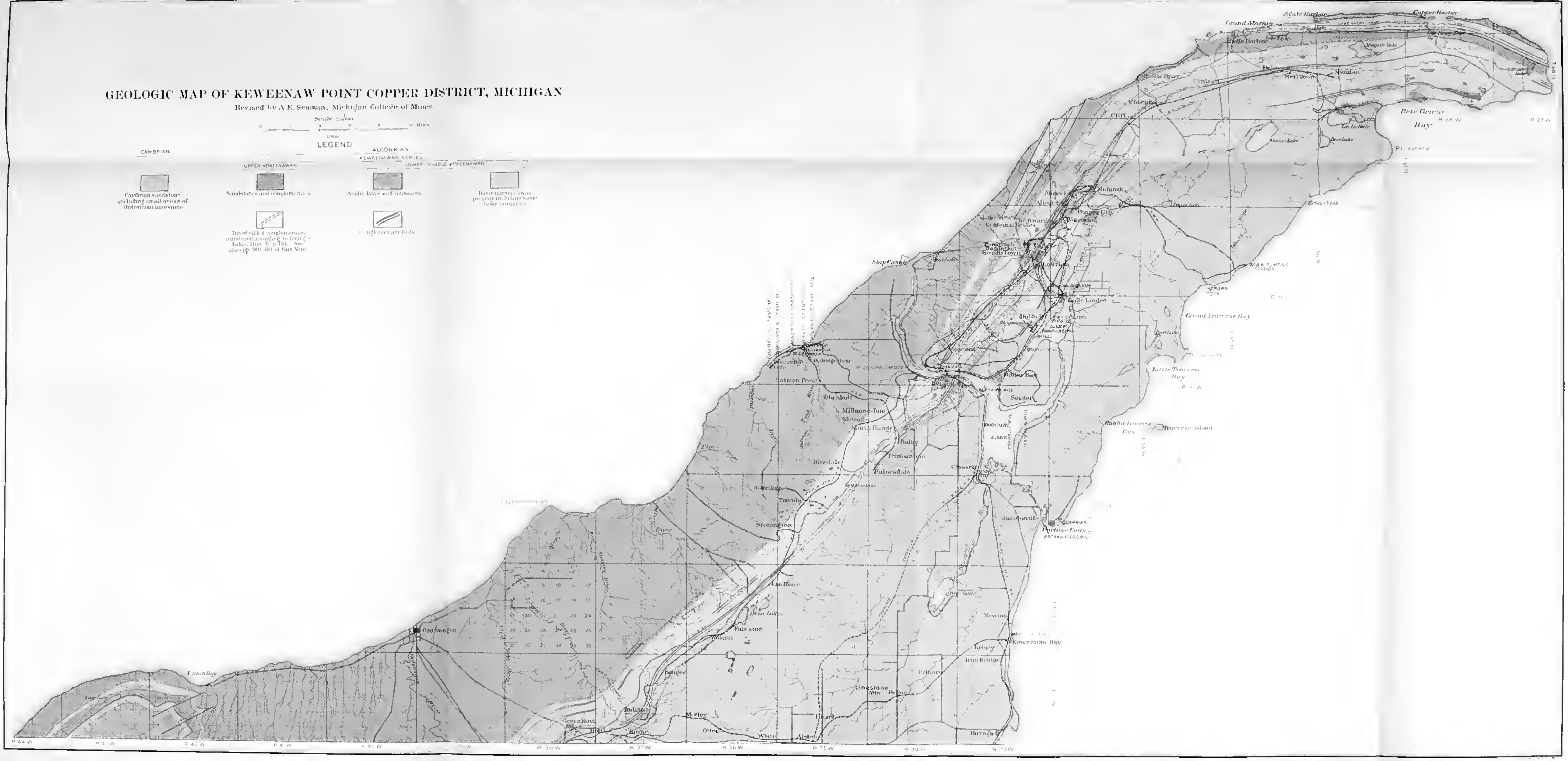
[d] Hubbard, L. L., Keweenaw Point, with particular reference to the felsites and their associated rocks: Geol. Survey Michigan, vol. 6, pt. 2, 1898.

[e] Wright, F. E., The intrusive rocks of Mount Bohemia, Michigan: Ann. Rept. Geol. Survey Michigan for 1908, 1909, pp. 361–402.

[f] Pumpelly, Raphael, Geol. Survey Michigan, 1869–1873, vol. 1, pt. 2, 1873, pp. 1–46, 62–94.

[g] Irving, R. D., Copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883.

[h] Jour. Geology, vol. 15, 1907, pp. 680–695.


GEOLOGIC MAP OF KEWEENAW POINT COPPER DISTRICT, MICHIGAN
Revised by A. E. Seaman, Michigan College of Mines
Scale
LEGEND
CAMBRIAN
ALGONKIAN
KEWEENAWAN SERIES
UPPER KEWEENAWAN
LOWER-MIDDLE KEWEENAWAN
Cambrian sandstone including small areas of Ordovician limestone
Sandstones and conglomerates
Acidic lavas and intrusives
Basic igneous lavas possibly including some basic intrusives
Interbedded conglomerates numbered according to Irving's table, Mon. V, p. 394. See also pp. 380-381 of this Mon.
Conglomerate beds
Agate Harbor
Copper Harbor
Grand Marais
Eagle Harbor
Eagle River
Central
Cliff
Phoenix
Bete Grise Bay
Lac La Belle
Mohawk
Ahmeek
Copper City
Lake View
Centennial Heights
Slap Cabin
Lake Linden
Grand Traverse Bay
Little Traverse Bay
Traverse Island
Hubbell
Dollar Bay
Senter
Redridge
Salmon Trout
Millman Jct.
South Range
Baltic
Trimountain
Painesdale
Atlantic
Chassell
Jacobsville
Portage Entry
Quarries
Toivola
Stronghton
Elm River
Twin Lakes
Paleston
Winona
Ontonagon
Keweenaw Bay
Kelsey
Iron Bridge
Newton
Limestone Mtn.
Pelkie
Baraga
Greenland
Mass
Rockland
Molley
Alston
White
Otter
R 44 W
R 42 W
R 41 W
R 40 W
R 38 W
R 37 W
R 36 W
R 35 W
R 34 W
R 33 W
R 28 W
R 27 W

Below are given the successions of Irving[a] for the entire point and of Hubbard[b] for the outer part of the point, with their correlation.

Sections of rocks on Keweenaw Point.

Irving.	Hubbard.
12. Eastern sandstone. *Keweenaw series.* Upper division: 11. Red sandstone. 10. Black shale and gray sandstone ("Nonesuch belt").	
9. Red sandstone and conglomerate ("Outer conglomerate").	Outer conglomerate.
Lower division: 8. Diabase and diabase amygdaloid, including at least one conglomerate belt ("Lake Shore trap").	Lake Shore trap (upper). Middle conglomerate. Lake Shore trap (lower).
7. Red sandstone and conglomerate ("Great conglomerate").	Great conglomerate.
6. Diabase and diabase amygdaloid, including several sandstone belts (Marvine's "Group C" of the Eagle River section). 5. Diabase and diabase amygdaloid, including conglomerates. 4. Luster-mottled melaphyres and coarse-grained gabbros and diabases ("Greenstone group").	Ophites and porphyrites with interbedded conglomerates and sandstones.
3. Diabase, diabase amygdaloid, and luster-mottled melaphyre, including a number of conglomerate beds.	Melaphyres and interbedded conglomerates.
2. Quartz porphyry and felsite.	(*a*) Bohemia conglomerate. } Locally Mount Houghton felsite replaces *a* and *b*. (*b*) Melaphyre. (*c*) Porphyrite and felsite porphyrite.
1. Diabase, diabase amygdaloid, melaphyre, diabase porphyry, and orthoclase gabbro, including also conglomerate beds and beds or areas of quartz porphyry and granitic porphyry ("Bohemian Range group").	Ophite belt. Lac la Belle conglomerate.

LOWER AND MIDDLE KEWEENAWAN OF KEWEENAW POINT.

ORDER OF EXTRUSION.

Hubbard[c] has studied the order of extrusion for the outer part of Keweenaw Point. He finds the oldest lavas to be melaphyres and these are interstratified with melaphyre conglomerates. Following the melaphyres are porphyrites and interstratified with the porphyrites are porphyrite conglomerates. Next come the felsites and interstratified with these and above them are the felsite conglomerates. All these rocks are at very low horizons. Above them lies a great mass of melaphyres, ophites, and porphyrites with their various interbedded conglomerates and sandstones. Still higher are the "Great" conglomerate and the "Lake Shore" trap with the "Middle" conglomerate. Thus Hubbard's studies of Keweenaw Point led him to the conclusion that there was a regular order of extrusion of the igneous rocks—(1) basic melaphyres, (2) intermediate porphyrites, (3) acidic felsites and porphyries, and (4) the upper basic rocks represented by melaphyres, ophites, porphyrites, etc.

PRESENCE OF BASIC INTRUSIVE ROCKS.

Curiously the descriptions of the basic rocks of Keweenaw Point mention no interstratified intrusive sills, all the basic rocks being assumed to be flows. However, certain groups, as for instance the greenstone group, are described as contrasting sharply with the rocks above and below them. They contain no intercalated amygdaloidal beds. They consist of massive layers. In texture they vary from diabases to gabbros. Although this and other masses were not sufficiently examined to make any positive assertion possible, it is our impression that a large part of the greenstone is an intrusive sill. The other masses of rocks which have been described as gabbro or orthoclase gabbro, especially those on the southwestern part of the point, are intrusive.

[a] Mon. U. S. Geol. Survey, vol. 5, 1883, Pl. XVII. [b] Geol. Survey Michigan, vol. 6, pt. 2, 1898, Pl. IV. [c] Op. cit.

On Mount Bohemia the intrusive gabbro has produced contact effects on the invaded ophites. The problem of separating the intrusive basic rocks from the extrusives remains partly to be accomplished.

ACIDIC INTRUSIVE ROCKS.

Hubbard's[a] studies show that the felsites of Bare Hill and West Pond at very low horizons are intrusive. The felsite of Bare Hill, when mapped in detail, is seen to cut across the beds of other rocks, although in a single section near its center it would seem to be interstratified. The felsite of West Pond has disturbed the beds in its immediate area. They are broken into fragments and in places are even changed into typical breccias, some of which are almost undistinguishable from the conglomerates. These intrusive rocks were perhaps correlative with the extrusive felsites of Mount Houghton and others of approximately the same age found at higher horizons. The intrusive nature of these felsites explains the absence of pebbles derived from them in the melaphyre conglomerates interstratified with the melaphyres adjacent to and at horizons above the felsites. While some of the felsites and porphyries are extrusive, even these have a very minor extent. This is very well illustrated at Mount Houghton, where the felsite locally replaces the "Bohemia" conglomerate and the melaphyre flow below. (See preceding table.)

NATURE AND SOURCE OF DETRITAL MATERIAL.

It is well known that the felsite and porphyry pebbles are very prevalent and in places dominant in the numerous conglomerate beds interstratified with the basic rocks at the higher horizons of Keweenaw Point, and even in the "Great" conglomerate, "Middle" conglomerate, and "Outer" conglomerate. There seems to be an enormous amount of felsite and porphyry detritus in the sediments as compared with the known original areas from which it may have been derived. Doubtless a part of the acidic detritus of Keweenaw Point may have been derived from porphyries farther east and west than the point, as, for instance, those of the Stannard Rock area to the east and the Porcupine Mountains to the west. But also the lack of large areas of felsites may be due to the exceptional erosion to which they have been subjected because of their viscous and bunchy character, which raised them and made them the objects of excessive attack. Finally, a considerable portion of the acidic detritus may have been in the form of volcanic fragmental material that was scattered far and wide from the original cones from which it was ejected and therefore never formed a part of any continuous solid intrusion or extrusion.

Lane[b] states that the detritus of several conglomerates, especially of the "Great" conglomerate, includes numerous pebbles of intrusive red rock and gabbro. He says that if he is correct in his identification of the materials there is evidence of an erosion of sufficient magnitude during middle Keweenawan time to expose these plutonic rocks at the surface. He also finds agate pebbles which he believes to have formed in the lavas lower in the series, and thus he concludes that extensive metasomatic changes have taken place in this part of the series before the higher interstratified conglomerates were laid down.

VARIATIONS IN THICKNESS OF SEDIMENTARY BEDS.

Close studies of Keweenaw Point show rapid variations in the thickness and character of the interstratified sedimentary beds. These have been especially studied in the mineralized area. Many illustrations could be given, but perhaps one of the clearest is that of the "Great" conglomerate which Hubbard[c] says thins 400 to 700 feet in passing from Copper Harbor to a point 7 miles farther east. Not only do the beds change in their character, but a single sedimentary bed may be split into several beds separated by lava flows. Thus in the Bohemia basin a conglomerate is first split into two parts by a bed of melaphyre and the lower part is in turn split into two beds by a mass of felsite. The beds are in general lenticular, broadly considered, but some of these lenses may be only a few miles in length, as illustrated by the Calumet and Hecla conglomerate.

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[a] Hubbard, L. L., Michigan Geol. Survey, vol. 6, pt. 2, 1898, pp. 35, 43.
[b] Lane, A. C., Geology of Keweenaw Point: Proc. Lake Superior Min. Inst., vol. 12, 1907, p. 93.
[c] Op. cit., p. 64.

FAULTS.

Hubbard's [a] detailed studies of small areas have led also to the conclusion that the middle Keweenawan has been displaced by a very large number of dip faults, the throws of which, however, are of minor extent. These have been worked out in great detail with reference to the melaphyre and melaphyre conglomerates at West Pond. Here are figured no less than twelve cross faults, the throws of which, however, are not sufficiently great to be traced into the thick overlying formations, and hence they do not appear on his general map. Similarly Lane [b] states that there are a large number of small transverse faults in the mining district. The throws of most of these faults are not more than 25 feet and very few exceed 50 feet. However, the presence of many faults at each of the two areas that have been closely studied on Keweenaw Point suggests very strongly that when like thorough studies are made of other areas on this point similar faulting will be found.

In the mining district there are also many slide faults. According to Lane,[c] the dip of many of these slide faults is somewhat steeper than the bedding, so as to cut diagonally across the beds at acute angles. As to the direction of movement along these dip faults, he thinks it is more commonly down than up on the hanging-wall side, for beds are more likely to be cut out than repeated. Hubbard[a] described one very important slide fault, the major movement of which, instead of being parallel to the dip, is nearly parallel to the strike. This is the fault at the top of the Kearsarge conglomerate, which is well illustrated in the Central mine. Hubbard makes a calculation of throw and reaches the conclusion that "the part of the Keweenawan series that lies above the Kearsarge conglomerate has moved from its original position, in a northerly direction, horizontally, about 2.7 miles, or along an inclined plane its equivalent distance of about 2.9 miles." Such a slide fault as this approaches the ordinary strike faults, the chief difference being that of hade, the bedding fault having such a hade as not to intersect the bedding, whereas ordinary strike faults do intersect the bedding. Although the Kearsarge slide fault is nearly in the direction of the strike, it is believed to be probable that the most common direction of movement in the faults of this area is parallel to the dip. In this case the movements are largely explained by the natural adjustments which are necessary when a set of beds is folded.

UPPER KEWEENAWAN.

The upper Keweenawan consists, from the base upward, of three members—(1) the "Outer" conglomerate, (2) the Nonesuch shale, and (3) the Freda sandstone.

The "Outer" conglomerate is found at the north side of the east end of Keweenaw Point as far as Gate Harbor, where it passes under the water; it reappears on the point some miles west of Eagle River and continues along to the point and westward through Michigan into Wisconsin. It is in no respect different from the underlying "Great" conglomerate or other conglomerates interstratified with the Keweenawan, except that, according to Lane,[d] it contains near its top fragments derived from the jaspery and other Huronian formations.

The Nonesuch formation ranges from a soft, fine-grained, highly argillaceous shale to a sandstone. The shale is predominant, the sandstones being interbedded. In color the shale is dark purplish gray to nearly black and the sandstone dark gray to black. The thin sections of the sandstones show detritus from the porphyries and other acidic original rocks of the Keweenawan. With these materials in all the sections is mingled more or less basic detritus. Indeed, the basic material is usually abundant and not uncommonly becomes dominant. The basic material is more abundant in the darker-colored rocks. In these rocks there is also a plentiful calcite

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[a] Hubbard, L. L., Michigan Geol. Survey, vol. 6, pt. 2, 1898, pp. 87-91.
[b] Lane, A. C., Geology of Keweenaw Point: Proc. Lake Superior Min. Inst., vol. 12, 1907, pp. 83-84.
[c] Idem, pp. 84-85.
[d] Lane, A. C., Jour. Geology, vol. 15, 1907, p. 690.

cement filling all interstices between the fragments. The basic detritus appears in the shape of particles of the basic rocks, showing more or less plainly the several ingredients, always much altered, and of particles of the single minerals—augite, almost wholly altered to a greenish substance, triclinic feldspar, and magnetite. The formation also contains materials which must have been contributed by the Huronian, Keweenawan, and Laurentian rocks. The Nonesuch shale therefore differs from the sediments interstratified with the Keweenawan in the greatly decreased amount of acidic material, the abundance of basic material, and the presence of detritus derived from other formations than the Keweenawan.

The Freda sandstone is in no respect different from the sandstone of the larger areas in Wisconsin, which are a continuation of the sandstone in Michigan. It need here be only remarked that the materials have the same varieties of sources as the Nonesuch shale, but the materia derived from the basic lavas seems to be even more prominent.

RELATIONS TO CAMBRIAN ROCKS.

On the north and west sides of the Keweenawan the series nowhere comes into contact with the Cambrian. The possible relations between the two are discussed in another place. (See pp. 415–416.)

On the southeast side the Keweenawan is in contact with the Cambrian. Irving and Chamberlin,[a] in their bulletin on this contact, conclude that the sandstone was deposited unconformably against an ancient fault scarp of Keweenawan rocks and that it was subsequently faulted down along the old fault plane. This relation is apparently similar to those observed at the fault on the north side of the Keweenawan syncline in Douglas County, Wis., and thence southwestward into Minnesota.

MAIN AREA WEST OF KEWEENAW POINT, INCLUDING BLACK RIVER AND THE PORCUPINE MOUNTAINS.

A very detailed study of the entire Keweenawan section at Black River has been made by Gordon.[b] According to him, this river shows the following descending succession,[c] the classification into middle and lower Keweenawan being added by us.

Section of Keweenawan rocks at Black River, Mich.

	Feet.	
Upper Keweenawan:		
I. Upper sandstone lacking.		
II. Nonesuch formation	500	
III. Outer conglomerate	5,000	
		5,500
Middle Keweenawan:		
IV. Lake Shore trap, consisting of five flows, having from the top downward the following thicknesses: 35, 35, 115, 85, 130 feet, respectively	400	
V. Conglomerate	350	
VI. Mixed eruptives and sedimentaries	5,500	
VII. Felsite	450	
VIII. Eruptives with very few sedimentaries	26,000	
IX. Mixed eruptives among which are conspicuous labradorite porphyrites	4,800	
X. Gabbro	200	
XI. Melaphyres and labradorite porphyrites that are not conspicuous	4,500	
		42,200
Lower Keweenawan:		
XII. Basal sandstone		300
		48,000

[a] Irving, R. D., and Chamberlin, T. C., Observations on the junction between the Eastern sandstone and the Keweenaw series on Keweenaw Point, Lake Superior: Bull. U. S. Geol. Survey No. 23, 1885.

[b] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Michigan Geol. Survey for 1906, 1907, pp. 397-507.

[c] Idem, p. 421.

Throughout the Black River section there is no evidence of a physical break in the Keweenawan. Lane,[a] because of the character of the formation, suggests that possibly there might be a slight break at the base of the Nonesuch shale, but Gordon's detailed descriptions give no evidence in support of this view.

It is known that in this district dip faults occur. According to Gordon,[b] at least four such faults traverse the Trap Range north of Bessemer, the throws of three of which are 80, 350, and 1,500 feet, the throw of the fourth not being determinable. It is very likely that strike faults occur, for great strike faults occur elsewhere in the Keweenawan. (See p. 383.) Though such faults have not been detected, they may very readily occur at any of the very numerous stretches of the river where exposures are lacking. The presence of faults at these places is very probable because of the brecciation and consequent more easily erosible condition of rocks along fault planes.

In the Porcupine Mountains the same divisions of rocks occur as in Keweenaw Point, but the order is only in a general way similar to that on the point, the difference being that comparatively high in the series are large masses of quartz porphyry and felsite, and the acidic rocks at these horizons perhaps largely explain the source of the abundant felsite, quartz porphyry, and augite syenite pebbles in the "Great," "Middle," and "Outer" conglomerates.

In the Porcupine Mountains the great synclinal basin of Lake Superior, which controls the general dip of the Keweenawan rocks about the lake, is disturbed by a subordinate fold, so that in a section diagonally northeast and southwest across the mountains the lower beds are regarded by Irving[c] as repeated. He shows a subordinate anticline and syncline between the monoclinal beds north of Lake Gogebic, at the south side of the middle division and the northward-dipping beds at the lake. This area is a forest-covered one in which the exposures are somewhat imperfect, and it is hinted by Hubbard[d] that possibly the abundant felsite and porphyry here are intrusive, as they are at Bare Hill and West Pond, and that the unusual structure may be explained by these intrusive masses rather than by exceptional orogenic movement. This suggestion is made because of very considerable disturbances in the regular bedding of the rocks about the intrusive felsite of Bare Hill. The Porcupine Mountains are now being studied in detail by F. E. Wright for the Michigan Geological Survey, but the results of his work have not been available in the preparation of this monograph.

The upper Keweenawan of this area is the same in all respects as that described for Keweenaw Point.

THE SOUTH RANGE.

Beginning in T. 47 N., R. 44 W., Michigan, from the lower Keweenawan, which there consists of diabase, diabase amygdaloid, melaphyre, and a few coarse interbedded thin conglomerates, an arm projects to the east and south nearly to Gogebic Lake and east of this lake again for some distance. This is the so-called South Range. It is separated from the main range of the Keweenawan by the Jacobsville or "Eastern" sandstone. At the eastern point the South Range is 18 miles south of the northern area of the Keweenawan. This range varies from less than half a mile to 2 miles or more in breadth. The rocks of the South Range dip to the north at angles of 30° to 50°. At some places at the base of the Keweenawan series in the South Range there is a coarse sandstone. At other places the lowest rock is a basic lava. Locally sediments are interstratified with the lavas. Thus the conditions prevalent in early Keweenawan time, as indicated by the rocks at the base of the Keweenawan of the South Range, are similar to those of other districts. In no respects do these rocks differ from those near the base of the Keweenawan to the west. West of Gogebic Lake the Keweenawan rocks rest directly upon the upper Huronian. The western part of this belt of Keweenawan rests directly upon the Tyler slate. When followed to the east it is seen to pass diagonally to lower and lower horizons, until at Sunday Lake it is in contact with the Ironwood formation. These relations have been more fully described in connection with the Penokee district.

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[a] Lane, A. C., Jour. Geology, vol. 15, 1907, p. 691.
[b] Op. cit., pp. 464-465.
[c] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 209-225.
[d] Hubbard, L. L., Geol. Survey Michigan, vol. 6, pt. 2, 1898, pp. 5-8.

It is believed that the separation of the South Range from the main range is due to a great strike fault between the two which results in a repetition of the beds of the main range in the South Range.

ROCKS OF POSSIBLE KEWEENAWAN AGE IN OUTLYING AREAS.

Certain reddish feldspathic and little-consolidated sandstones of low dip, lying unconformably across the end of the upper Huronian of the Felch Mountain trough, may possibly be classed as Keweenawan. Similar rocks are known also in the Sturgeon trough to the north.

THICKNESS OF THE KEWEENAWAN OF MICHIGAN.

Irving[a] gives an estimate of the thickness of the Keweenawan of northern Michigan at Eagle River and Portage Lake, and Gordon[b] estimates a section on Black River.

EAGLE RIVER SECTION.

Irving's section at Eagle River,[c] based largely on the detailed work of Marvine, is as follows:

Section of Keweenawan rocks at Eagle River, Michigan.

	Feet.
Upper division:	
Outer conglomerate; porphyry conglomerate and sandstone; about	1,000
Lower division:	
Lake Shore trap; very plainly bedded fine-grained diabases, strongly marked amygdaloids, and one or more thin porphyry conglomerates; about	1,500
Great conglomerate; porphyry conglomerate and sandstone	2,200
Marvine's group "c;" plainly bedded and separable fine-grained diabases, with strongly marked amygdaloids, predominatingly calcitic; and some 850 to 900 feet, in all, of interstratified sandstones	1,417
Marvine's group "b," or the Ashbed group; made up mostly of thin, fine-grained diabases, which vary a good deal in appearance, but are generally provided with distinct amygdaloids; including some beds of the peculiar type known as ashbed diabase; also several scoriaceous amygdaloids, being intermingled sandstone and amygdaloid; also one thin sandstone seam	618
Marvine's group "a;" made up of relatively heavy beds without strongly developed amygdaloids; including one thin seam of sandstone	925
Greenstone group; made up of relatively heavy beds, without amygdaloids, of rocks for the most part relatively coarse grained; these belong mostly to the coarse-grained olivine-free diabases and gabbros and to the luster-mottled melaphyres, or fine-grained olivine-diabases, the greenstone at the base of the group being of the last-named class	1,200
Subgreenstone group, in which all of the fissure-vein mines are working; having at top a thin conglomerate, the equivalent of the "Allouez" and "Albany and Boston" conglomerates in the Portage Lake district; composed of fine-grained diabases, with not very strongly developed amygdaloids; about	1,600
Central Valley beds; the layers not well exposed, but evidently chiefly fine-grained diabases and amygdaloids, with a number of thin porphyry conglomerates, in all respects like the overlying group; about	5,540
Bohemian Range beds; made up chiefly of diabases and melaphyres in all respects like the higher layers, and including some of the usual porphyry conglomerates; but also in part made up of quartziferous porphyry, felsite, nonquartziferous porphyry, and coarse-grained orthoclase gabbro; in all, about	10,000
	26,000

Of this thickness, the "Great" conglomerate and the ten conglomerates and sandstones in "group c" together constitute 3,100 feet. These sediments are all in the upper 5,000 feet of the lower Keweenawan. The lower part contains only a few seams of detrital material. The lower five-sixths of the lower Keweenawan for this section is therefore almost exclusively volcanic, and of the total lower Keweenawan somewhat less than one-ninth is sedimentary, the remaining eight-ninths being igneous.

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 166–197.

[b] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Michigan Geol. Survey for 1906, 1907, p. 421.

[c] Irving, R. D., op. cit., pp. 186–187.

PORTAGE LAKE SECTION.

At Portage Lake the section is as follows:

Section of Keweenawan rocks at Portage Lake.[a]

	Feet.
Upper division:	
Largely covered, but apparently for the most part red shales and sandstone; toward the base there is a considerable thickness (upward of 200 feet) of dark-colored, fine-grained sandstone and black shale, in which the usual porphyry detritus is mingled with more or less basic detritus; the lowest layers are also conglomeratic; in all about	9,000
Lower division:	
Covered space of some 1,200 feet, in which must be the equivalents of the outer trap of the eastern part of Keweenaw Point, corresponding to a thickness of about	500
The Great conglomerate, including the sandstone and conglomerate at the Atlantic mill and conglomerate 22 on the south side of Portage Lake, with some intervening exposures, about	1,500
Diabase	66
Conglomerate 21	15
Diabase and amygdaloid	51
Conglomerate 20	19
Diabase	100
Conglomerate 19	13
Diabase	94
Conglomerate 18	155
Diabases and amygdaloids	340
Conglomerate 17 (Hancock West)	32
Diabases and amygdaloids; including the South Pewabic cupriferous amygdaloid at 50 feet below 17	550
Conglomerate 16 (not seen on south side of Portage Lake)	10
Diabases and amygdaloids; including, at 400 feet above conglomerate 15, the Pewabic cupriferous amygdaloid or "lode" so largely worked for copper on the west side of Portage Lake	900
Conglomerate 15 (Albany and Boston conglomerate on the north side of Portage Lake)	33
Diabases and amygdaloids	330
Conglomerate 14 (the Houghton conglomerate of the north shore)	2
Diabases and amygdaloids	1,460
Conglomerate 12 (north side of Portage Lake)	3
Diabases and amygdaloids	680
Conglomerate 11	20
Diabases and amygdaloids	200
Conglomerate 10	60
Diabases and amygdaloids	460
Conglomerate 9 (sandstone seam).	
Diabases and amygdaloids; including, at 670 feet above conglomerate 8, the Grand Portage cupriferous amygdaloid, and at 510 feet the Isle Royal cupriferous amygdaloid, largely worked on the south shore ot Portage Lake	2,050
Conglomerate 8	12
Diabases and amygdaloids	420
Conglomerate 7	24
Diabases and amygdaloids	260
Conglomerate 6	3
Diabases and amygdaloids	181
Conglomerate 5	24
Diabases and amygdaloids	240
Conglomerate 4	12
Diabases and amygdaloids	1,149
Conglomerate 3	56
Diabases and amygdaloids	370
Conglomerate 2	35
Diabases and amygdaloids	1,140
Conglomerate 1	97
Amygdaloid	14
	22,680

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 194-195.

In the above section of the lower Keweenawan the thickness of the conglomerates amounts to 2,125 feet, leaving 11,555 feet for the igneous rocks. Thus the lower Keweenawan is about one-sixth sediment and about five-sixths igneous.

The Portage Lake section differs in one important respect from the Eagle River section. At Portage Lake the interstratified conglomerates extend to the bottom of the section, whereas at Eagle River the conglomerates and sandstones do not occur in the lower five-sixths of the section, the thickness of which as a whole is about the same as at Portage Lake.

BLACK RIVER SECTION.

In the Black River section the total thickness, according to Gordon,[a] is 48,000 feet. Irving[b] estimates the thickness of the upper sandstone at Montreal River, a few miles west of Black River, at 12,000 feet. This part of the section is absent on Black River, and if it were added to the Black River section this would give for this district a thickness of 60,000 feet for the entire Keweenawan series.

In the middle Keweenawan of the Black River section (p. 384) the sediments are mainly in the upper 6,000 feet, and of this amount sediments are known to make up 575 feet, distributed as follows:

		Feet.
In V, conglomerate		350
In VI, mixed eruptive and sedimentary rocks:		
Sandstone	30	
Conglomerate	20	
Sandstone	25	
Sandstone	30	
Sandstone	20	
Conglomerate	100	
		225
		575

As a space corresponding to 3,000 feet is not exposed, doubtless the total thickness of the sediments is much greater than this, though a part of this 3,000 feet is certain to be volcanic. However, the addition of all of it would make the maximum possible thickness of sediment 3,575 feet. Thus the sediments at most make up only about one-twelfth of the middle Keweenawan and are largely concentrated in the upper sixth of the division.

The question now arises whether this apparent thickness for the several sections represents the real thickness of the series as laid down. It is believed to be probable that the real thickness is less than the apparent thickness. The reasons for this belief apply as well to the estimated thicknesses of other districts, and therefore they are given later. (See pp. 418–419.)

RELATIONS OF THE KEWEENAWAN OF MICHIGAN TO UNDERLYING AND OVERLYING FORMATIONS.

The only locality in which the relations of the Keweenawan with the underlying formations are shown is in the Penokee-Gogebic district. It has been stated (pp. 234–235) that these relations are those of unconformity, erosion amounting to several thousand feet having taken place after Huronian time and before the deposition of the Keweenawan. Still, the strike and dip of the two series are very nearly the same, and the greatness of the break between the two appears only by their stratigraphic relations.

The Upper Cambrian ("Eastern") sandstone comes against the lower part of the Keweenawan from the outer end of Keweenaw Point to the region west of Gogebic Lake. It is agreed by all who have studied this contact that it marks a great fault. The Keweenawan along the contact has its usual steep northern dips. The sandstone at the contact is bent and locally broken, so that it strikes and dips in various directions, in some places dipping away from the

[a] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Michigan Geol. Survey for 1906, 1907, p. 421.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, p. 230.

Keweenawan and in others apparently dipping under it. A short distance away from the Keweenawan, usually within a few hundred feet, the sandstone assumes its normal horizontal attitude.

At only a few localities has the Upper Cambrian sandstone been found in close relations with the rocks of the South Range. Irving[a] concluded that in the South Range this sandstone rests unconformably against the Keweenawan rocks. However, the particular locality he described as showing unconformable relations has been interpreted differently by Seaman,[b] who finds there a dike of igneous rock penetrating the so-called "Eastern" sandstone and spreading out above. Seaman regards the "Eastern" sandstone here as probably Keweenawan and believes that there is no way of proving that it is of different age from the "Western" sandstone (upper Keweenawan).

ISLE ROYAL.

Isle Royal is 45 miles in length and varies in width from 3 to 8 miles. From the Rock of Ages, the farthest outlying reef to the southwest, to the Gull Island rocks on the northeast, the distance is 57 miles. The island lies off Thunder Bay, northwest of the outer part of Keweenaw Point. The strike of Isle Royal and Keweenaw Point are substantially the same, northeast and southwest. This island has been mapped geologically by Lane.[c] His succession in descending order is as follows:

Section of Keweenawan rocks on Isle Royal.

Sandstone and conglomerate ("the Great conglomerate"?).
Ophites down to Island mine conglomerate (Marvine's group C).
Intercalated sandstones and conglomerates.
Melaphyre porphyrites and scoriaceous conglomerates ("Ashbed" group).
"The greenstone"—thickest ophite.
Amygdaloids and thin ophites down to Minong breccia (Kearsarge conglomerate).
Minong porphyrite and Minong trap.
Ophites and conglomerates, including Huginnin porphyrite, down to felsite.

It is clear from the general character of the succession that it is like that of the middle Keweenawan of the remainder of the Lake Superior region; that is to say, it consists of igneous rocks and sediments. The igneous rocks are dominantly basic. They are all regarded as extrusive by Lane.[d]

However, the same question may be raised with reference to the greenstone, which is given a thickness of 233 feet, as was raised concerning that of Keweenaw Point. Is it an extrusive or is it a later intrusive? Certainly it has all the characteristics of the diabase of Beaver Bay on the Minnesota coast, which is almost certainly intrusive.

The intercalated sandstones and conglomerates, from lowest to highest, contain a much greater proportion of material from acidic rocks than would be expected from the small proportion of original acidic rocks. The sandstones and conglomerates are subordinate in amount in the major portion of the section and only become of great volume with the appearance of the "Great" conglomerate. The field terms for the igneous rocks and their relations are expressed by Lane[d] as follows:

Felsite		Melaphyre
		Trap—nonamygdaloidal dark rocks
	Amygdaloid	
Porphyry	Porphyrite	Ophite

Lane[e] gives one very detailed section based largely on drill records. Its thickness is 9,000 feet. In this section the felsite flows are confined to the lower 150 feet, but at a high horizon one bed of porphyry tuff 10 feet thick is noted. This tuff may be regarded as a confirmation

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 360-361.
[b] Personal communication.
[c] Lane, A. C., Geological report on Isle Royale, Michigan: Geol. Survey Michigan, vol. 6, pt. 1, 1898, 281 pp.
[d] Idem, p. 53.
[e] Idem, pp. 27 et seq.

of the suggestion made in another place (p. 382) that volcanic fragmental rocks of the acidic type are much more abundant in the Keweenawan than had been supposed. Most of the interstratified sedimentary beds are conglomerates and, with three exceptions, they range from a knife-edge to 50 feet in thickness. Two of the thicker beds are mainly sandstone. In addition to a number of seams which were too small to be measured, the total number of sedimentary beds in the district is 24 and the total thickness is 430 feet. To the "Great" conglomerate is given a thickness of 2,600 feet, making a total thickness of sediments of 3,030 feet. This leaves 5,970 feet for the lavas.

In the matter of correlation, Lane[a] assumes that the thick conglomerate at the top of the series is a continuation of the "Great" conglomerate of Keweenaw Point, and with this horizon as a starting point he attempts to correlate somewhat closely the beds of Isle Royal with those of Keweenaw Point, as is indicated by the succession given on page 389, the names in parentheses being those of formations on Keweenaw Point. Although it is probable that the top conglomerate corresponds to the "Great" conglomerate of Keweenaw Point, and although it may be possible that the formations are to some extent equivalent, it may perhaps be doubted whether the correlation of individual thin beds, such as the interstratified conglomerates, is justified, especially as there is so remarkable a likeness in the petrography of the beds of the Keweenawan at different horizons in the several districts of Lake Superior. If the bed of greenstone more than 200 feet thick is really intrusive, as suggested, its correlation with the greenstone of Keweenaw Point on a stratigraphic basis is very questionable.

In any section on Isle Royal there is a lessening of the dip in passing from lower to higher horizons, just as at Keweenaw Point and at Michipicoten. For instance, at the west end of the island on the north side the dips are 16° S. and on the south side in the "Great" conglomerate 8° S., a difference of 8°. Toward the east end of the island the dips on the north side are 26° and on the south side 18°, again a difference of 8°.

MICHIPICOTEN ISLAND.

The following account of Michipicoten Island is taken almost wholly from Burwash,[b] who alone has made a close study of this area. However, it should be said that Logan's general account of this district[c] is remarkably accurate.

The island is roughly ellipsoidal in shape, about 16⅝ miles long by 6 miles in greatest width. Its longer axis lies east and west parallel to the coast, and its west end is south and a little west of Pukaskwa River.

The Keweenawan rocks occupy the entire island as well as the row of smaller islands off its south shore. They are confined wholly to the middle Keweenawan. The igneous rocks overwhelmingly dominate in mass. They are described as extrusive, no intrusive rocks being mentioned. Lithologically they include all the varieties of the ordinary extrusive rocks, ophitic and diabasic melaphyres, amygdaloids, porphyrites, felsites, and quartz porphyries. The acidic rocks are much more readily eroded than the basic rocks. In consequence they usually occupy depressions, whereas the basic rocks constitute the ridges. In this respect there is a contrast between Michipicoten Island and Keweenaw Point, where the acidic rocks constitute elevations. It may be suggested that the difference is due to the fact that the Michipicoten acidic rocks are largely extrusive, while those of Keweenaw Point are largely intrusive. No order of extrusion of the lavas is suggested, the acidic and basic rocks both occurring from the highest to the lowest horizons. As to volume, there does not seem to be much difference between the basic and acidic varieties. Selwyn and Coleman state that pyroclastic rocks occur on Michipicoten Island, but such rocks were not observed by Burwash[d] and if present are certainly extremely insignificant in amount. The lava beds attain their maximum thickness in the eastern and central parts of the island and are thinner toward the

[a] Lane, A. C., Geological report on Isle Royale, Michigan: Geol. Survey Michigan, vol. 6, pt. 1, 1898, pp. 99 et seq.
[b] Burwash, E. N., The geology of Michipicoten Island: Univ. Toronto Studies, Geol. ser., No. 3, Toronto, 1905, with map.
[c] Logan, W. E., Report of progress to 1863, Geol. Survey Canada, 1863.
[d] Op. cit., pp. 27, 47.

west, where they are interstratified with the conglomerates. The lower beds strike approximately northeast and southwest. In passing to higher horizons the strike approaches east and west. Thus there is an appearance of minor unconformity between the lower and upper beds.

The débris of the conglomerates is as usual derived largely from the acidic rocks, but with them are included granites, greenstones, and biotite gneisses derived from pre-Keweenawan formations. Abundant material derived from the basic rocks is also recognized. The sedimentary rocks occur mainly at lower horizons, although one conglomerate is found at a comparatively high horizon. These conglomerates are confined to the northwestern part of the island, being thickest at the west and thinning out to the northeast.

These facts suggest that the central and eastern parts of the island formed a center of volcanic dispersion, that the lavas flowed toward the west, and that in the part of the area somewhat removed from the main volcanic outbursts there was opportunity to build conglomerates between the successive lava flows.

The dip of the beds on the north and northwest sides of the island is 55° S. From this there is a steady decrease in dip until on the islands off the south shore of Michipicoten the dips are about 14° S., the lessening of dip across the series being therefore 40°.

Burwash[a] gives the following descending succession:

Section of Keweenawan rocks on Michipicoten Island.

	Feet.
1. Felsite of islands off the south shore	1,000
2. Pitchstone bed	530
3. Quartzless porphyry of Quebec Harbor	695
4. Melaphyre porphyrites of Channel Lake	1,660
5. Quartz porphyries: 1	355
2	1,160
3	1,493
6. Beds exposed at lake on road	1,575
7. Felsite	513
8. Diabase porphyrite	463
9. Beds underlying farm (three)	1,140
10. Several beds at mine	645
	11,230

This result, obtained by accurate measurement of three sections and by careful studies, is a remarkable confirmation of the judgment of Logan,[b] who states that the thickness of the formations developed in Michipicoten Island, at the most moderate dips observed, would not fall far short of 12,000 feet.

It is stated that on the mainland near the mouth of Pukaskwa River there are rocks of Keweenawan age, and this leads to the suggestion that the Keweenawan constitutes a monoclinal succession from the north shore of Lake Superior to the south side of Michipicoten. For the intervening distance between the mainland and the island an estimated thickness is given of 34,000 feet, and thus a suggested thickness for the entire Keweenawan series of 45,000 feet. But it seems to us more probable that between Michipicoten Island and the main shore there is a strike fault and that therefore the Michipicoten rocks may be near the bottom of the Keweenawan series. This idea is perhaps confirmed by the presence in the conglomerates of the Michipicoten district of material from pre-Keweenawan sources.

EAST COAST OF LAKE SUPERIOR.

Several prominent points along the east coast of Lake Superior exhibit Keweenawan rocks. While none of these areas are large, they are significant, extending along nearly the entire east coast of Lake Superior from Cape Choyye, near Michipicoten Harbor, to Gros Cap, intervening localities being Cape Gargantua, Pointe aux Mines, and Mamainse Peninsula. At all these local-

[a] Op. cit., pp. 40-41.
[b] Logan, W. E., Report of progress to 1863, Geol. Survey Canada, 1863, p. 82.

ities the rocks belong to the middle Keweenawan. They consist of basic lavas, including melaphyres, porphyrites, and amygdaloids, and interstratified sandstones and conglomerates. The sandstones and conglomerates differ from the ordinary sedimentary rocks interstratified with the lavas in that they contain a considerable amount of detritus derived from the subjacent Archean rocks. This is particularly noticeable at Mamainse. For the most part the masses exposed are small, but Logan[a] estimates the thickness of the series at Pointe aux Mines to be 3,000 feet. At Mamainse Peninsula the Keweenawan rocks occupy much the largest area along the east coast. Macfarlane[b] calculates a total thickness in this locality of 16,208 feet, of which interstratified conglomerates make up 2,138 feet. Macfarlane's section, from the base upward, is as follows:

Section of Keweenawan rocks on Mamainse Peninsula.

	Feet.
1. Granular melaphyre, consisting of a small-grained mixture of dark-brown feldspar with angular grains of a dark-green chloritic mineral. It varies frequently in its structure, and in the upper part contains amygdules of calc spar and delessite (iron chlorite)	3,930
2. Brown argillaceous sandstone, striking N. 20° W. and dipping 35° SW	12
3. Compact greenish-gray melaphyre, with grains of feldspar, iron chlorite, and hematite; strike N. 10° W.; dip 32° SW	1,787
4. Conglomerate holding granitic or gneissoid bowlders	852
5. Granular melaphyre, containing feldspar, which weathers white, and dark-green chlorite.	426
6. Sandstone	20
7. Dark-brown compact trap	71
8. Conglomerate	70
9. Dark-green melaphyre, slightly amygdaloidal	710
10. Conglomerate	43
11. Melaphyre, striking N. 5° W., dip 30° W.; fine grained and of a dark-brownish color	1,207
12. Conglomerate	71
13. Granular melaphyre, containing brownish-red feldspar and abundance of delessite	355
14. Conglomerate	35
15. Fine-grained greenish-red melaphyre, becoming amygdaloidal in the upper part of the bed. Strike N. 20° W., dip 35° SW., where it adjoins conglomerate N. 15° W.>45° SW.	489
16. Conglomerate, with a small layer of sandstone, the latter striking N. 17° W., dip 40° SW	163
17. Compact dark-brown crystalline trap	340
18. Conglomerate	170
19. Melaphyre	160
20. Conglomerate, striking N. 5° W. and dipping 42° W. at junction with overlying rocks	204
21. Melaphyre	240
22. Conglomerate, striking N. 12° W. In this bed the bowlders are smaller than in those hitherto mentioned	34
23. Melaphyre, striking N. 23° W. and dipping 37° SW	682
24. Conglomerate and sandstone, striking N. 14° W. and dipping 44° SW	12
25. Melaphyre; strike N. 33° W.; dip 28° SW	250
26. Measures concealed	160
27. Melaphyre, granular and of a reddish-green color, striking N. 30° W. and dipping 18° SW.	25
28. Measures concealed	125
29. Melaphyre; strike N. 33° W.; dip 28° SW	272
30. Measures concealed	180
31. Melaphyre, amygdaloidal in part	436
32. Measures concealed	400
33. Conglomerate, consisting of bowlders of Laurentian rocks in matrix of red sandstone	330
34. Measures concealed	172
35. Melaphyre, striking N. 35° W. and dipping 20° SW	100
36. Conglomerate, in which the bowlders consist to a much greater extent than heretofore of amygdaloidal and other varieties of melaphyre. Strike N. 20° W.; dip 25° SW. at the junction with the overlying rock	50
37. Reddish-gray granular melaphyre, becoming amygdaloidal in the upper part	200
38. Sandstone, striking N. 30° W. and dipping 24° SW	12
39. Conglomerate, containing here and there layers of sandstone, striking N. 40° W. and dipping 15° SW	30

[a] Logan, W. E., Report of progress to 1863, Geol. Survey Canada, 1863, p. 82.
[b] Macfarlane, Thomas, Report of progress from 1863 to 1866, Geol. Survey Canada, 1866, pp. 132–134.

	Feet.
40. Dark-green glittering melaphyre, striking, at its junction with the underlying conglomerate, N. 50° W. and dipping 30° SW	114
41. Measures concealed	137
42. Melaphyre, striking N. 50° W. and dipping 29° SW	16
43. Measures concealed	114
44. Melaphyre, dark reddish green, striking N. 50° to 55° W. and dipping 21° to 25° SW	300
45. Dark-green and glittering melaphyre; N. 25° W.>20° SW	250
46. Compact fine-grained trap, containing geodes of agate, in which calc spar frequently occupies the center	350
47. Porphyritic conglomerate and sandstone; N. 8° W.>21° W	30
48. Compact fine-grained trap, containing agates in many places	72
	16,208

This thickness does not include the basal sandstone to be mentioned below. It is to be noted that in the 5,729 feet at the bottom of the section there is only one layer of sediment—a sandstone 12 feet thick. In the remainder of the section, 10,479 feet, conglomerates and sandstones are interstratified at several places, the thickest bed being 852 feet thick and lying at the bottom of the part containing sandstones and conglomerates. Thus the lower third of the middle Keweenawan is essentially igneous and the upper two-thirds consists of igneous and sedimentary rocks.

At Mamainse, Pointe aux Mines, and Cape Choyye the lower Keweenawan beds are conglomerates and sandstones. At Mamainse these basal beds of sandstone, according to Macfarlane,[a] seem to have a very considerable thickness. At Pointe aux Mines, according to Logan,[b] there are sandstones at the base of the series nearly in contact with the gneiss. At Cape Choyye the basal bed is a red sandstone of considerable thickness. However, at Cape Gargantua and at Batchewanung Bay the amygdaloidal trap rests unconformably upon the Archean, and thus at these points igneous rocks are at the lowest horizon of the Keweenawan series.

Thus for eastern Lake Superior the Keweenawan may be divided into lower Keweenawan and middle Keweenawan, the former being represented by the sediments at the bottom of the series and the latter by the lavas and interstratified sediments.

The dips at Mamainse are 20° to 30° lakeward, and from these amounts on the east coast they range up to 60°, as at Gros Cap. In general direction the strike of the strata of the Keweenawan of the east coast curves in and out, corresponding to the minor folds of the synclinorium, but the average strike is somewhat west of north, corresponding with the general direction of the east coast, and the dips are to the west, varying from as low as 10° at Cape Choyye to as high as 45° or even 60° at Gros Cap. The usual dips, however, run between 20° and 35°.

From the general relation of the Cambrian sandstone (Sault Ste. Marie, "Eastern" or Potsdam sandstone of several writers) and its extensions adjacent to the Keweenawan, Logan concluded that there was an unconformity between the two. He says:[c]

> The contrast between the general moderate dips of these sandstones and the higher inclination of the igneous strata at Gargantua, Mamainse, and Gros Cap, combined with the fact that the sandstones always keep to the lake side of these, while none of the many dikes which cut the trappean strata, it is believed, are known to intersect the sandstones (at any rate on the Canadian side of the lake), seems to support the suspicion that the sandstones may overlie unconformably those rocks which, associated with the trap, constitute the copper-bearing series.

GENERAL CONSIDERATION OF THE KEWEENAWAN SERIES.

LOWER KEWEENAWAN.

In reference to the lower Keweenawan, it need here only be remarked that these sediments are in no way peculiar. They are derived from the preexisting Huronian and Archean precisely as similar detrital formations are built up. At the bottom are conglomerates; over these lie sandstones; and in the Black and Nipigon bay districts above these are interstratified marls, limestones, shales, and sandstones.

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[a] Report of progress from 1863 to 1866, Geol. Survey Canada, 1866, p. 134.
[b] Report of progress to 1863, Geol. Survey Canada, 1863, p. 82.
[c] Idem, p. 85.

Though it is not known that sediments were everywhere deposited at the base of the Keweenawan, it is a remarkable fact that in most places where the actual contact between the nonintrusive parts of the Keweenawan and the next underlying rocks can be seen such sediments occur. These deposits have their greatest volume and widest extent in the region about Black and Nipigon bays, where the thickness is variously estimated from 550 to 1,400 feet. In northeastern Minnesota, at the base of the series is the Puckwunge conglomerate. In Michigan, at Black River, at the bottom of the succession is a basal sandstone known to be 300 feet thick, and it may be considerably thicker than this, occupying a part of the unexposed area to the south. How far this sandstone extends east and west is not known, as the formations next underlying the Keweenawan are not usually exposed. However, the formation is known to be present north of Ironwood and also in sec. 11, T. 45 N., R. 1 W., near Potato River, in Wisconsin, more than 20 miles west of Black River (Michigan). At the latter place the conglomerate and quartzite below the lavas are probably as thick as at Black River. On the east side of Lake Superior the actual contacts between the pre-Keweenawan and the Keweenawan are found at a number of localities, and at the more extensive of these exposures the lowest formation of the Keweenawan is a conglomerate, although at other localities the lavas lie directly against the gneiss. Where the lowest Keweenawan rock is an intrusive, as for instance the Duluth gabbro, this must of course be excluded from all consideration in connection with the oldest formation of the Keweenawan. Also there must be excluded from consideration the localities, such as Keweenaw Point and western Wisconsin, where the base of the Keweenawan is not exposed.

MIDDLE KEWEENAWAN.

The middle Keweenawan was the great epoch of combined igneous and aqueous activities. There are two divisions of its rocks—original igneous and derived sedimentary.

IGNEOUS ROCKS.

VARIETIES.

The igneous rocks constitute a province of rather remarkable uniformity. The different kinds and their relations are substantially the same in each of the important districts. Chemically the igneous rocks include basic, acidic, and intermediate varieties. The basic materials overwhelmingly dominate, the acidic rocks are considerable in quantity, and the intermediate rocks are few and local. Each variety of rocks includes both intrusive and extrusive facies, so that the basic, acidic, and intermediate groups all have textures characteristic for plutonic and volcanic rocks. Barring the work of Kloos and Streng,[a] which was limited in scope, Pumpelly[b] made the first careful petrographic study of the Keweenawan rocks. In general Irving[c] followed Pumpelly in the use of terms, but his studies were more extensive and disclosed new variations.

According to Irving, the basic plutonic igneous rocks comprise olivinitic and nonolivinitic gabbros, olivinitic and nonolivinitic diabases, and "anorthite rock." The surface varieties include melaphyres, porphyrites, and amygdaloids. The coarser-grained melaphyres have often been called dolerites, diabases, or ophites, depending on their texture. The deep-seated phase of the acidic rocks is granite, augitic, or hornblendic, and the extrusive phase is made up of porphyry, quartziferous and nonquartziferous, and felsite. The intermediate rocks occur in subordinate amounts. The most important intrusive phases of them are described by Irving as augite syenites and orthoclase gabbros, and the extrusive varieties as porphyrites. The term "trap" is used by Irving in its usual sense to include both basic and intermediate fine-grained rocks.

[a] Streng, A., and Kloos, J. H., Über die krystallinischen Gesteine von Minnesota in Nord-Amerika: Neues Jahrb., 1877.
[b] Pumpelly, Raphael, Copper-bearing rocks: Geol. Survey Michigan, vol. 1, pt. 2, 1873, pp 1-46, 62-94.
[c] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883.

The plutonic igneous rocks are very little altered. The very readily changeable olivine may be altered to chlorite, serpentine, etc., to a small extent. The augite and plagioclase are locally chloritized, but still these alterations are purely subordinate.

The volcanic rocks are much altered. This is especially true of the vesicular amygdaloidal basic lavas. In these rocks the original minerals, which were dominantly augite, olivine, plagioclase feldspars, magnetite, and glassy base, have been extensively altered and the vesicules of the amygdaloids filled with secondary products. These are mainly alterations of the belt of cementation in the zone of katamorphism. A complicated set of secondary minerals has been produced, of which the following are very common: Various zeolites, such as laumontite, thomsonite, stilbite, and mesolite; also calcite, chlorite, epidote, quartz, prehnite, orthoclase, hematite, and limonite.

The acidic rocks, the original minerals of which were mainly quartz, orthoclase, plagioclase, and glass, have also been extensively decomposed, with the development of much secondary quartz and other alteration products, which are not always completely determinable but which certainly include epidote and chlorite. Hematite and limonite are common. Many microliths have formed, the exact nature of which it is difficult to determine.

REVIEW OF NOMENCLATURE OF KEWEENAWAN IGNEOUS ROCKS.[a]

By Alexander N. Winchell.

The Keweenawan igneous rocks of the Lake Superior region have been studied and discussed by many geologists during the past thirty years. At the beginning of that period microscopic petrography was in its infancy and minor errors, due to faulty methods, inevitably resulted. In the course of the years these have been gradually corrected, involving changes of nomenclature. Some variations in nomenclature have resulted from the varying points of views of the authors. But the general progress of petrography has brought more numerous and important modifications.

In order to make the names used by the prominent writers on the subject more readily intelligible, a correlation of these names is presented herewith. It must be remembered that, since the basis of petrographic classification used by the authors has varied somewhat, such a correlation can be only an approximation, but it will nevertheless serve the purpose of showing the various changes that have occurred and of presenting, at least in its outlines, the main facts of nomenclature of each writer.

In order to give precision to such a correlation, it is desirable that the nomenclature of each writer be compared, not simply with that used by other authors but also with an expressed and definite classification. Therefore the following classification has been prepared, on the basis of textures and mineral composition. It is not a general classification of igneous rocks but is intended to include merely the types represented in the Keweenawan of the Lake Superior region.

[a] Revision of article published in Jour. Geology, vol. 16, 1908, pp. 765-774. Originally prepared for this monograph.

Mineralogical classification of Keweenawan igneous rocks of the Lake Superior region.

Texture.	Chief feldspar orthoclase.			Orthoclase with equal plagioclase.	Chief feldspar plagioclase.	
	+Quartz.		−Quartz.		With quartz.	
	± Mica ± Amphibole ± Pyroxene.				+Monoclinic pyroxene.	
	± Microcline.	+Anorthoclase.	± Microcline.		+Orthoclase.	−Orthoclase.
Granitic.	Granite.	Soda granite.	Syenite.	Monzonite.	Orthoclase gabbro.	Quartz gabbro.
Ophitic.					Orthoclase diabase.	Quartz diabase.
Porphyritic (phenocrysts prominent).	Rhyolite porphyry (quartz porphyry).	Quartz keratophyre.	Trachyte porphyry.			
Felsitic or porphyritic (phenocrysts few).	Rhyolite.	Quartz keratophyre.	Trachyte.			
Fragmental.	Acidic tuffs.					
Glassy.	Obsidian.					

Texture.	Chief feldspar plagioclase—Continued.					
	With quartz—Continued.		Without quartz.			
	+Orthorhombic pyroxene.	+Amphibole. ± Biotite.	No ferromagnesian mineral.	+Amphibole. ± Biotite.	+Monoclinic pyroxene.	
					−Olivine.	+Olivine.
Granitic.	Quartz norite.	Quartz diorite.	Plagioclasite.	Diorite.	Gabbro.	Olivine gabbro.
Ophitic.	Quartz-enstatite diabase.				Diabase.	Olivine diabase.
Porphyritic (phenocrysts prominent).				Andesite porphyry.	Augite andesite porphyry.	Basalt porphyry.
Felsitic or porphyritic (phenocrysts few).		Dacite.		Andesite.	Augite andesite.	Basalt.
Fragmental.						Basalt tuffs.
Glassy.						Tachylyte.

Texture.	Chief feldspar plagioclase—Continued.				No feldspar.	
	Without quartz—Continued.			+Olivine.	± Pyroxene ± Amphibole ± Biotite.	
	+Orthorhombic pyroxene.					
	+Monoclinic pyroxene.	−Olivine.	+Olivine.		−Olivine.	+Olivine.
Granitic.	Augite norite.	Norite.	Olivine norite.	Troctolite.	Pyroxenite.	Peridotite.
Ophitic.	Hypersthene diabase					
Porphyritic (phenocrysts prominent).						
Felsitic or porphyritic (phenocrysts few).						
Fragmental.	Basalt tuffs.					
Glassy.	Tachylyte.					

Macfarlane,[a] in 1866, described the Keweenawan rocks of Michipicoten Island. He found melaphyre, trap, amygdaloid, quartz porphyry, porphyrite, and trachytic phonolite. His "quartz porphyry," which occurred at the contact of the sandstone and trap, was doubtless a modified quartzite. His "trachytic phonolite" is not fully described, and correlation is uncertain.

Kloos,[b] in 1871, described gabbro or hypersthenite, black porphyry or melaphyre, porphyry, and amygdaloid. The first named was probably a gabbro and the second a diabase.

Pumpelly,[c] in 1873, described melaphyre, trap, and amygdaloid without microscopic study; he distinguished three kinds of melaphyre—coarse grained, fine grained, and melaphyre porphyry. Correlations of these names are impracticable and would be misleading rather than helpful.

Marvine,[d] in the same year, described melaphyre, trap, diorite, and amygdaloid. Pumpelly later claimed, probably correctly, that Marvine's diorite included samples of diabase, melaphyre, and gabbro, but no true diorite.

Streng,[e] in 1877, described melaphyre, melaphyre porphyry, and hornblende gabbro from the Keweenawan of Minnesota. He published chemical analyses of two of these, which permit their correlation on the quantitative basis. (See table on p. 402.)

Pumpelly,[f] in 1878, described the alterations which some of the Keweenawan rocks had suffered in great detail, but brought to light no additional varieties of the unaltered rocks.

The same author,[g] in 1880, identified eight or ten kinds of igneous rocks in the Keweenawan. (See table on p. 400.) He distinguished diallage from augite by means of the parting in the former, and, in accordance with the usage at that time, called a massive igneous rock containing plagioclase and diallage a gabbro, while one containing plagioclase and augite he called a diabase. But all the diabase covered by his descriptions and illustrations seems to have an ophitic texture. His identifications of the plagioclase feldspars were all based on incorrect methods, so that his so-called albite and oligoclase are actually andesine-oligoclase, his labradorite is andesine, and his anorthite is chiefly labradorite with some bytownite.

Irving[h] followed the practice of Pumpelly, but described about twice as many petrographic varieties. He protested against the practice of basing rock names on any such distinction as that between diallage and augite, but followed the custom, nevertheless, in the main, although he tried to discriminate between diabase and gabbro on the basis of coarseness of crystallization, assigning the name gabbro to the coarser grained varieties. Irving's orthoclase gabbro has been called hornblende gabbro by Wadsworth and porphyritic gabbro by N. H. Winchell; it is nearly the same as Lane's gabbro-aplite; recently it has been called oligoclase gabbro by F. E. Wright.[i]

N. H. Winchell,[j] in 1881, described thin sections of dolerite, labradorite rock, hyperite, and gabbro. He made the name "dolerite" so general in meaning as to include gabbro, diabase, olivine gabbro, olivine diabase, augite andesite, and basalt. His "labradorite rock" was called "anorthite rock" by Irving and is now called plagioclasite (or anorthosite); his hyperite is now known as norite.

Wadsworth,[k] in 1887, proposed a new classification of the Keweenawan igneous rocks on the basis of the alterations which a given type has undergone. Thus a gabbro whose augite had altered to hornblende he would call a gabbro-diorite. A peridotite may by alteration become a serpentine or a talc schist; in either case Wadsworth would call it still a peridotite, adding a name to indicate its present condition. Consequently, a rock called, for example, a

[a] Macfarlane, Thomas, Report of progress from 1863 to 1866, Geol. Survey Canada, 1866.
[b] Kloos, J. H., Zeitschr. Deutsch. geol. Gesell., 1871, p. 417.
[c] Pumpelly, Raphael, Geology of Michigan, vol. 1, pt. 2, 1873.
[d] Marvine, A. R., idem.
[e] Streng, A., Neues Jahrb., 1877.
[f] Pumpelly, Raphael, Proc. Am. Acad. Arts and Sci., vol. 13, 1878, p. 285.
[g] Pumpelly, Raphael, Geology of Wisconsin, vol. 3, 1880, pp. 27–49.
[h] Irving, R. D., Geology of Wisconsin, vol. 3, 1880, pp. 167–206; Mon. U. S. Geol. Survey, vol. 5, 1883; Geology of Wisconsin, vol. 1, 1883, p. 340.
[i] Wright, F. E., Science, vol. 27, June, 1908, p. 892.
[j] Winchell, N. H., Proc. Am. Assoc. Adv. Sci., vol. 30, 1881, p. 160.
[k] Wadsworth, M. E., Bull. Geol. and Nat. Hist. Survey Minnesota No. 2, 1887.

gabbro by Wadsworth may belong to any one of a dozen types as commonly recognized. Nevertheless, Wadsworth's names as actually applied in this case may be correlated approximately with the names of other writers, as shown in the table on page 400.

Wadsworth indorsed Irving's protest against using the distinction between augite and diallage as a basis of rock classification, and yet, like Irving, he used it. He did not discriminate sharply between the ophitic and the poikilitic textures, both of which may be found, sometimes together, in Minnesota diabases.

Bayley,[a] in 1889–1897, described the gabbro batholith of Minnesota in considerable detail and also studied the peripheral phases of the gabbro. To emphasize the close connection in origin between the peridotite and the gabbro of the district, he called the former nonfeldspathic gabbro. Although some of the peripheral phases described by Bayley may be of later date than the gabbro, if we assume that they all belong in the Keweenawan, we find that Bayley recognizes not only the augite syenite of Irving, but also a porphyritic equivalent which he calls quartz keratophyre on account of the presence of anorthoclase. He speaks of olivine-pyroxene aggregates which should apparently be correlated with wehrlite, dunite, and pyroxenite.

In the peripheral phases he finds a texture which he considers somewhat characteristic; it consists of the presence of many rounded grains of the more important constituents inclosed by other minerals. Bayley calls it the granulitic texture. It has been called the contact structure by Salomon and the globular by Fouqué. It is well described by the term globular or globulitic.

Grant,[b] in 1893 and 1894, described gabbro, diabase, granite, and fine-grained rocks previously called muscovadites in the Minnesota reports. Grant's granite is the equivalent of Irving's augite syenite, later called soda-augite granite by Bayley. (See table on p. 400.) The fine-grained rocks, called muscovadites, include border facies of the gabbro mass of various types, but especially norite, fine-grained gabbro often with hypersthene, olivine norite, cordierite norite, etc.

Hubbard,[c] in 1898, described various types of the Keweenawan of Keweenaw Point. His melaphyre is chiefly andesite or basalt; his doleritic melaphyre is a coarser basalt or a gabbro; his ophitic melaphyre is a poikilitic and luster-mottled diabase; and his porphyrite is chiefly andesite and trachyte.

Lane,[d] in 1898–1906, described the Keweenawan rocks of Isle Royal and northern Michigan. His melaphyre porphyrite is the equivalent of Pumpelly's "Ashbed" diabase and Irving's diabase porphyrite, Lane's melaphyre ophite is an olivine diabase, luster-mottled by means of poikilitic textures; his doleritic melaphyre is a basalt porphyry. Lane would confine the name diabase to dike rocks. His augite syenite is said to be at least in part an equivalent of Bayley's quartz diabase. He uses the term ophitic in a narrow sense, not justified by the original definition of Michel Lévy,[e] nor by his usage.[f] He applies it to those luster-mottled rocks in which single pyroxene individuals inclose several plagioclase crystals, usually lath-shaped and irregularly placed. It denotes thus, for Lane, a variety of the poikilitic texture. In its original meaning, still commonly used by many and adopted here, it refers to that texture of a basic igneous rock produced when the plagioclase crystallizes in lath-shaped forms before the pyroxene solidifies.

A. N. Winchell,[g] in 1900, described in detail a few samples of the Keweenawan rocks of Minnesota. He used the new term plagioclasite for the rocks previously known usually as anorthosites.

[a] Bayley, W. S., Am. Jour. Sci., 3d ser., vol. 37, 1889, p. 54; vol. 39, 1890, p. 273; Bull. U. S. Geol. Survey No. 109, 1893; Jour. Geology, vol. 1, 1893, p. 433; vol. 2, 1894, p. 814; vol. 3, 1895, p. 1; Mon. U. S. Geol. Survey, vol. 28, 1897, p. 519.

[b] Grant, U. S., Twenty-first Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, p. 5; Twenty-second Ann. Rept., 1894, p. 76.

[c] Hubbard, L. L., Geol. Survey Michigan, vol. 6, pt. 2, 1898.

[d] Lane, A. C., Geol. Survey Michigan, vol. 6, pt. 1, 1898; Bull. Geol. Soc. America, vol. 14, 1903, pp. 369, 385; Jour. Geology, vol. 12, 1904, p. 83; Ann. Rept. Geol. Survey Michigan for 1903, 1905, pp. 205, 239; idem for 1904, 1905, p. 113; Proc. Lake Superior Min. Inst., vol. 12, 1906, p. 85.

[e] Bull. Soc. géol. France, vol. 6, 1878, p. 158.

[f] Minéralogie micrographique, 1879, Pl. XXXVI. See also p. 153.

[g] Winchell, A. N., Am. Geologist, vol. 26, 1900, pp. 151 (197), 261, 348.

N. H. Winchell and U. S. Grant[a] published in 1900 by far the most complete accounts of the petrography of the Keweenawan igneous rocks. Their nomenclature varies very little from that commonly in use at present. They described practically all the petrographic types of the Keweenawan previously known and added some half dozen new varieties. They used diorite-porphyrite or diabase-porphyrite to designate more or less ophitic types of andesite porphyry or augite andesite porphyry. They used Wadsworth's name zirkelite for a devitrified basalt, basaltic tuff, or tachylyte; devitrified obsidian they called an apobsidian, and a devitrified rhyolite an aporhyolite, as suggested by Bascom. Wadsworth's quartz-biotite diorite is called syenite by Grant. It is an intermediate type corresponding to a monzonite.

[a] Winchell, N. H., and Grant, U. S., Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 5, 1900.

Correlation of nomenclatures of Keweenawan igneous rocks.

R. Pumpelly, 1880.	R. D. Irving, 1880–1883.	M. E. Wadsworth, 1887–1893.	W. S. Bayley, 1889–1897.	L. L. Hubbard, 1898.	A. C. Lane, 1898–1906.	A. N. Winchell, 1900.	N. H. Winchell and U. S. Grant, 1900.	Mineralogical classification.
	Granite.						Granite.	Granite.
Quartz porphyry.	Quartz prophyry.			Porphyry.	Quartz porphyry.		Quartz porphyry.	Rhyolite porphyry.
				Felsite.	1. Felsite. 2. Felsophyre. 3. Orthophyre.		Rhyolite.	Rhyolite.
							Tuff.	Acidic tuffs.
							Obsidian and apobsidian.	Obsidian.
	1. Augite syenite. 2. Granitell.		1. Granite. 2. Soda-augite granite.		1. Augite porphyrite? 2. Granophyre. 3. Augite syenite. 4. Gabbro-aplite.		1. Granite. 2. Soda granite.	Soda granite.
	Granitic porphyry.		Quartz keratophyre.				Quartz keratophyre.	Quartz keratophyre.
							Syenite?	Syenite.
	Quartzless porphyry.				Quartzless porphyry.			Trachyte porphyry.
Felsite porphyry.	1. Felsite? 2. Felsitic porphyry.			Felsite.	1. Felsite. 2. Orthophyre.		Trachyte.	Trachyte.
		Quartz-biotite diorite.					Syenite or granophyre.	Monzonite.
1. Augite diorite. 2. Melaphyre.	1. Hornblende gabbro. 2. Orthoclase gabbro.	Altered gabbro.	Hornblendic gabbro.		Gabbro-aplite?	Orthoclase gabbro.	Porphyritic gabbro.	Orthoclase gabbro.
	Orthoclase diabase.							Orthoclase diabase.
						Quartz gabbro.	Quartz gabbro.	Quartz gabbro.
			Quartz diabase.		1. Quartz diabase. 2. Diabase granophyrite.		Diabase.	Quartz diabase.
							Quartz norite.	Quartz norite.
					Enstatite diabase.		Diabase with hypersthene.	Quartz-enstatite diabase.
		1. Gabbro? 2. Quartz diorite.	Quartz diorite.				Quartz diorite.	Quartz diorite.
					Quartz porphyrite.			Dacite.
	Anorthite rock.					Plagioclasite.	Anorthosite.	Plagioclasite.
	Diorite?						1. Diorite. 2. Gabbro.	Diorite.
	Quartzless porphyry.			Doleritic melaphyre.			Porphyrite.	Andesite porphyry.
	Diabase-porphyrite.	1. Augite andesite. 2. Hornblende porphyrite.		1. Felsite porphyrite. 2. Melaphyre.	1. Felsite porphyrite. 2. Felsophyrite.		Andesite.	Andesite.

1. Diabase. 2. Gabbro.	1. Diabase. 2. Gabbro.			Doleritic melaphyre.		Gabbro.	1. Gabbro. 2. Diabase.	Gabbro.
1. Diabase. 2. Gabbro.	1. Diabase. 2. Gabbro.	Diabase.	Diabase.	Diabasic melaphyre.	Diabase (in dikes).	Diabase.	Diabase.	Diabase.
Phorphyritic diabase.	Diabase-porphyrite				1. Porphyrite. 2. Labradorite porphyrite.		1. Diorite-porphyrite. 2. Diabase-porphyrite.	Augite andesite porphyry.
	1. "Ashbed" diabase. 2. Diabase-porphyrite.		Porphyrite.	Porphyrite.	Augite andesite.		Basalt.	Augite andesite.
	1. Olivine diabase. 2. Olivine gabbro.		Olivine gabbro.			Olivine gabbro.	Olivine gabbro.	Olivine gabbro.
1. Chrysolitic diabase. 2. Melaphyre.	1. Olivine diabase. 2. Olivine gabbro. 3. Melaphyre.	1. Diabase. 2. Granophyrite.	1. Olivine diabase. 2. Olivine gabbro.	Ophitic melaphyre.	1. Melaphyre ophite. 2. Melaphyre porphyrite. 3. Olivine diabase (in dikes).	Olivine diabase.	Diabase with olivine.	Olivine diabase.
	Diabase-porphyrite.			Doleritic melaphyre.	Melaphyre dolerite.		Porphyritic basalt or zirkelite.	Basalt porphyry.
"Ashbed" diabase.	1. Diabase-porphyrite. 2. Melaphyre.	1. Basalt. 2. Melaphyre.		Melaphyre.	1. Felsite. 2. Melaphyre porphyrite. 3. Labradorite porphyrite.	Basalt.	Basalt.	Basalt.
							Tuff or zirkelite.	Basalt tuffs.
							Zirkelite.	Tachylyte.
			Hypersthene gabbro.				Hypersthene gabbro.	Augite norite.
	Norite.						Norite (muscovadite).	Norite.
					Enstatite diabase.		Hypersthene diabase.	Hypersthene diabase.
							Norite with olivine.	Olivine norite.
		1. Forellenstein. 2. Troctolite.			Troctolite.	Troctolite.	Forellenstein or troctolite.	Troctolite.
			Granulitic pyroxene rock.				Pyroxenite.	Pyroxenite.
			Nonfeldspathic gabbro.			Peridotite.	Peridotite	Peridotite.

Correlation of nomenclatures of Keweenawan igneous rocks of the Lake Superior region according to the quantitative classification.

A. Streng, 1877.[a]	R. Pumpelly, 1878.[b]	E. T. Sweet, 1880.[c]	M. E. Wadsworth, 1887–1893.[d e]	C. R. Van Hise, 1892.[f]	N. H. Winchell, 1893.[g]	W. S. Bayley, 1889–1895.[h i j k]	A. C. Lane, 1898.[l]	L. L. Hubbard, 1898.[m n o p]	A. N. Winchell, 1900–1908.[q r]	A. C. Lane, 1905–1906.[s t u]	Quantitative classification.
								Felsite, Keweenaw Point, Mich.[m]			I. 3. 1. 2. Magdeburgose.
								Felsite (No. 17193A), Keweenaw Point, Mich.[n]			I. 3. 2. 3. Tehamose.
								Felsite (No. 16951), Keweenaw Point, Mich.[n]			I. 4. 1. 1. Lebachose.
						Granite, Pigeon Point, Minn.[h] Soda granite, Pigeon Point, Minn.[i] Quartz keratophyre, Pigeon Point, Minn.[h]					I. 4. 1. 3. Liparose.
						Quartz keratophyre, Pigeon Point, Minn.[i]					I. 4. 2. 3. Toscanose.
									Plagioclasite, Carlton Peak, Minn.[q]		I. 5. 4. 4,5. Labradorose.
			Gabbro?, Pigeon Point, Minn.[d]			Quartz diorite, Pigeon Point, Minn.[i]					II. 4. 2. 3. Adamellose.
										Gabbro-aplite, Mount Bohemia, Mich.[s]	II. 4. 3-2. 4. Tonalose-daeose.
								Felsite porphyrite, Keweenaw Point, Mich.[o]			II. 5. 1. 4. Umptekose.
								Porphyrite, Keweenaw Point, Mich.[p]			II. 5. 2. 4. Akerose.
Hornblende gabbro, Duluth, Minn.	Melaphyre, middle of bed 87, Eagle River section, Keweenaw Point, Mich.						Porphyrite (V and VI), Isle Royal, Mich.		Orthoclase gabbro, Duluth, Minn.[q]		II. 5. 3. 4. Andose.
Melaphyre porphyry, Duluth, Minn.			Gabbro, Baptism River, Minn.[d]								II. 5. 3. 5-4. Beerbachose-andose.
									Quartz gabbro, Little Saganaga Lake, Minn.[q]		II. 4-5. 3. 5. Placerose-beerbachose.

							Porphyrite (i), Isle Royal, Mich.				II. 5. 3. 5. Beerbachose.
		Diabase, Fond du Lac mine, Douglas County, Wis.	Diabase granophyrite, Cleveland mine, Keweenaw Point, Mich.[e]			Olivine gabbro, Pigeon Point, Minn.[i] Olivine gabbro, T. 61 N., R. 12 W., Minn.[j]	Porphyrite (IV), and ophite (VII), Isle Royal, Mich.		Olivine gabbro and diabase, Birch Lake, Minn.[q]		II. 5. 4. 4,5. Hessose.
			Diabase granophyrite, sec. 2, T. 48 N., R. 27 W., Houghton County, Mich.[e]								III. 4. 3. 4. Vaalose.
									"Ashbed diabase," bed 65, Eagle River section, Keweenaw Point, Mich.[r]		III. 5. 2-3. 4. Kilauose-camptonose.
	Melaphyre, bottom of bed 87, Eagle River section, Keweenaw Point, Mich.								Orthoclase gabbro (basic part), Duluth, Minn.[q]		III. 5. 3. 4. Camptonose.
	Melaphyre, lower part of bed 64, Eagle River section, Keweenaw Point, Mich.			Diabase, sec. 13, T. 47 N., R. 46 W., Gogebic County, Mich.	Gabbro (granular) Bashitanaqnab Lake, Minn.	Olivine gabbro, Birch Lake, Minn.[j] Gabbro, T. 64 N., R. 8 W., Minn.[k]			Troctolite, Duluth, Minn.[q] Olivine diabase, bed 108, Eagle River section, Greenstone Cliff, Keweenaw Point, Mich.[r]	Ophite, Mount Bohemia, Mich.[s] Diabase, Lighthouse Point, Mich.[t] Ophite, St. Mary Land Co., Keweenaw Point, Mich.[u]	III. 5. 4. 4,5. Auvergnose.
						Hypersthene gabbro, Gunflint Lake, Minn.[k]					IV. 1^1. 1^1. 2. Cookose.

[a] Streng, A., and Kloos, J. H., Neues Jahrb., 1877, pp. 48, 117; A. Streng, analyst.
[b] Pumpelly, Raphael, Proc. Am. Acad. Arts and Sci., vol. 13, 1878, pp. 285, 293; R. W. Woodward, analyst.
[c] Sweet, E. T., Geology of Wisconsin, vol. 3, 1880, p. 350; E. T. Sweet, analyst.
[d] Wadsworth, M. E., Bull. Geol. and Nat. Hist. Survey Minnesota No. 2, 1887, pp. 79, 82; Dodge and Sidener, analysts.
[e] Wadsworth, M. E. (H. B. Patton), Ann. Rept. Geol. Survey Michigan for 1891, 1893, pp. 134, 141; F. F. Sharpless, analyst. See also Geol. Survey Michigan, vol. 6, pt. 1, 1898, pp. 250, 265.
[f] Van Hise, C. R., Mon. U. S. Geol. Survey, vol. 19, 1892, p. 357; T. M. Chatard, analyst.
[g] Winchell, N. H., Twenty-first Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, p. 151; A. D. Meeds, analyst.
[h] Bayley, W. S., Bull. U. S. Geol. Survey No. 109, 1893, pp. 58, 90; L. G. Eakins and J. E. Whitfield, analysts.
[i] Bayley, W. S., Am. Jour. Sci., 3d ser., vol. 37, 1889, pp. 59, 61; W. F. Hillebrand, analyst.
[j] Bayley, W. S., Jour. Geology, vol. 1, 1893, p. 712; H. N. Stokes, analyst.
[k] Bayley, W. S., Jour. Geology, vol. 3, 1895, p. 10; H. N. Stokes and W. H. Melville, analysts.
[l] Lane, A. C., Geol. Survey Michigan, vol. 6, pt. 1, 1898, p. 215; F. P. Burrall, analyst. Lane calls attention to the fact that the titanium was not determined in analysis VII if 1.5 per cent TiO_2 was weighed with the Al_2O_3 the classification would be changed from hessose to auvergnose.
[m] Hubbard, L. L., Geol. Survey Michigan, vol. 6, pt. 2, 1898, p. 28; F. P. Burrall, analyst.
[n] Idem., p. 42.
[o] Idem., p. 26.
[p] Idem., p. 25.
[q] Winchell, A. N., Am. Geologist, vol. 26, 1900, p. 374; A. N. Winchell, analyst.
[r] Winchell, A. N., Jour. Geology, vol. 16, 1908, p. 772; George Steiger, analyst.
[s] Lane, A. C., Ann. Rept. Geol. Survey Michigan for 1904, 1905, p. 154; L. Kirschbraun, analyst.
[t] Lane, A. C., Ann. Rept. Geol. Survey Michigan for 1903, 1905, p. 244; E. E. Ware, analyst.
[u] Lane, A. C., Proc. Lake Superior Min. Inst., vol. 12, 1906, p. 85; F. K. Ovitz, analyst. The "red rock dike" of analysis 12 is called gabbro-aplite by the author in Ann. Rept. Geol. Survey Michigan for 1903, p. 236. Analysis 9 of "ophite" is now referred to "oligoclase gabbro" by F. E. Wright (Science, vol. 27, June, 1908, p. 892).

The quantitative classification of igneous rocks as proposed by Cross, Iddings, Pirsson, and Washington may be used as the basis of a correlation of the Keweenawan igneous rocks. With respect to chemical composition such a correlation (see table on pp. 402–403) is more exact than one based on the mineral composition and texture, but it can include only those rock types of which satisfactory quantitative analyses are available.

An examination of the table of correlation on this basis will reveal the fact that the number of satisfactory analyses available is not great, especially when compared with the descriptions previously mentioned. Several of the early analyses are not included in the tabulation because of manifest inaccuracy or incompleteness.

The analyses of Streng and Pumpelly are good for the time at which they were made. Calculation of the norms of the analyses made for Pumpelly by R. W. Woodward yields the results tabulated below in columns 1, 2, and 3:

	1. Andose, middle of bed 87.	2. Camptonose, bottom of bed 87.	3. Auvergnose, lower part of bed 64.	4. Hessose, Cleveland mine.	5. Vaalose, Houghton County, Mich.
Q				5.10	8.46
or	7.78	7.23	0.56	8.34	8.90
ab	42.44	22.01	16.24	16.77	23.06
an	17.24	23.91	36.97	32.25	16.40
ne		4.26			
di		22.55	15.88	11.02	13.75
hy	1.30		20.34	9.90	20.82
ol	17.97	7.47	1.11		
mt	4.41	4.18	3.71	8.45	5.80
il	4.41	5.32	1.98	5.17	
ap					.34
H_2O	4.51	3.25	2.73	2.64	1.39
	100.06	100.18	99.52	99.64	98.92

Sweet published two analyses of Keweenawan rocks. One, of diabase from the Ashland mine, Ashland County, Wis., is wholly unsatisfactory; the other, which represents a "greenish-gray diabase" from the Fond du Lac copper mine, Douglas County, Wis., seems to be approximately correct. As it stands it classifies as bandose, but this is on the basis of a content of 13 per cent of magnetite and 10 per cent of quartz. Both of these figures are extremely improbable for this rock, and point to an error in the determination of the state of oxidation of the iron. If the analysis is corrected in this particular it classifies as hessose.

The analyses of gabbros published by Wadsworth are recalculated in Washington's tables of chemical analyses of igneous rocks;[a] the norms of his diabase-granophyrites from the Cleveland mine and from Houghton County are given in columns 4 and 5 of the table above. Washington's tables give full details regarding the recalculation of the analyses of Keweenawan rocks published by Van Hise, N. H. Winchell, and Bayley.

The norms of the analyses reported by Hubbard may be summarized as follows:

	Magdeburgose.	Tehamose.	Lebachose.	Umptekose.		Akerose.
				No. 17039.	No. 17007.	
Q	38.58	48.90	18.60	1.14		
C	1.94					
or	39.48	26.13	70.61	20.57	20.57	15.01
ab	16.77	18.34	.52	57.64	57.64	48.21
an		3.61		1.67		7.78
ne					2.27	3.69
ac			4.16		3.70	
ns			3.66			
di		.12	1.43	5.62	.43	5.18
hy			.86	2.70		
ol					3.22	5.32
mt	.46	.70		6.03	5.57	8.12
hm	1.92	1.28		3.04	5.92	4.00
H_2O	.41	1.03	.42	2.23	1.23	2.76
	99.56	100.11	100.27	100.64	100.55	100.07

[a] Washington, H. S., Prof. Paper U. S. Geol. Survey No. 14, 1903.

It is to be remarked that not one of these rock types described by Hubbard corresponds chemically with any variety described by any other author. The fact suggests possible inaccuracies in Hubbard's analyses.

Lane's analyses, as well as Hubbard's, were overlooked and omitted from Washington's tables. Recalculations of the analyses given by Lane yield the following norms:

	Tonalose-dacose.	Andose.			Hessose.		Auvergnose.		
		No. V.	No. VI.	Beerbachose.	No. IV.	No. VII.	No. 8 Lighthouse Point.	St. Mary Land Co.	Mount Bohemia.
Q	13.08							1.80	
C	1.02								
or	17.79	6.12	6.12	2.78	1.67	2.78	3.89	1.67	10.01
ab	36.15	28.82	23.58	45.59	28.82	21.48	18.35	20.96	18.34
an	16.96	24.19	30.30	20.02	34.19	41.14	36.14	31.41	31.69
ne		2.84	4.26						
di		3.80	18.41	1.30	10.66	10.64	13.52	12.74	1.36
hy	11.06			2.76	1.56	5.76	10.77	12.20	21.62
ol		23.25	2.10	12.58	12.97	6.01	13.06		2.08
mt	2.32	3.94	11.14	11.37	6.50	10.44	3.71	10.67	7.42
hm								2.24	
il	1.98							4.10	4.71
ap							.34	.34	
cc		.90	2.30	2.00		.70		1.10	
pr							.36	.10	
H_2O		5.01	3.49	2.82	3.90	1.83		.67	
	100.36	98.87	101.62	101.22	100.27	100.78	100.14	100.00	97.23

Lane's gabbro-aplite differs in its norm from the orthoclase gabbro of Duluth in having a greater abundance of quartz and also a greater proportion of alkalies as compared with salic lime. His porphyrite VI, on the contrary, belongs to the same type (andose) as the orthoclase gabbro. His porphyrite No. 1 is a beerbachose; the others belong to the classes hessose and auvergnose, so well represented in the Keweenawan.

The analyses published by A. N. Winchell in 1900 were recalculated by Washington with the exception of that of the troctolite, the norm of which is given with those derived from the new analyses of diabase in the second table below.

In view of the scarcity of analyses of the typical volcanic rocks of the Keweenawan the following new analyses are of much interest. They were made by George Steiger in the laboratory of the Survey.

Analyses of Keweenawan diabase.

	1.	2.		1.	2.
SiO_2	47.69	50.07	ZrO_2	None.	None.
Al_2O_3	16.02	12.63	CO_2	None.	None.
Fe_2O_3	2.41	3.84	P_2O_5	.06	.22
FeO	8.70	10.30	SO_3	None.	None.
MgO	8.31	5.23	S	None.	None.
CaO	10.54	6.55	MnO	.26	.42
Na_2O	2.44	3.53	BaO	None.	.02
K_2O	None.	1.90	SrO	None.	None.
H_2O-	.44	.86			
H_2O+	2.04	1.96		100.29	100.03
TiO_2	1.38	2.50			

1. Olivine diabase from bed 108, Eagle River section, Greenstone Cliff, Keweenaw Point, Mich. Sample No. 5 of Rohn's collection of Lake Superior rocks. Rock powdered to pass a 100-mesh sieve before analysis.
2. "Ashbed" diabase from bed 65, Eagle River section, Keweenaw Point, Mich. Sample No. 7 of Rohn's collection of Lake Superior rocks. Rock powdered to pass a 100-mesh sieve before analysis, thus improving the accuracy of the figures for ferrous iron and water.

Recalculation of these analyses, together with that of the troctolite, on the basis of the quantitative classification gives the following norms:

	Olivine diabase.	"Ashbed" diabase.	Troctolite.
or	....	11.12	2.22
ab	20.44	29.87	7.86
an	32.80	13.07	28.63
ne	....	....	5.11
di	15.60	15.12	5.91
hy	15.64	15.32	....
ol	7.06	2.00	30.21
mt	3.48	5.57	10.67
il	2.74	4.71	4.41
ap	.14	.50	....
MnO	....	....	.18
H_2O	2.48	2.82	5.23
	100.38	100.10	100.43

The olivine diabase belongs to the same class as the olivine gabbros of Birch Lake, the diabase of Lighthouse Point, and several others—that is, to the auvergnose type, which seems to be the dominant type of the Keweenawan, although the hessose type, which differs only in having a greater proportion of salic minerals, is also fairly abundant. But the "Ashbed" diabase classifies as a camptonose, very near a kilauose. It is therefore related to Irving's melaphyre of bed 87 of the Eagle River section, and to the more basic phases of the orthoclase gabbro of Duluth.

On summarizing the results of this correlation of chemical analyses of Keweenawan igneous rocks on the basis of the quantitative classification, it appears that eight analyses belong to Class I, the persalanes, in which less than one-eighth of the rock consists of ferric minerals; 22 analyses fall in Class II, the dosalanes, in which more than one-eighth and less than three-eighths of the rock consists of ferric minerals; 14 analyses belong in Class III, the salfemanes, in which the salic and ferric constituents are in nearly equal proportions; while the single remaining rock represents Class IV, the dofemanes, in which the ferric constituents make up about three-fourths of the whole.

Barring the peculiar analyses of Hubbard and the hypersthene gabbro of Bayley, which is known to be a border facies, several general characteristics of the Keweenawan igneous rocks appear. The salic constituents always make up at least one-half of the rock; they are usually all feldspar and everywhere are dominantly feldspar; quartz is nowhere very abundant; and the lenads are almost unknown in the norms, as they are also in the modes. In all except the Pigeon Point rocks and one sample from Mount Bohemia, the anorthite molecules either equal or dominate over the alkali feldspar molecules and the albite molecules dominate over orthoclase.

Still other relations may be brought out by considering separately the analyses belonging to each class.

Class I. The eight persalanes fall in six subrangs, half of which are due to Hubbard's analyses. They range from the quartz-rich felsites of Hubbard to the quartz-free plagioclasite. The four intermediate types, belonging to two subrangs, are all derived from Pigeon Point. In all the rocks of this class except the plagioclasite, alkali feldspar molecules greatly predominate over anorthite, and orthoclase is notably abundant in only two of the rocks.

Class II. The 22 dosalanes fall in nine subrangs, but these would be reduced to seven if compound names like beerbachose-andose were omitted. These rocks are chiefly perfelic, containing no quartz, but four samples are quardofelic, from the presence of small amounts of quartz. The silica in no case falls so low as to produce lenads. Here, as in Class I, the anorthite molecules dominate over the alkali feldspars in only one subrang, in this case hessose. The albite molecules always dominate over the orthoclase.

Class III. The 14 salfemanes fall in four subrangs, and 10 of them fall in a single subrang, namely auvergnose, which undoubtedly represents the prevailing rock type of the Keweenawan of the district. The commonest variation from this type is an increase of salic constituents, with no other change. This produces hessose, of which eight analyses are recorded. The silica content of the rocks of Class III is high enough in all cases to prevent normative lenads;

only one analysis shows any normative quartz. In the feldspars the albite molecules again dominate clearly over the orthoclase.

Class IV. The single analysis falling in Class IV is clearly not representative; it is a border facies of the great gabbro intrusion. It is characterized by dominance of ferric constituents, of which pyroxene is the most important. It is low in soda and lime and high in ferrous iron, and especially in magnesia.

It is to be expected that additional analyses of the Keweenawan volcanic rocks would disclose still other types, especially such as would parallel the known plutonic types. The parallelism in composition already established is remarkable, considering the relatively small number of analyses available. Thus it appears that Lane's porphyrite (No. IV) and ophite (No. VII), as well as Sweet's Douglas County diabase and Wadsworth's diabase-granophyrite from the Cleveland mine, are the chemical equivalents among the volcanic and dike rocks of Bayley's olivine gabbro from Pigeon Point and from T. 61 N., R. 12 W., and of A. N. Winchell's olivine gabbro and diabase from Birch Lake among the plutonic rocks. Again, Pumpelly's melaphyre from the middle of bed 87 and Lane's porphyrite (Nos. V and VII) from Isle Royal correspond chemically with the coarse hornblende gabbro and orthoclase gabbro from Duluth. Finally, the same chemical type, auvergnose, includes plutonic rocks such as Bayley's gabbro and olivine gabbro from Birch Lake, N. H. Winchell's gabbro from Bashitanaquab Lake, and A. N. Winchell's troctolite, together with volcanic or dike rocks, such as Pumpelly's melaphyre from bed 64, Van Hise's Gogebic County diabase, and Lane's ophite from the property of the St. Mary Land Company and from Mount Bohemia.

THE GRAIN OF KEWEENAWAN IGNEOUS ROCKS—THE PRACTICAL USE OF OBSERVATIONS.[a]

A. C. Lane has found that the grain of the Keweenawan igneous rocks has sufficiently close relation to the size and thickness of the masses to be of some practical importance in exploratory work. Lane's theory of the causes of the variations in grain is not here discussed; it may be found in his papers.[b] The facts which he has developed are briefly as follows:

The Keweenawan igneous rocks most commonly occur in dikes, sills, sheets, and lava floods. It is found in most places in the Lake Superior region that crystallization in such forms has resulted in finer grain near the margin and coarser grain near the center. The relative coarseness of crystallization may be determined by measuring grains of any mineral, but experience shows that in the Keweenawan rocks of the Lake Superior region measurement of the grains of pyroxene (augite) is usually most feasible and most satisfactory. Such measurements show that the size of grain in narrow dikes increases from the margin to the center, the size at any point being approximately proportional to the distance from the margin. In wider dikes measurements show a coarse central zone of variable width in which the pyroxene grains have approximately equal size or increase much more slowly. On each side of this central zone the law already stated is found to hold approximately. In surface flows, where convection was probably active, the size of grain of the augite increases usually all the way from the margin to the center. In wide dikes and thick flows the augite is found to increase in size at a rapid rate near the margin and at a much slower rate near the center. The rapid rate of increase is confined to a marginal zone, usually less than 10 feet wide. The slower rate of increase is fairly uniform for any one flow, and in the luster-mottled melaphyres or ophites is usually between 1 millimeter in 10 feet and 1 millimeter in 20 feet, or say 1 millimeter in 3 to 5 meters. In more feldspathic flows it is less. The very highest rate of increase in the inner zone is 1 millimeter for each 8.5 feet, but in most cases the rate comes out as 1 millimeter in 11 to 16 feet. This refers to the linear diameters of the augite grains, as indicated by the mottlings on the drill cores. It makes some difference whether they are measured in this way, or by the luster mottlings due to the flashes in the sunlight, or by the knobs in the weathered surface.

[a] Adapted from article by A. C. Lane.

[b] Bull. Geol. Soc. America, vol. 8, 1896, pp. 403–407; Geological report on Isle Royale: Geol. Survey Michigan, vol. 6, 1898, pp. 106–151; Am. Jour. Sci., 4th ser., vol. 14, 1902, pp. 393–395; Bull. Geol. Soc. America, vol. 14, 1903, pp. 369–406; Ann. Rept. Geol. Survey Michigan for 1903, 1904, pp. 205–237; idem for 1904, 1905, pp. 147–153, 163; idem for 1908, 1909, pp. 380–384; Am. Geologist, vol. 35, 1905, pp. 65–72; Jour. Canadian Min. Inst., vol. 9. Die Korngrosse der Auvergnosen: Suppl. to Rosenbusch Festschrift, 1906; Tufts' College Studies, III, pp. 41–42.

The practical applications of this study of the size of augite grains in mining have been numerous, especially where contacts of igneous rock are an important factor, as in the Keweenaw copper mines, where the desire is to find the amygdaloids at the tops of massive lava flows.

1. One may distinguish in drill cores between amygdaloid streaks or inclusions in the body of a flow and the main amygdaloid top by the fining of the grain of the rock as a whole toward the latter. There is also a finer grain just around individual amygdules, but in a zone of only microscopic breadth.

2. Extra wide flows may be identified by the relative coarseness in all parts, the maximum grain, and the rate of increase of grain. Of course such flows will run out or grow thinner in a sufficient distance. For instance, an ophite attaining an augite grain of 7 millimeters is rather persistent just about 200 feet above the Baltic lode. The coarsest ophite of all, attaining a maximum augite grain of 76 millimeters (3 inches), is several hundred feet thick out on Keweenaw Point and runs over to Isle Royal, but diminishes in thickness to 50 feet at Portage Lake. It lies just above the Allouez conglomerate and a group of former mines, and where thickest is easily identified by its grain.

3. With due regard to the possibility of being deceived by an extra feldspathic bed, it is possible from a slow increase in coarseness of grain in the diamond-drill cores to infer that the bed is being traversed obliquely and to obtain an idea of its true dip. L. L. Hubbard had to open the Challenge exploration through a heavy covering of drift in a region where no outcrops were near. The first drill hole was put down vertically. The rate of coarsening of grain in normal-looking ophites being about half what would be expected, a dip of about 60° was inferred—correctly, as it proved later.

4. A shaft sinking through drift entered massive trap. The question arose, Which way lies the nearest amygdaloid? A drift in the direction of the finer grain soon found it.

5. A crosscut encountered a clay seam in a heavy trap, which was proved to be more than a mere seam, a displacement, by a marked difference in the coarseness of grain on the two sides. This difference acted as a guide until the displaced lode was found.

6. It is possible to tell how far one has to go through a bed already more than half penetrated. For instance, Kearsarge shaft 21 of the Calumet and Hecla did not strike the lode where it was expected, owing to an unknown displacement. Search was made in two opposite directions. Neither drill hole reached the lode, but it was possible from the grain to say that the lode was probably about 30 feet beyond the end of one hole, which had penetrated the foot-wall trap.

7. A regularity and harmony in grain may distinguish obscure outcrops from casual bowlders. In the case just mentioned some insignificant outcrops were found which passed this test and indicated from their fineness that they were in the hanging wall of the lode, a little above it. The lode was thus found in a week, when it might have taken months without this means of testing.

8. Conversely a very coarse grain indicates a heavy bed of trap, and thus gaps and covered spots in a section may be bridged.

9. The ways of recognizing extremely feldspathic beds and intrusives have already been mentioned.

THE EXTRUSIVE MASSES.

The extrusive rocks are almost altogether lava beds, piled one upon another, the volcanic clastic rocks being insignificant in quantity. The total volume of the extrusives is vast.

The basic lavas greatly predominate. They occupy about 6,000 square miles. It is scarcely necessary to describe them in full, for notwithstanding their age they show all the textures and structures characteristic of the Tertiary volcanic basalts of the West, the only important difference between the two being that the Keweenawan lavas have suffered extensive metasomatic alterations. The beds vary from those less than 2 feet to those which are 100 feet or more in thickness, although lava beds thicker than 100 feet are rather rare and those

200 feet thick very rare. Lane[a] mentioned two ophites in the Black River section, each of which, according to him, has a thickness of at least 500 feet, and Wilson [b] describes a known thickness of more than 500 feet of apparently one mass in the Nipigon basin.

The textures exhibited by the lavas are to a considerable extent a function of the thickness of the flows. The surfaces of the flows show an aphanitic or glassy texture. In the thin beds the aphanitic texture may prevail to the center of the flow. In many of the beds of moderate thickness, from 10 to 20 feet, there is a well-developed ophitic texture. As already noted, Lane[c] has worked out very carefully the relations between the textures exhibited by the lava flows and their thickness, and he holds that the textures are definite functions of the thickness.

The borders of the flows are commonly amygdaloidal. As a rule the amygdaloidal borders are thicker at the upper parts of the flows than at the lower parts. This texture may extend 2 to 10 feet, or even to 20 feet, from the tops of the flows. The amygdules decrease in size in passing from the surface inward. In many places the lower borders showing this texture exhibit the peculiar type known as the spike amygdule. Where the lava beds are thin the amygdaloidal texture may extend to the centers, but this is not common.

The lavas show in places the usual volcanic structures. Many of the beds are columnar. Some flows present ropy surfaces. The upper parts of many flows have a fragmental appearance. In some flows this is due to the breaking up of the upper part of the lava mass while it was still liquid or semiliquid, and in such places the débris is likely to be cemented by the other parts of the lava. Here and there the broken material at the top of the lava beds seems to be truly volcanic. In other places the broken fragments, whether formed by flowage or by the action of air and water, are cemented by their own débris. More rarely volcanic fragmental deposits, bombs and ashes, seem to have been laid down upon the surface of one flow between the time of its consolidation and the extrusion of the next flow. While there is undoubtedly some volcanic fragmental material, as, for instance, the tuff at Taylors Falls on St. Croix River described by Winchell,[d] on the whole for the basic lavas this is extraordinarily small in amount, considering the great extent and volume of the igneous series.

The distance for which a single bed can be followed is to a considerable extent a function of its thickness. The thin flows have a very moderate extent, and even the thicker flows for the most part have not been traced for any great distance. The greatest distances for single flows which have been recorded are 30 miles, by Irving,[e] for the greenstone, and 22 miles, by Grant,[f] for one of the melaphyres of the St. Croix Range. Irving[e] says that he has traced individual flows with certainty on the Minnesota coast for 10 to 15 miles. Groups of lava beds have been traced for much greater distances. For instance, the thin belt of amygdaloids and diabases above the "Great" conglomerate of Keweenaw Point has been traced uninterruptedly for 150 miles. Although a group of lava beds may be traced throughout a district, no group is known to be regional in extent; so that in general it is impossible to correlate lava groups from district to district, as, for instance, those of Keweenaw Point with those of the Minnesota coast. The only such correlation yet attempted is that by Lane [g] between the flows of Keweenaw Point and those of Isle Royal.

The acidic flows differ physically from the basic flows. In general they appear to have been much less fluid, and therefore have a much shorter lateral extent in proportion to their thickness. In fact, a bunchy or lenticular form is characteristic of these flows, as is illustrated by Mounts Houghton and Bohemia on Keweenaw Point. Amygdaloidal textures are not so common in the acidic as in the basic lavas. A flowage structure, on the other hand, is much more prevalent in them than in the basic lavas, and glassy textures are exceedingly common.

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[a] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Geol. Survey Michigan for 1906, 1907, p. 461.

[b] Wilson, A. W. G., Trap sheets of the Lake Nipigon basin: Bull. Geol. Soc. America, vol. 20, 1909, p. 198.

[c] Geol. Survey Michigan, vol. 6, pt. 1, 1898, pp. 123 et seq.

[d] Winchell, N. H., The significance of the fragmental eruptive débris at Taylors Falls, Minn.: Am. Geologist, vol. 22, 1898, pp. 72-78.

[e] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, p. 140.

[f] Grant, U. S., Preliminary report on the copper-bearing rocks of Douglas County, Wis.: Bull. Geol. and Nat. Hist. Survey Wisconsin No. 6, 2d ed., 1901, p. 12.

[g] Lane, A. C., Geological report on Isle Royale, Mich.: Geol. Survey Michigan, vol. 6, pt. 1, 1898, pp. 99-102.

The basic and acidic extrusives may correspond roughly to the gabbro-like intrusives, which are regarded by Wright [a] and others as differentiates from the same magma.

As a rule the dips of the lava beds range between 10° and 45°, but locally they go beyond these extremes, sinking to horizontal and rising to 80° or even to vertical. A mass of rock made up of lava beds having moderate dips gives a very characteristic topography, which may be described as steplike or sawtoothed. Where the beds are thin the steps are low; where thick, they are high. When one walks across a set of lava beds in the direction of the dip, as he approaches a lava flow he finds a steep slope, or even a precipitous wall, which indicates approximately the thickness of the flow. As he climbs to the top of this wall he finds a gentle slope, which corresponds roughly with the dip of the rocks, and down which he may travel until he comes to the next flow, where he will encounter another steep wall, and so on. The character of this topography has been very well figured by Irving [b] for the sawtooth range of Minnesota and for the Eagle River section of Keweenaw Point.

THE INTRUSIVE MASSES.

Chemically the intrusive rocks include basic, acidic, and intermediate varieties. Structurally they comprise every known form of intrusive rocks except batholiths. There are great laccoliths, many large bosses, numerous and extensive sills, and abundant dikes, from those of small size to those hundreds of feet across. Many of the dikes and sills beautifully show a columnar structure. In some of the earlier studies the sills were not separated from the lava flows.

As to magnitude, the masses vary from the Duluth gabbro of Minnesota, which, as showr in another place, has an exposed area of 2,000 square miles and a possible diameter of 100 miles, to emanations so small as to be lost in the intruded rocks. It appears probable that the volume of the intrusive rocks within the previously formed extrusive lavas and conglomerates is really greater than the volume of the lavas themselves.

The greatest of the intrusions of late Keweenawan time are basic. These are represented by the gabbro laccoliths of Minnesota and Wisconsin. Some of the acidic masses also are large, but they are likely to occur in bosslike forms. Representatives of these are the masses at Bare Hill and West Pond on Keweenaw Point.

In the description of the areas of Huronian and Archean rocks it has been shown that varying quantities of the Keweenawan igneous rocks intrude all the previous formations. In these great series throughout the Lake Superior region is a mass of Keweenawan rocks which is perhaps as great as the lavas. The most conspicuous examples of this class are the intrusive sills of the Animikie group, called the Logan sills, which are conspicuously illustrated at Thunder Bay. Larger masses of granite intrude and highly metamorphose the Animikie rocks westward from St. Louis River in central Minnesota through the Cuyuna and Little Falls areas. The granite of northeastern Wisconsin intrudes green schists, which are interbedded with the Animikie group, and is probably of the same age as the central Minnesota granites. Both are regarded as Keweenawan.

Wright [a] regards the aplite of Mount Bohemia as differentiation from the gabbro magma. The aplite antedates the gabbro slightly in its period of crystallization. The aplite occurs not only as a central large mass but also as small dikes and patches in the gabbro mass itself and as small apophyses of gabbro in the adjacent ophites. Wright suggests that the gabbro and aplite are respectively the deep-seated equivalents of the basic and acidic flows of the Keweenawan series.

The close genetic association of the aplites and gabbros has been recognized at many places in Minnesota, Wisconsin, Michigan, and Ontario. The aplite was regarded as effused acidic sediment by Bayley [c] in his studies on Pigeon Point and by Bowen [d] in his studies on

[a] Wright, F. E., The intrusive rocks of Mount Bohemia, Michigan: Ann. Rept. Geol. Survey Michigan for 1908, 1909, p. 393.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, fig. 1, p. 142; fig. 2, p. 178.

[c] Bayley, W. S., The eruptive and sedimentary rocks on Pigeon Point, Minnesota, and their contact phenomena: Bull. U. S. Geol. Survey No. 109, 1893.

[d] Bowen, N. L., Diabase and granophyre of the Gowganda district, Ontario: Jour. Geology, vol. 18, 1910, pp. 658–674.

the Cobalt district, but practically all others who have studied the subject, including Wright, Collins,[a] and the authors, regard the aplites and gabbros as magmatic differentiations from a single magma.

In general, the later intrusives have not greatly metamorphosed the early Keweenawan rocks intruded by them, but there are some exceptions. The far-reaching metamorphic effect of the great laccoliths and bosses upon the lower series has already been described in connection with the Penokee, Vermilion, and Animikie districts. It is probable that future studies will also show pronounced metamorphic effects of these laccoliths on the intruded Keweenawan rocks. Already this has been found to be true for the gabbro of Black River.

In several places the acidic and especially the granitic rocks have produced notable metamorphic effects on the Keweenawan as well as on the lower series. Indeed it is believed that the so-called orthoclase gabbros of Irving[b] at several places, at least, along the Minnesota coast are due to the granitization of ordinary gabbros by the acidic rocks.

SOURCE OF LAVAS.

As to the location of the fissures from which the lavas issued it is not possible to make any very definite statement. It has been suggested that they were situated along the south shore of Lake Superior. It seems to us that a much more probable suggestion is that the entire border of Lake Superior, with the possible exception of the south side of the east end, was the locus of a series of great fissures which extended inland from the lake for a very considerable distance, certainly in Wisconsin and Minnesota for at least 100 miles. That such fissures existed on an extensive scale is shown by the numerous dikes cutting the Huronian of the Gogebic district, presumably constituting necks for the flows of the Keweenawan just to the north. Some upper Huronian dikes in the Marquette district may also be so classed. Along the north shore of Lake Superior are many dikes which may well be related to the flows as necks. Farther to the west both basic and acidic intrusive dikes cut the flows of the Mesabi and Cuyuna districts. The convex outline of the Duluth gabbro laccolith away from the Lake Superior shore suggests a source somewhere in the direction of Lake Superior. It is not certain that similar vents may not underlie the lake.

No evidence has been found of volcanic vents. Fragmental ejectamenta of volcanoes are very subordinate in the Keweenawan lavas, and the extent of the lavas is greater than is usual for lavas coming from ordinary volcanoes.

So far as evidence is available, the lavas welled through widely distributed fissures certainly bordering and possibly underlying the present area of the lake.

It is well known that volcanism is a function of orogenic movements. In this connection it is to be noted that Keweenawan volcanism followed in general the axis of the Lake Superior synclinorium. Plutonic intrusives, probably equivalent in age to the Keweenawan flows, are the large granite masses cutting the slates of the Animikie group in the Cuyuna and St. Louis districts in central Minnesota, near the principal axis of deformation of the Lake Superior syncline. The lavas issuing from the many known fissures bordering the synclinorium doubtless flowed down the slopes toward the Lake Superior basin. The movement would be to the south from the north side, to the northwest from the south side, and to the west from the east side, and not improbably northeastward from the west end of the basin.

How far out into the basin of what is now the lake the orifices went is uncertain, but Stannards Rock, Michipicoten, and Isle Royal show that if they did not extend some distance beyond the shore the lavas have flowed a considerable distance. As the orogenic movements which produced the Lake Superior basin occurred largely during middle Keweenawan time the conditions would continue to be favorable for the further issuance of lava and the slopes would

[a] Collins, W. H., The quartz diabases of Nipissing district, Ontario: Econ. Geology, vol. 5, 1910, pp. 538-550.

[b] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 50-56.

remain adequate to control its flows, notwithstanding the tendency for the earlier lavas to lessen the slope. It is believed that the analogy of the Keweenawan lavas is with the Tertiary volcanic rocks of the West, such as those of the Snake and Columbia River plateaus, which were poured out from parallel and intersecting lines of fissures scattered over a broad area. In short the middle Keweenawan is believed to have been a time of fissure eruption, comparable with the great Tertiary outbreaks rather than with local volcanism, such as occurs at the present time.

SEDIMENTARY ROCKS.

SOURCE AND NATURE OF MATERIAL.

The sedimentary rocks of the middle Keweenawan are dominantly conglomerates and sandstones. Shales are subordinate. A light-red to dark-red color is very characteristic for the Keweenawan detritus interstratified with the lava beds. Among these rocks gray sandstones are unknown. The conglomerates range in coarseness from great bowlder conglomerates to fine conglomerates and these grade into sandstones and the sandstones into shales. All the sediments are interstratified with the lava beds.

The detritus of the sandstones and conglomerates is dominantly derived from the Keweenawan igneous rocks themselves. It comprises bowlders, pebbles, and grains of sand and includes materials from all varieties of the basic, intermediate, and acidic rocks. The ease of recognizing the fragments, which are of considerable size, has led to a closer study of the conglomerates than of the sandstones and shales.

Usually the coarse detritus of the conglomerates is largely or even dominantly from the acidic group of lavas—felsites, porphyries, and granites—and in places also from the intermediate rock, augite syenite, even where the sedimentary beds are between basic lavas. This is doubtless explained in a measure by the more resistant character of these formations as compared with the basic rocks, but it is also probable that the explanation rests partly in the fact that the acidic lavas were viscous and therefore they built up mountains which rose to great height and were subject to exceptional erosion, while the basic lavas formed areas of relatively low relief. Not uncommonly, however, where the conglomerates immediately overlie basic or intermediate rocks, detritus from this source is especially likely to be present and may be dominant. In some places, as in the localities near the mouth of Little Montreal River on Keweenaw Point, described by Hubbard,[a] the pebbles and bowlders are derived wholly from the earlier beds of lava. Thus between beds of melaphyre are melaphyre conglomerates and between beds of porphyrite are porphyrite conglomerates. Similarly between beds of felsite are felsite conglomerates. There are, however, all gradations from conglomerates whose pebbles and bowlders are derived largely or exclusively from the immediately subjacent flow to those in which the pebbles are from various sources and thus comprise basic, acidic, and intermediate materials all mingled in different proportions.

In the conglomerates the finer material between the pebbles is usually composed of detritus from the same rocks as the pebbles themselves. However, in a particular conglomerate the matrix may include material from different sources and in different proportions from that of the pebbles. Thus even in the melaphyre and porphyrite conglomerates described by Hubbard[b] the matrix is derived largely from acidic rocks.

Commonly many of the particles, even in the matrix, are sufficiently coarse to be composed of more than one mineral. But where the mechanical subdivision of the material has gone far, the original rocks are broken into their constituent minerals and thus in the matrix of the conglomerates there are likely to be minerals from the chief varieties of the original igneous rocks. Generally the original minerals from the acidic rocks are more noticeable, as the basic constituents are more subject to alteration. Still it is usually easy to recognize constituents from the basic rocks. Of these, magnetite, being the least destructible, is especially likely to be conspicuous.

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[a] Geol. Survey Michigan, vol. 6, pt. 2, 1898, p. 38.

[b] Idem, p. 21.

As a rule there have been extensive alterations of the constituents of the conglomerates. These are more pervasive in the matrix than in the original pebbles, but may extend throughout even large bowlders. As a result of this alteration there are commonly present the secondary minerals zeolite, chlorite, epidote, calcite, quartz, and in places copper, which have been brought in by infiltrating waters or have formed in place by metasomatic changes. Lane [a] has discussed the chemical features of one of these alterations.

The sandstones, so far as they have been studied, seem to have about the same variations as the conglomerates. In general the particles are composed largely of fragments of the same acidic rocks whose fragments compose the conglomerate. This means that their dominant constituents are feldspar and quartz, with which there is always more or less clayey material and abundant ferrite. Ordinarily also there are subordinate contributions from the basic rocks, which furnish feldspar, augite, and magnetite. Hematite staining the grains is also pervasive. Perhaps their most characteristic feature as compared with common quartzose sandstones is the fact that quartz is not a dominating constituent. As in the conglomerates, so also in the sandstone beds, secondary calcite, chlorite, epidote, and the other alteration products of the original rocks are common, and even copper is to be found here and there.

EXTENT OF SEDIMENTS.

As to the extent of the sediments interstratified with the lavas, the same statements may be made as with reference to the lavas; none of them are regional. In proportion as they are thick they naturally have a greater lateral extent. The thickest of these formations, the "Great" conglomerate of Keweenaw Point, which has a maximum thickness of 2,300 feet, has been traced for over 100 miles, and one of the comparatively thin conglomerates lying immediately under the greenstone of Keweenaw Point has been traced for a distance of 50 miles. A conglomerate bed may vary greatly along the strike in the proportion of the constituents from a particular source; also in thickness and coarseness. At many places where conglomerate beds thin they run laterally into sandstones or shales, the coarser fragments failing altogether. Finally, a single sedimentary bed along the strike may be split into more than one bed by interleaved lavas.

UPPER KEWEENAWAN.

The upper Keweenawan is confined to northern Wisconsin and Michigan, where it constitutes a great sedimentary division, consisting of conglomerates, sandstones, and shales. It extends from Manitou Island, east of Keweenaw Point, along the border of the outer end of Keweenaw Point, where its strike carries it out into the waters of Lake Superior at Gate Harbor. It reappears about 6 miles west of Eagle Harbor and extends continuously as a northwestward-dipping monocline to the head of Chequamegon Bay in Wisconsin, the other side of the synclinal fold being under the waters of Lake Superior. The peninsula north of Chequamegon Bay brings to the surface the north side of the syncline, so that inland to the southwest in Wisconsin the full fold is present in a canoe-shaped area.

The upper Keweenawan consists from the base up of the "Outer" conglomerate, the Nonesuch shale, and the Freda sandstone.

The "Outer" conglomerate on Keweenaw Point has a thickness of 1,000 feet. To the west it increases in thickness and at Black River apparently attains 5,000 feet. Farther west it becomes thinner, the thickness at Potato River being 800 to 1,200 feet and at Bad River only 350 feet. The "Outer" conglomerate has thus been traced from the east side of Manitou Island to Penokee Gap, a distance between 175 and 200 miles. Petrographically this conglomerate is like the conglomerate interstratified with the lavas and is therefore composed mainly of detritus from the acidic rocks.

Above the "Outer" conglomerate is the Nonesuch shale, which has been traced from Portage Lake to Bad River, a distance of 125 miles. Its thickness at Portage Lake is about

[a] Lane, A. C., The decomposition of a bowlder in the Calumet and Hecla conglomerate: Econ. Geology, vol. 4, 1909, pp. 158-173.

200 feet, at Montreal River 500 feet, at Potato River from 250 to 400 feet, and at Bad River 125 feet. Although this formation is chiefly shale it has interstratified sandstone layers, and unlike the sandstones and conglomerates interstratified with the lavas it contains large amounts of basic detritus. In places, indeed, the basic material is so abundant as almost to exclude the acidic. Thus at the base of the Nonesuch shale there is an important change in the character of the material of the Keweenawan sediments.

The Freda sandstone composes much the larger portion of the upper division of the Keweenawan. The apparent thickness of the entire formation is not less than 19,000 feet. Irving [a] gives the thickness of the sandstone exposed at Montreal River as 12,000 feet, and 7,000 feet of overlying beds are seen near Ashland. According to Irving it is a characteristic feature of this sandstone that quartz is very subordinate. Indeed, in places it is nearly quartzless. The detritus has therefore been derived dominantly from the basic igneous rocks and only subordinately from the acidic igneous rocks of the Keweenawan, and apparently the pre-Keweenawan rocks have contributed but small amounts of material. However, Lane [b] states that pebbles of banded jaspery hematite and other iron-bearing rocks occur abundantly in the "Outer" conglomerate and further that the detritus of the sandstones themselves is derived predominantly from the Huronian and Keewatin rocks. Probably the statements of Irving and Lane were made with different areas in mind, and more extensive studies of the upper Keweenawan are perhaps necessary in order to make exact general statements concerning the sources of its detritus.

As the upper Keweenawan is confined to Michigan and Wisconsin, it, like the middle and lower Keweenawan, fails to be regional in extent, although it has a greater linear and surface extent than the other two divisions. It is probable, however, that the upper Keweenawan originally occupied a large part of the Lake Superior basin. It is the softest division of the series and was therefore more deeply eroded than the others. At present the area once probably covered by this sandstone is occupied by the Cambrian sandstone or the waters of the lake.

RELATIONS TO UNDERLYING SERIES.

The Keweenawan rests unconformably on all of the lower series with which it comes into contact. This unconformity is so perfectly clear for the Archean gneisses that it has been recognized since the days of Logan, [c] that great geologist having noted this relation at Granite Island, on the north side of Lake Superior, and at several points on the east shore of the lake. The Keweenawan has unconformable relations with each of the Huronian divisions with which it comes into contact, but in earlier days the unconformity between the Keweenawan and the upper Huronian was not recognized.

The relations of the Keweenawan series and the Animikie group have been especially studied north of Thunder Bay, and here the Animikie was indurated and yielded well-rounded fragments to the Keweenawan basal conglomerate at many points. Details as to these relations are more fully given on pages 207–208. In the Penokee district the Keweenawan extends for many miles along the upper Huronian, and here there is evidence of even a greater erosion interval between the two series than on the north shore.

It has been noted that the Duluth gabbro at its bottom is in contact at many places with the Huronian and with the Archean. Near its border, in areas occupied by the rocks of these periods, are numerous dikes and bosses which are identical in chemical composition and even correspond very closely in mineralogical character with the Duluth gabbro. Indeed, some of the masses may be actually connected with the Duluth gabbro. There can scarcely be any doubt that these intrusive rocks in the lower series are of Keweenawan age.

The Keweenawan age of the great dikes and sills of diabase, which are so abundant in the Animikie group, is scarcely less clear. These dikes and sills are identical in their chemical and

[a] Mon. U. S. Geol. Survey, vol. 5, 1883, p. 230.
[b] Jour. Geology, vol. 15, 1907, p. 690.
[c] Logan, W. E., Report of progress to 1863, Geol. Survey Canada, 1863, p. 78.

mineralogical composition and in their structural and textural characters with those which are found in the Keweenawan itself east of the Animikie at Thunder and Black bays and west of the Animikie in Minnesota. Some of the capping diabases of the Nipigon basin may be flows resting unconformably upon lower Keweenawan, Huronian, and Archean rocks.

In the Penokee-Gogebic district numerous diabase dikes cut the iron-bearing formation. These have attitudes at right angles to the dips and in chemical composition are like the basic lavas on the overlying Keweenawan traps. It can hardly be doubted that these are the pipes through which the lavas issued.

The Animikie group, including the latest Huronian formations, is cut by acidic intrusive rocks which are almost certainly Keweenawan. The largest of these that has been recognized is the Embarrass granite of the Giants Range, the granites south of the Cuyuna district of Minnesota, and the granite intrusive into the Quinnesec schist of northeastern Wisconsin. Dikes of granite are known to cut the Animikie group along the Giants Range.

RELATIONS TO OVERLYING SERIES.

The lowest fossiliferous Cambrian rocks in the Lake Superior region are of Upper Cambrian age. These rest unconformably upon the middle Keweenawan in the St. Croix Valley and on the southeast side of Keweenaw Point. In the former locality an actual unconformable contact is observed, but in the latter the relations are complicated by faulting. The middle Keweenawan throughout is considerably tilted, while the Upper Cambrian beds are uniformly flat-lying. These facts prove only that the middle Keweenawan is pre-Upper Cambrian.

The upper Keweenawan is in contact only with the Lake Superior sandstone (supposedly Upper Cambrian), a red, quartzose sandstone outcropping along the southwest shore of Lake Superior. The feldspathic sandstones and shales of the upper Keweenawan grade conformably up into the red quartzose Lake Superior sandstone. Exposures of the gradation are observed on Fish Creek, on Middle River, and on St. Louis River. The only possible doubt about the gradation is the fact that the feldspathic sandstones and mud-cracked shales have not been absolutely proved to be Keweenawan, although from their character, distribution, and relations to the Keweenawan there is every reason to believe that they are the uppermost Keweenawan. At no place are there fragments of the Keweenawan sandstone within the Lake Superior sandstone. Finally, the upper Keweenawan sandstone and the Lake Superior sandstone are closely related in their deformation, for while the upper Keweenawan as a whole is folded, and the Lake Superior sandstone as a whole is flat-lying, along the axis of the synclinorium in the vicinity of Ashland and eastward, both are tilted. The western Lake Superior sandstone seems to be areally connected with the known Upper Cambrian of the St. Croix River valley and has been correlated with the Upper Cambrian. However, it is nonfossiliferous, areal continuity with the known Cambrian is not established, and it is entirely possible that the western Lake Superior sandstone as a whole may be older than the Upper Cambrian. If the Lake Superior sandstone is Upper Cambrian, as it is now correlated, then the upper Keweenawan is pre-Upper Cambrian.

In the absence of the Middle and Lower Cambrian, it is difficult decisively to prove that the Keweenawan is pre-Cambrian rather than Middle or Lower Cambrian. It has seemed to us, as it has to Irving,[a] to Chamberlin,[b] and, in fact, to most of the geologists who have studied this area, that in lithology, lack of fossils, deformation, and separation of the middle Keweenawan from the Upper Cambrian by unconformity the Keweenawan series as a whole is much more closely allied to the pre-Cambrian than to the Cambrian. Another group of geologists, while admitting all these differences, nevertheless hold that the Keweenawan is probably Cambrian.

Our reasons for assigning the Keweenawan as a whole to the pre-Cambrian rather than to the Middle or Lower Cambrian are summarized below. While we assume the Upper Cambrian

[a] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883. [b] Chamberlin, T. C., Bull. U. S. Geol. Survey No. 23, 1885.

age of the Lake Superior sandstone, these conclusions are not wholly dependent upon such interpretation of age of the Lake Superior sandstone.

The Cambrian is fossiliferous; the Keweenawan is not.

The Cambrian is largely a subaqueous deposit; the Keweenawan is largely subaerial.

The Cambrian contrasts with the Keweenawan in lacking volcanism.

The known Upper Cambrian is almost flat-lying. The same is true for most of the Lake Superior sandstone. The Keweenawan as a whole is tilted. In the few localities where the Lake Superior sandstone and upper Keweenawan are tilted together, this may be due partly to movements as late as the Cretaceous. Also, as already noted, there is possible doubt about the Upper Cambrian age of the Lake Superior sandstone. It is agreed by all that the known Upper Cambrian rests unconformably upon middle Keweenawan beds.

The Cambrian rests upon a peneplain of continental extent, over which the Paleozoic sea swept and deposited Paleozoic sediments, with overlap relations to the pre-Cambrian rocks. This sea did not reach the Lake Superior country until Upper Cambrian time, and parts of Canada were not reached until Ordovician time. If the Keweenawan is Cambrian it constitutes a marked local variation from the general uniform conditions of overlap. The upper Keweenawan sediments rest on a plane which cuts the pre-Cambrian peneplain at a considerable angle, as is well shown on Keweenaw Point. (See p. 97.) If the Keweenawan were to be regarded as Middle or Lower Cambrian, it would be necessary to conclude that the Middle or Lower Cambrian in this district had taken on remarkable local characteristics different from those of the Middle and Lower Cambrian elsewhere. On the other hand these local characteristics are accordant with those of the pre-Cambrian rocks of this area.

The similarity of lithology and accordance of structure between upper Keweenawan and Cambrian are the natural sequence of transgression of a sea over flat-lying sediments. The conditions are not different from those that would prevail if the ocean were to transgress to-day from the Gulf of Mexico across the flat-lying and little-consolidated Paleozoic sediments of the upper Mississippi Valley. It would be extremely difficult to prove the unconformity in any limited area, especially where exposures are not numerous. In fact, it is known that the Lake Superior basin was formed during Keweenawan time, and it is entirely probable that local sedimentation within this basin would merge upwards into the sedimentation from the overlapping Upper Cambrian ocean, while upper Keweenawan beds may locally have unconformably overlapped the lower-middle member, from whose detritus they are in large part built up. It is concluded that the Keweenawan is mainly pre-Cambrian.

Our view of the sequence of deposition is this: The main portion of the Keweenawan was put down in pre-Cambrian time. During and subsequent to its deposition folding developed the Lake Superior basin. In late Keweenawan time erosion of the lower beds near the rim of the basin and deposition of the upper beds within the basin were going on simultaneously. The deposition within the basin continued nearly or quite to the time that the Paleozoic sea, encroaching from the south, reached the basin. The Paleozoic sea then deposited its beds with marked structural discordance upon the lower-middle Keweenawan, and with substantial accordance upon upper Keweenawan beds in parts of the Lake Superior basin in which deposition was continuous up to the time of the arrival of this sea.

CONDITIONS OF DEPOSITION.

The question now arises as to the physical conditions under which the Keweenawan was laid down. According to the standard interpretation the widespread sandstones and conglomerates at the bottom of the Keweenawan would be taken as evidence that at the beginning of Keweenawan time this region was submerged. Under this interpretation the occurrence of sandstones and conglomerates between the lavas has been taken as evidence that the effusive rocks were largely submarine. The persistence of sedimentary beds such as those that occur at the upper horizons and especially the "Great" conglomerate of the middle Keweenawan has usually been taken as decisive evidence of this conclusion. However, work by Medlicott and

Blanford,[a] Walther,[b] Passarge,[c] Davis,[d] Huntington,[e] Johnson,[f] Barrell,[g] Chamberlin and Salisbury,[h] and others has emphasized the importance of continental sedimentary deposits. As yet the criteria for discriminating continental and submarine deposits have not been fully worked out, and therefore there must be considerable uncertainty as to our conclusions upon this matter concerning the Keweenawan, especially as the Keweenawan sediments have never been studied with reference to this particular point.

The following evidence we take to favor the terrestrial origin of at least a part of the Keweenawan:

1. The thickness of the sediments.

2. The repetition of conglomerate beds at many horizons through several thousand feet. This would involve too rapid fluctuation of water level for the beds to be satisfactorily explained as aqueous deposits. The continuity of thick beds of conglomerate also is in accord with terrestrial sedimentation, for subaqueous sedimentation is more likely to develop thick beds over only local areas, as about steep shores.

3. The feldspathic, poorly assorted, and almost completely oxidized character of the Keweenawan sediments, as shown by their prevailing red colors and lack of graphitic material. They also show locally alternating beds of red, yellow, and purple, suggestive of seasonal variations.

4. Many ripple marks in the Freda sandstone are of the horseshoe shape made by rills of water at the surface. These contrast with the ripple marks made by wave action.

5. The fact that except for alterations, the basic flows are in all essential respects like the subaerial basaltic lava flows of Tertiary time. Their upper and lower surfaces are amygdaloidal. Although in places their surfaces have a broken or pseudoconglomerate appearance, they usually lack the peculiar ellipsoidal structure which is characteristic of the Keewatin and Huronian basic lavas described in another place (pp. 510–512) and which has been shown to be especially characteristic of subaqueous basic lava flows.

6. The fact that the matrix of the basal conglomerate on the north shore is in places a limestone, suggesting deposition of evaporation under surface arid or semiarid conditions, as may be observed to-day in the Bighorn Mountains and elsewhere in the West.

7. The lack of fossils.

8. The general contrast with the underlying Huronian sediments, in which evidence of water deposition is fairly good.

9. Mud cracks are common in some shales.

10. The rapid alternation of thin beds of coarse unweathered débris with fine red mud-cracked and ripple-marked shales.

We are therefore inclined to believe that terrestrial deposition has played an important part in the development of this portion of the Keweenawan, but with the information now available we are unable to say how much of a part it has played.

The truth probably lies between the two extremes of the subaqueous and subaerial hypotheses; that is, the Keweenawan lavas and sediments were neither exclusively terrestrial nor exclusively subaqueous, though too little is known to warrant definite statements concerning their origin. For the middle and upper Keweenawan it is believed to be largely subaerial, but also in considerable measure subaqueous. When the orogenic movement and the period of volcanism of middle Keweenawan time were well under way it would be very natural that the areas where

[a] Medlicott, H. B., and Blanford, W. T., Geology of India, 2d ed., revised by R. D. Oldham, 1879, pp. 149-156, 391-458.

[b] Walther, Johannes, Das Gesetz der Wüstenbildung, Berlin, 1900.

[c] Passarge, Siegfried, Die Kalahari, Berlin, 1904.

[d] Davis, W. M., The fresh-water Tertiary formations of the Rocky Mountain region: Proc. Am. Acad. Arts and Sci., vol. 35, 1900, pp. 345-373; Bull. Geol. Soc. America, vol. 11, 1900, pp. 596-601, 603-604; A journey across Turkestan: Carnegie Inst. Washington, Pub. 26, 1905.

[e] Huntington, Ellsworth, Pulse of Asia, 1907.

[f] Johnson, W. D., The High Plains and their utilization: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 4, 1901, pp. 609-741.

[g] Barrell, Joseph, Origin and significance of the Mauch Chunk shale: Bull. Geol. Soc. America, vol. 18, 1907, pp. 449-476; Relations between climate and terrestrial deposits: Jour. Geology, vol. 16, 1908, pp. 159-190, 255-295, 363-384.

[h] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 2, 1906.

the flexures were large and where the lavas were issuing rapidly, that is, along the border of the lake, should be above the water. However, the movement producing the synclinal basin would certainly make a depression in the center of the lake which would naturally be filled with water. Thus along the borders of the Keweenawan the conditions may have favored terrestrial deposits and in the basin of the lake the conditions may have favored subaqueous deposits, and at the shore zone there were various combinations of the two.

If these tentative conclusions are correct, the question still remains open as to whether the water-deposited parts of the Keweenawan were submarine or continental, for deposits laid down in great lakes are usually classed as continental. Whether this basin connected with a sea or was inclosed there is now no means of knowing, unless the possible extension of the Keweenawan into central Minnesota, cited on pages 376–379, may indicate such a connection.

THICKNESS OF THE KEWEENAWAN ROCKS.

In the descriptions of the individual districts the estimated thicknesses of the Keweenawan have been given. Wherever there is a full section the estimated thickness is very large. For northern Minnesota it is 17,000 or 18,000 feet exclusive of the gabbro laccolith, for northern Wisconsin and Michigan a maximum of 60,000 feet, and for Mamainse, at the east end of Lake Superior, 16,000 feet. Only relatively small parts of these thicknesses are made up by the sediments. There are a number of factors which make all these estimates of very uncertain accuracy. The more important of these factors are faults, intrusive rocks, and initial dips.

It has been seen that during the formation of the Lake Superior syncline strike, dip, and bedding joints and faults were produced, and that some of the strike faults are of great magnitude. The different conglomerates and lava beds of the middle Keweenawan are very similar lithologically and it is therefore extremely difficult, indeed usually impossible, to recognize the individual beds except those of large size, like the "Great" conglomerate. Hence, it has only been in the vicinity of the mining areas, where studies of the most detailed nature have been made, that the extent of the faulting is appreciated. There can be no doubt that strike faults have repeated the beds at numerous localities. It is to be said that the close studies of Hubbard[a] on Keweenaw Point, those of Gordon[b] at Black River, those of Lane[c] on Isle Royal, and those of Burwash[d] at Michipicoten have not discovered faults which have repeated the beds of these areas to any considerable extent. It has been seen, however, that the strike fault between the north and south ranges of Keweenaw Point reproduces the lower parts of the rocks of the Keweenawan in the south range. Similarly it is probable that between Isle Royal and Black and Nipigon bays is a great strike fault which results in the repetition of the Black and Nipigon bays Keweenawan on Isle Royal.

In the estimates of the thickness of the Keweenawan the intrusive rocks have been ignored. It is certain that in northern Minnesota the intrusive lavas constitute a considerable proportion of the igneous rocks of the Minnesota coast. Also it is suspected that closer studies will show that the intrusive rocks are more extensive in other areas, as, for instance, at Keweenaw Point, than has been supposed. Indeed, the recent studies of Hubbard[a] have shown this to be true for the acidic rocks, but as yet studies have not been made along the same lines for the basic rocks.

In estimating the thickness of these rocks no account has been taken of initial dips. It is well known that the initial dips of basic lavas and all coarse conglomerates are in many places higher than 10°, and they may be more than 20°. This statement applies both to subaqueous and to subaerial deposits.

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[a] Hubbard, L. L., Keweenaw Point, with particular reference to the felsites and their associated rocks: Geol. Survey Michigan, vol. 6, pt. 2, 1898.

[b] Gordon, W. C., assisted by A. C. Lane, A geological section from Bessemer down Black River: Rept. Geol. Survey Michigan for 1906, 1907, pp. 397-507.

[c] Lane, A. C., Geological report on Isle Royale, Michigan: Geol. Survey Michigan, vol. 6, pt. 1, 1898.

[d] Burwash, E. N., The geology of Michipicoten Island: Univ. Toronto Studies (Geol. ser.), No. 3, 1905; with map.

There thus arises, in connection with the middle Keweenawan especially, the same problem that arises in determining the thickness of a delta deposit, the larger portion of which (the foreset beds) in a great delta has rather steep initial dips. If such a delta could be truncated through its central part and the thickness of the beds determined on the basis of dip it might be calculated that the delta represents many thousands of feet of strata, although as a matter of fact the deposit might not be vertically more than a few hundred feet thick. (See fig. 58.) However, there are reasons for believing that a large angle of dip is due to orogenic movements, and such an angle is sufficient to allow a large thickness.

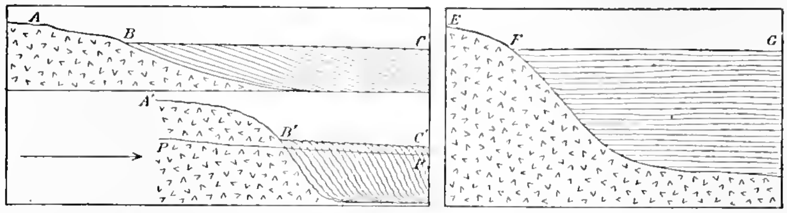

FIGURE 58.—Diagrammatic section illustrating the assigned change of attitude of a series of beds, like the Keweenawan, from an original depositional inclination (*B–C*) to a more highly inclined attitude (*B′–C′*), a comparatively simple change. If the beds were laid down horizontally in a sinking basin, as illustrated at the right (*F–G*), it is obvious that a greater and a more complicated movement would be necessary to bring the beds into the attitude represented in the lower figure at the left, which represents the present attitude of the Keweenawan beds. (After Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 2, 1906, fig. 110.)

Because of the factors named above it is extremely probable that all the estimates of the thickness of the Keweenawan based on appearances are excessive. To what extent they are excessive is a matter of conjecture, but we suspect that the vertical thickness of the Keweenawan at the time it was formed was probably not more than half and possibly only a third of the apparent thickness.

AREAS OF KEWEENAWAN ROCKS.

The areas of the different phases of the Keweenawan in square miles are as follows:

North shore:			
Basic intrusive rocks	2,170		
Acidic intrusive rocks	550		
Basic extrusive rocks	1,950		
		4,670	
Sediments		752	
			5,422
South shore:			
Basic intrusive rocks	95		
Acidic intrusive rocks	145		
Basic extrusive rocks	4,500		
		4,740	
Sediments		2,070	
			6,810
East shore:			
Basic extrusive rocks			145
Grand total			12,377
Total area of basic intrusive rocks			2,265
Total area of acidic intrusive rocks			695
Total area of basic extrusive rocks			6,595
Total area of sediments			2,822

VOLUME OF KEWEENAWAN ROCKS.

From the foregoing figures of thickness and area it is apparent that the volume of the Keweenawan rocks is very large. For the extrusive rocks an area of 6,000 square miles and a thickness of 4 miles would give a volume of 24,000 cubic miles. For the sediments an area of 2,800 square miles and a thickness of 4 miles would give a volume of 11,200 cubic miles.

These figures leave out of account the enormous masses of intrusive rocks. If the gabbro has a circular outline, as indicated by the convex border of Minnesota, and if its southern border is indicated by the Gogebic district, the diameter would be about 100 miles. With the ratio of thickness to diameter given by Gilbert [a] for the Henry Mountains the maximum thickness would be 15 miles. On calculating the thickness in another way, by assuming an average dip of 10° for a distance of 50 miles on the north shore, a maximum thickness of 8½ miles is obtained. With a thickness of 8½ miles at the center and a diameter of 100 miles approximately 30,000 cubic miles may be figured for these intrusive rocks.

Although these figures merit little consideration as actual measurements, it is believed that they are of value in showing the enormous dominance in volume of the igneous rocks over the sediments and of the intrusive igneous rocks over the extrusive igneous rocks. Reduced to terms of mass, these figures would be somewhat changed, but the essential conclusions would not be altered.

LENGTH OF KEWEENAWAN TIME.

Because of the facts discussed in the foregoing section on thickness it is of course impossible to give any estimate of the time involved in the deposition of the Keweenawan series, but allowing a wide margin for overestimates of thickness we can hardly escape the conclusion that the Keweenawan probably required as long a time for its formation as the average geologic period, such as the Silurian, Devonian, and Carboniferous, and it may have been as long as the Cambrian.

JOINTING AND FAULTING.

Commonly, where the dip of the lava beds is considerable, the beds are cut by two sets of joints, one of strike joints and the other of dip joints. Both sets are approximately at right angles to the beds, but the plane of the strike joints contains or does not vary greatly from the line of strike, and the plane of the dip joints contains or does not vary greatly from the line of dip. These positions for the joints have been noticed by Grant [b] for northern Wisconsin and by Hubbard [c] for northern Michigan. In many places there are also joints parallel to the beds or between them, and these may be called bedding joints. Where the intrusive rocks have disturbed the lava beds the jointing is very much less regular.

As would be expected in a fractured series of rocks, there is also somewhat extensive faulting. Indeed, faulting has been discovered in almost every locality where close studies have been made, but usually the greater number of the faults are not of sufficient magnitude to be an important factor in the stratigraphy. Like the joints, the common faults may be divided into strike faults and dip faults, there being a general correspondence between the planes of the faults and those of the joints. Most of the dip faults have no great throw, although locally the displacement may be very considerable. A beautiful illustration of the dip faults is furnished by Hubbard [d] for the West Pond area on the south side of Keweenaw Point. (See p. 383.) F. E. Wright's detailed mapping of the Porcupine Mountains and vicinity [e] discloses a large number of both strike and dip faults.

Some of the strike faults are of great magnitude and extent. The greatest of these known is that at the southeast side of the Keweenawan series, extending from the end of Keweenaw Point along the border of the Keweenawan to Gogebic Lake. Another great strike fault is known in Douglas County, in northern Wisconsin, and in Minnesota along the northern border of the Keweenawan. Both of these faults are at the contacts of the Keweenawan and the Lake Superior sandstone, and it is believed that the newer series represents the downthrow side. If so, this downthrow was to the south of the Keweenawan at Keweenaw Point and to the north of it in Douglas County. The latter fault plane dips 38° to 45° S. and in Wisconsin at least has aspects of an overthrust fault.

Martin (see pp. 112–115) concludes on physiographic grounds that there is a fault along the Minnesota coast having a throw of at least 1,000 feet. There is nothing to show that the throw

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[a] Gilbert, G. K., The geology of the Henry Mountains, 2d ed.: U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1880, p. 55.

[b] Grant, U. S., Preliminary report on the copper-bearing rocks of Douglas County, Wis.: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 6, 2d ed., 1901, p. 21.

[c] Hubbard, L. L., Keweenaw Point, with particular reference to the felsites and their associated rocks: Geol. Survey Michigan, vol. 6, pt. 2, 1898, pp. 19, 26, 35.

[d] Idem, pp. 87, 91.

[e] Ann. Rept. Geol. Survey Michigan for 1908, 1909, Pl. I.

is not much greater than this amount. The evidence given by Martin confirms what was before a belief as to the existence of this fault, based on the fact that if there were not such a fault between Isle Royal and the mainland, repeating the beds, it would be necessary to accept an almost incredible thickness for the Keweenawan. The faults in the zone between Isle Royal and the Minnesota coast are probably an extension of that in Douglas County, Wis., or, if not, they accomplish for the Minnesota area corresponding adjustment of the Keweenawan during deformation.

Just as there are bedding joints there are also bedding faults. These are especially likely to occur between the different beds of lava or of lava and conglomerate. In many of them the dip is slightly steeper than the bedding. The direction of movement along these bedding faults may be parallel to the strike, parallel to the dip, or at any angle between them. Although this is true, it would be natural to expect that the most common movement along the bedding faults would be approximately parallel to the dip, this being the natural direction of differential movement between beds in a folded series. As to the direction of movement along the dip, by differential movement in a fold of ordinary magnitude the higher bed moves upward as compared with the lower bed, but it is far from certain that this rule would hold in a great simple synclinorium like that of Lake Superior. It might be that gravity would be more important than the strength of the beds and that the upper members would move downward as compared with the lower.

Hubbard[a] and Lane[b] conclude from their close study of the Keweenawan district that bedding faulting or slide faulting is very common. Hubbard finds that at least one slide fault substantially parallel to the dip has a very large movement. Lane[b] says that many of the slide faults have a slightly steeper hade than the dip. The details of these occurrences are given in the section on Keweenaw Point (p. 383).

Along any of the faults there may be slickensides or even brecciation. Such brecciation is especially prevalent at the bedding faults, which follow an amygdaloidal lava surface, one of their most common positions, because the amygdaloidal belts are planes of weakness.

It will be seen on pages 575–576 that the several classes of fractures and faults have a very important bearing on the development of ore bodies.

The time of the fracturing is partly contemporaneous with the folding of the series and partly later; how much later is not known. Some of the faults, notably the great faults bounding the Keweenawan series on Keweenaw Point and in Douglas County, Wis., are partly post-Cambrian. It has been suggested by Wilson[c] and Weidman,[d] from work in other areas, that faulting may have affected these rocks as late as Cretaceous time.

THE LAKE SUPERIOR SYNCLINAL BASIN.

It is little short of certain that the great Lake Superior synclinal basin began to form during middle Keweenawan time. The general character of this syncline is admirably exhibited in figure 59, from Irving, and by the sections on the general map, Plate I. This synclinal basin is rather remarkable for its simplicity. Indeed only at one place does Irving figure a subordinate fold, that at Porcupine Mountains. The strikes and dips of the rocks show several prominent flexures, however, as, for instance, along St. Croix River of Wisconsin, near Ashland and Clinton Point at the head of Lake Superior, and at Michipicoten Harbor. Later strike faults have considerably modified the syncline. Doubtless future close studies will show that the Lake Superior synclinorium has a greater complexity in detail than has been supposed. Certainly one very important subordinate basin, that of Lake Nipigon, must be attached to the major synclinorium. It is to be remembered that along the main shore line and outer islands of Black and Nipigon bays the middle Keweenawan is found with lakeward dips at angles of

[a] Op. cit., pp. 87–91.
[b] Lane, A. C., Geology of Keweenaw Point, a brief description: Proc. Lake Superior Min. Inst., vol. 12, 1907, pp. 83–84.
[c] Geol. Soc. America, winter meeting, December, 1908.
[d] Personal communication.

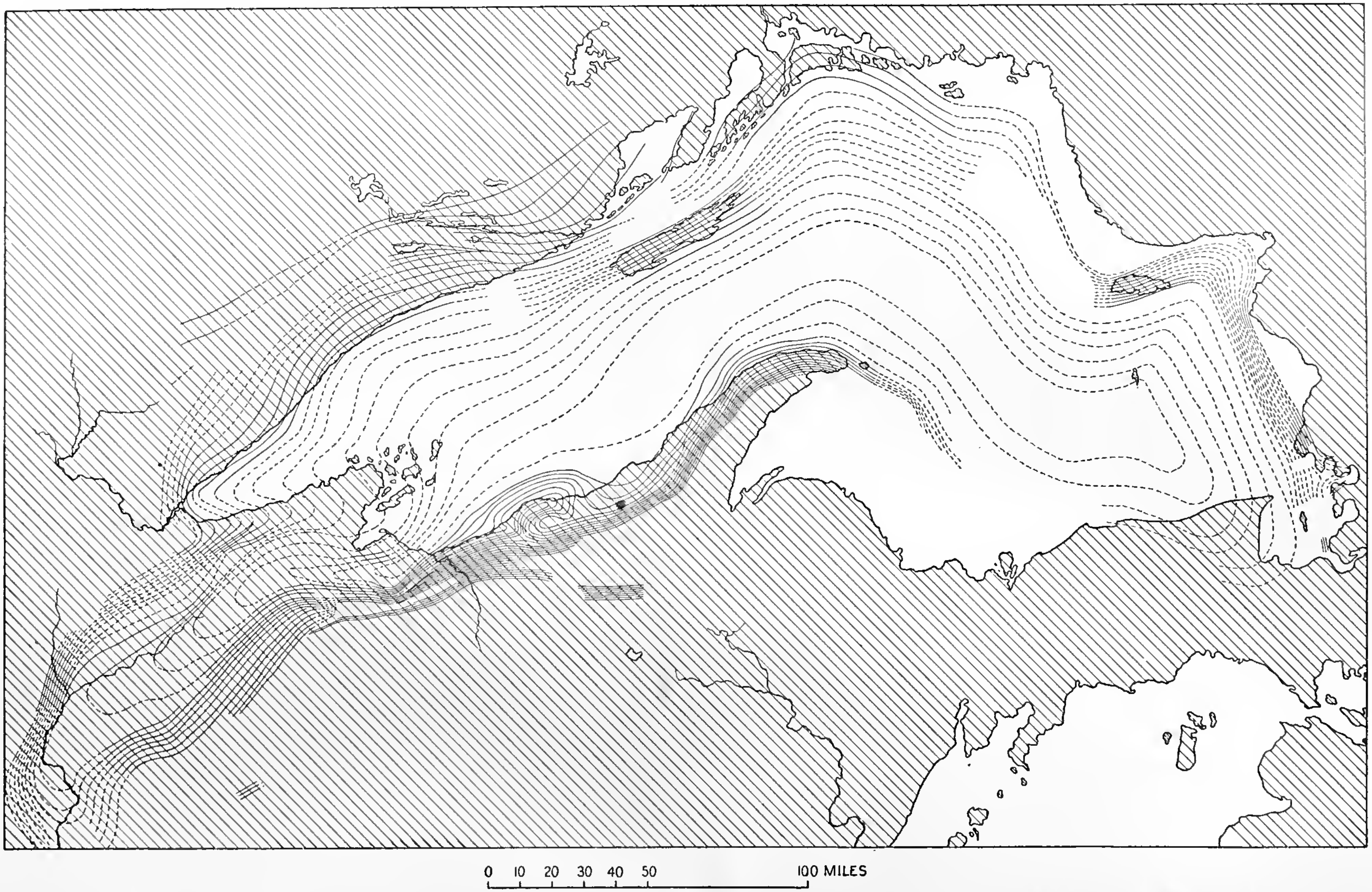


FIGURE 59.—Map of the Lake Superior basin, designed to show the structure and extent of the Keweenawan trough. (After Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, Pl. XXVIII.) The spaces between the contour lines of the map represent a total of approximately 2,500 feet of Keweenawan or copper-bearing beds. Where the dip is high the lines are closer together, and vice versa. Where thinning of the beds has been proved to exist, the lines are also made to approach, and in some places two or more coalesce into one on this account. The full lines are based on observation; the broken lines are more or less hypothetical.

8° to 10°. In the peninsulas between Thunder, Black, and Nipigon bays the lower Keweenawan lies substantially flat. Farther to the north the middle Keweenawan reappears, overlying the lower division with northern dips. It thus appears that at Black and Nipigon bays there is a subordinate anticlinal arch, which separates the great synclinal fold of Lake Superior from the subordinate synclinal fold of Lake Nipigon. The latter lake is in a subordinate basin of Keweenawan rocks, just as Lake Superior is in a great basin of that series.

Similarly Batchewanung Bay, at the east side of the Lake Superior basin, is a subordinate synclinal fold. A part of the shore is Archean. Inside of this is a fragmentary border of Huronian almost cut away; inside of this a partial border of Keweenawan, and the center of the basin is filled with Cambrian. In short this bay is a miniature of the Lake Superior basin, containing the four great divisions of rocks of the region—the Archean, Huronian, Keweenawan, and Cambrian—in a synclinal basin.

It has been seen that in general in any one section the dips are much steeper at the lower horizons than at the higher horizons. It is certain that the present dips at the lower horizons are largely due to the folding which formed the Lake Superior basin. To illustrate: The Keweenawan lava flows and sediments north of the Gogebic range have the same dip as the upper Huronian sediments, and therefore the main dips of both must have been produced by orogenic movements. Indeed it is thought probable that in general the major portion of the dips of the most steeply inclined lavas is due to orogenic movements, for the natural position of repose for basalts, such as those of Kilauea, is with dips of 10° to 18°. It is reasonably certain that if 15° is subtracted from the lakeward dip of the basic lavas the remainder of the dip is due to orogenic movement. The steadily lessening dips of the lavas at higher horizons are therefore to be largely explained by the progress of the orogenic movement which produced the Lake Superior basin, although they are doubtless in part explained by the natural lessening of the dip toward the center of a synclinal fold.

To illustrate again: In the Black River section the dips at the base are from 75° to 78° N., and at the highest strata exposed on the "Outer" conglomerate only 20°. In the Keweenaw Point section the lavas at the south side dip 55° N. and those of the middle division at the north side dip 25°, and it may be supposed that during the time in which the lavas and conglomerates of the middle Keweenawan in this area were built up the synclinal movement had tilted the lower beds 30° as a maximum, but from this amount to obtain the actual tilting there must be subtracted the unknown amount which is due to the normal decrease in dip toward the center of a syncline. Similarly at Michipicoten, on the northwest side of the synclinorium, the basal beds have a dip of 55° SE., and at the top of the exposed sections on the islands south of Michipicoten the dip is 14°, a maximum difference of 41°, which may be attributed to orogenic movement during the formation of the middle Keweenawan in this part of the region. The same thing is illustrated at Isle Royal, where at the southwest end of the island the dips on the north side are 16° and on the south side 8°, and at the east end of the island the dips on the north side are 26° and on the south side 18°. It thus appears that the decrease in dip from the north to the south side is 8°, without reference to the steepness. This fact strongly suggests that the steeper dips at the northeastern part of the island as compared with the southwestern part are to be explained by greater orogenic movements in that part of the island, and thus gives a confirmation to the suggestion made that the steep dips are mainly due to orogenic movement rather than to the original angle of deposition. The folding of the basin was practically complete at the end of Keweenawan time, but in post-Cambrian time and possibly in post-Cretaceous time the region suffered the great strike faulting already noted.

METAMORPHISM.

For the most part the metamorphism of the Keweenawan igneous rocks is that of the zone of katamorphism. The alterations, fully described by Pumpelly[a] and Irving,[b] have produced very extensive changes in the lavas, especially those which were scoriaceous. The

[a] Pumpelly, Raphael, Metasomatic development of the copper-bearing rocks of Lake Superior: Proc. Am. Acad. Arts and Sci., vol. 13, 1878, pp. 253–309.

[b] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883.

important secondary minerals produced in the basic rocks are the zeolites, epidotes, chlorites, calcite, quartz, laumontite, prehnite, datolite, etc. Many of the thin vesicular beds are largely transformed to these substances and the vesicles have been filled with them, forming amygdules. Although the porous beds are extensively altered, the massive centers of the thick lava flows, the dike rocks, and the sills and laccoliths are very fresh; indeed some of them are almost as little altered as similar rocks of Tertiary age. The felsite and quartz porphyries have undergone the usual metasomatic alterations for ancient acidic lavas. The glasses have devitrified. A wide variety of secondary minerals have formed, but they occur usually in such minute particles as to be determinable with difficulty.

The alterations of the Keweenawan lavas doubtless began as soon as they were consolidated. The process continued through Keweenawan time and the great erosion period between the Keweenawan and Cambrian, and indeed is still going on.

The alterations of the sedimentary rocks vary greatly in degree. The lower and middle Keweenawan sediments are much more changed than those of the upper Keweenawan. In the sandstones and conglomerates interstratified with the lavas the same metasomatic change took place as in the lavas, resulting in the formation of a like group of secondary minerals. The filling of the openings between the grains and pebbles, strictly analogous to the filling of the openings in the vesicular lavas, has been nearly complete, thus thoroughly indurating the rocks. The cementing materials in the sandstones and conglomerates interstratified with the lavas are much more varied than those of ordinary cementation. It was in these rocks that the senior author first noted the secondary enlargement of detrital feldspar. So thoroughly have the clastic materials been cemented that where the rocks have not been weathered fractures commonly pass across both pebbles and matrix. The sandstones are intermediate between sandstones and quartzites in their cementation. Though these sediments are well indurated they certainly are less metamorphosed than similar sediments of the Animikie group. Inasmuch as the conditions since they have been laid down have been practically the same as those that have affected the Animikie beds, upon which they rest, this difference in metamorphism confirms the conclusion as to a considerable time break between the two series.

The cementation in the sandstones of the upper Keweenawan has not proceeded so far as in the detrital rocks of the middle division. Indeed these sandstones are very similar to those of Cambrian age. The individual particles of these sandstones, being largely basic, are usually much altered, but it is difficult to say what part of these changes have taken place since they were deposited as sandstones and what part took place before they were broken from the lavas from which they came.

The segregation producing copper ores was an incident of the metasomatic changes above summarized, and the details of it are considered in another place (pp. 580 et seq.)

The intrusive rocks, especially the great basal gabbros, and the large masses of acidic rock, as has been noted in another place (p. 411), produced profound anamorphic changes in the pre-Keweenawan rocks which they cut. It is believed that later studies will show that in connection with the deep-seated batholiths of Minnesota and Wisconsin anamorphic changes will be found in the intruded Keweenawan lavas and sediments, but as yet studies have not been made along the border of the gabbros in order to ascertain whether or not this conjecture is correct. This suggestion gains much probability from the fact that along the borders of the much smaller laccolith of Black River in Michigan F. E. Wright has found the intruded Keweenawan lavas and sediments to be greatly metamorphosed.

RÉSUMÉ OF KEWEENAWAN HISTORY.

From the facts which have been presented we may make the following general statements:

After the great epoch of upper Huronian deposition the Lake Superior region was raised above the sea and was subjected to denudation for a long time, during which the erosion amounted to thousands of feet. The Keweenawan period was begun by the deposition of sediments, consisting of conglomerates, sandstones, shales, and limestones, now found generally at the base of the known intrusive part of the Keweenawan where it has been looked for. These may be subaerial deposits.

After the deposition of sediments of very moderate thickness occurred the events of the middle Keweenawan, which especially characterize the series. The chief event was the outbreak of regional volcanism in the larger part of the Lake Superior basin.

In a large part of the region, and perhaps all of it, igneous rocks practically excluded sediments in the lower portion of the middle Keweenawan. Igneous rocks, with an almost inappreciable proportion of sediments, constitute the Minnesota coast, the lower eight-ninths of the Eagle River section, nine-tenths of the Portage Lake section, all of the Douglas County range of Wisconsin, all of the 4,000 feet of the Taylors Falls section, more than eleven-twelfths of the section at Black River, and about 4,000 feet, or one-fourth of the section, at Mamainse. It does not follow that the time represented by the sediments may not be as long as or even longer than that represented by the lavas. After the period of dominating volcanism had continued until thousands of feet of lava had been built up, there was a decrease in volcanic activity and the sediments again became of sufficient importance to be recognized in the section. This was the later part of the middle Keweenawan.

The change in conditions in the middle Keweenawan by which the sediments, insignificant in the lower part, became important in the upper part is not supposed to have occurred at the same time over the entire Lake Superior basin. Indeed, it seems extremely probable that the change was not simultaneous in all parts of the region. This may be illustrated by the Portage Lake and Eagle River sections on Keweenaw Point. The alterations of notable masses of sediments with the lavas seem to have become important in the Portage Lake section before they did in the Eagle River section, for at Eagle River lavas, to the practical exclusion of sediments, constitute all but the upper 5,000 feet of the middle Keweenawan, whereas at Portage Lake the portion containing sediments is much thicker.

As the middle Keweenawan epoch neared its close igneous activity ceased. In northern Michigan the longest cessation of volcanism was marked by the deposition of the "Great" conglomerate, which is locally more than 2,000 feet thick. After this conglomerate was laid down there were further outbreaks of volcanic activity, which resulted in the "Lake Shore" trap. But the outbreaks represented by this formation were relatively feeble, as is indicated by the fact that the lava beds are separated by conglomerates of considerable thickness. For Michigan this "Lake Shore" trap represents the last dying effort of the epoch of regional volcanic activity.

Thus middle Keweenawan time witnessed a sudden beginning of volcanic activity, which was dominant for a long time, then intermittent volcanic activity, then total cessation. Evidence has been presented which seems to favor the view that the middle Keweenawan was deposited largely under subaerial rather than subaqueous conditions.

The present distribution of the middle Keweenawan shows that much, if not all, of the Lake Superior basin must have been covered by volcanic flows, for the igneous material, besides occurring along the rim of the lake, constitutes Isle Royal, Michipicoten, and Stannard Rock, off Marquette.

During middle Keweenawan time there were at least two alternations of basic and acidic rocks, and locally between basic and acidic rocks of the first cycle there were intermediate rocks, as on Keweenaw Point and Isle Royal. Whether these cycles were general for the Keweenawan over the Lake Superior region and whether there were more cycles than two is as yet undetermined.

As already stated (p. 410), during middle Keweenawan time, contemporaneous with and following the extrusions of the lavas, there were also intrusions, and these intrusive rocks are of very great quantitative importance. In many places in the lava series the intrusions in the form of beds and dikes compose a considerable percentage of the mass. Although the intrusives to a large extent rose into the middle Keweenawan beds, still greater masses spread out approximately along the contact between the Keweenawan and the lower rocks, and also between the layers of the lower formations. The vastest intrusive body of this class is the great Duluth laccolith, which extends from Duluth to the international boundary and has a breadth reaching 30 miles. Another of these great intrusive masses is that at Bad River. The bodies intruded between the beds of the Animikie group are so prominent that they have been called the Logan sills. The so-called crowning overflow of Thunder Cape may fall here. The peculiar topography of the steep cliffs about Thunder Bay and Pic Island is due largely to these intrusive flat-lying sills. The acidic rocks intrusive in the lower Keweenawan are also important. Granite bosses of considerable size intrude upper Huronian rocks in central Minnesota and northeastern Wisconsin.

During middle Keweenawan time progressive folding of the Lake Superior basin went on, with the result that the upper beds have a lower dip than the lower ones.

Conformably upon the rocks of the middle division were built up the sediments of the upper Keweenawan. These sediments consist, in ascending order, of the "Outer" conglomerate, having a maximum thickness of 5,000 feet; the Nonesuch shale, having a maximum thickness of 500 feet; and the Freda sandstone, having a maximum thickness of 19,000 feet. As the "Outer" conglomerate lies directly upon the basic lavas and in its main mass is lithologically like the conglomerates interstratified with the lavas there is no reason to suppose that the conditions at the time this conglomerate was deposited were in any way different from those prevailing at the time of the earlier conglomerates, except that late in the epoch detritus from pre-Keweenawan rocks appeared. Beginning with the Nonesuch shale, the sediments are of a different character from those lower in the Keweenawan series. This formation and the Freda sandstone are largely and in places mainly composed of detritus derived from the basic lavas. Also, they contain contributions from the Huronian, Keewatin, and Laurentian rocks. This means that by the erosion of the basic lavas, or by this cause combined with uplift, the pre-Keweenawan became the subject of attack by atmospheric agents. The relative lack of abundance of material from the acidic lavas may also mean that the volcanic mountains composed of acidic rocks had by late Keweenawan time become so reduced as to yield only a small amount of material.

As the change in the nature of the materials of the sediments from those interstratified with the lavas to the Freda sandstone was gradual, there is no reason to place a break at any definite horizon. Volcanic activity gradually died out, orogenic movement and erosion continued, and these afford sufficient explanations for the increasing variety of the detritus of the upper Keweenawan.

As the Nonesuch shale and Freda sandstone together are of very great thickness and are made up of fine-grained sediments, there must have been steady and long-continued subsidence of the basin where these formations were deposited. Also, their volume is so great as to indicate steady uplift in some other part of the region, exposing the lavas and other rocks to erosion.

The development of the Lake Superior syncline continued to the end of Keweenawan time and was then substantially complete. The basin was modified afterwards only by post-Cambrian faulting.

Keweenawan sedimentation was largely subaerial, but it may have become subaqueous toward the close of the period in the water-filled Keweenawan syncline and may have ultimately merged into Upper Cambrian subaqueous deposition.

CHAPTER XVI. THE PLEISTOCENE.

By Lawrence Martin.

THE GLACIAL EPOCH.

PLAN OF PRESENTATION.

The statement that the Lake Superior region has been invaded and profoundly modified by a continental glacier or ice sheet does not require proof. It will suffice to name some of the localities in which the proofs are found and to describe the glacial phenomena and their effects on the present topography and the life of the region.[a]

The ice, which advanced from two centers, one east and one west of Hudson Bay, in a series of lobes, oscillated so that glacial deposits thought to be of two or more ages were produced. The latest of these are called the deposits of the Wisconsin stage of glaciation and cover the greater part of the area here discussed. In advancing, the ice produced striæ, roches moutonnées, cirques, broadened, deepened, and hanging valleys, etc. It transported great quantities of the materials eroded in producing these forms. As the ice melted, these materials were deposited as an overmantle of glacial drift. The drift, which is partly stratified, was formerly known as modified and unmodified drift. Later studies show, however, that the largely unstratified (unmodified) drift, including terminal or recessional moraines, ground moraine, and drumlins, was deposited directly by the ice. The drift deposited by running water either under or in front of the ice or in standing water is stratified, though not essentially modified, and includes outwash deposits, lake deposits, loess, kames, eskers, etc. Most of these varieties of drift are found both in the older and in the latest glacial drift, as will be discussed. In all the glaciated area the drainage was greatly modified by the erosion and deposition due to the ice. During deglaciation there was a great series of marginal glacial lakes, the ancestors of the present Great Lakes. Since the glacial period there has been warping in the region, resulting in tilting of the shore lines of the former lakes. Streams have made slight modifications of the glacial drift and of the topography of the land. The lake shores, especially those of Lakes Superior and Michigan, are the seat of active work, and in these lakes the detritus carried from the land by the rivers and from the shores by waves and currents is being deposited.

ICE ADVANCES.

The scratches and grooves upon the ledges in the Lake Superior region afford the principal evidence of the direction of movement of the glaciers, and the sketch map (fig. 60) is a generalization based on these marks. It will be seen that in general the ice moved in a series of lobes of which those in the Lake Michigan basin, the Lake Superior basin, and the valley of Red River were the most important, the lobes between these, especially one extending from the highland region of northern Wisconsin, known as the Chippewa-Keweenaw lobe, and one extending from the highland region of northern Minnesota, known as the Rainy Lake lobe, being less extensive.

[a] The author is indebted to Messrs. Frank Leverett and W. C. Alden, of the United States Geological Survey, who have more recently done detailed work on the glacial features of the south coast of Lake Superior and in eastern Wisconsin, respectively, for critical suggestions concerning this chapter. The author, however, assumes responsibility for any errors in interpretation.

The ice which overspread the Lake Superior region came from two principal sources, one in the highlands of eastern Canada, generally called the Labrador glacier, and one in the region west of Hudson Bay, usually known as the Keewatin glacier. It seems probable that fully two-thirds of the ice which covered the Lake Superior basin came from the Labrador glacier. It is supposed, however, that this glacier was not the first to spread over the region, but that the Keewatin glacier, while largely synchronous and confluent with the Labrador glacier, arrived earlier and stayed longer, probably advancing over parts of the region formerly covered by lobes of the Labrador glacier after these lobes had retreated to the northeast. Whether or not the ice advance from the northwest covered all the Lake Superior region is unknown.

In the area covered by this monograph the glacial lobes were profoundly affected by the areas of highland and lowland, and, as would naturally be expected, the ice was the thickest and moved fastest in the deepest depressions; consequently, the Lake Michigan lobe of the Labrador glacier (figs. 4, p. 87, and 60) extended farther south than any of the others, and the

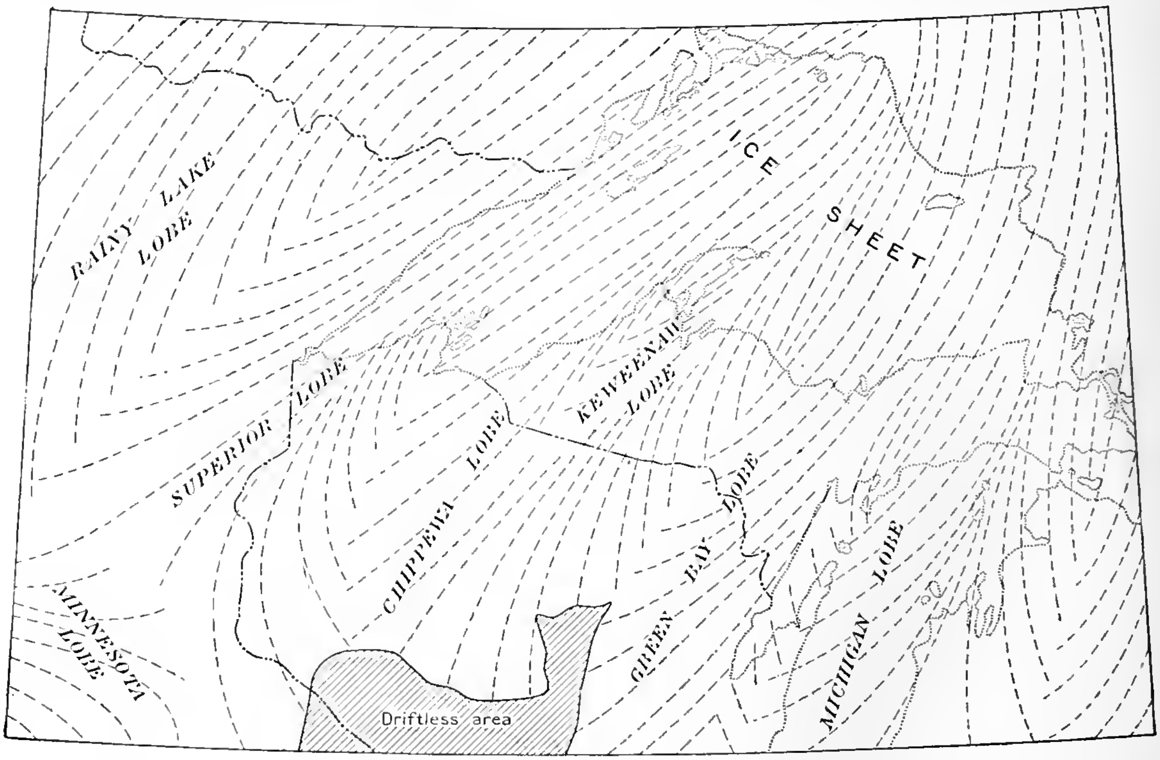


FIGURE 60.—Sketch map showing the glaciation of the Lake Superior region, giving names of lobes and probable directions of ice flow. There may have been an earlier stage with ice advance from the northwest through a large part of the area.

Green Bay lobe of the Labrador glacier, also having a deep axis of flow, extended nearly as far south as the Lake Michigan lobe. The Keweenaw and Chippewa lobes of the Labrador glacier, being obliged to advance over the highland region of upper Michigan and northern Wisconsin, did not advance as far south as the lobes to the east, though the Chippewa lobe overrode the part of Keweenaw Peninsula west of Ontonagon River and advanced farther south than the adjacent Keweenaw lobe. The Lake Superior lobe of the Labrador glacier, turned westward by the topography, advanced to the west end of Lake Superior, where it escaped from the confining walls of the rift valley or trough near Duluth and spread out in a much broader lobe (fig. 60), part of which advanced nearly westward in the region south of Leech Lake, probably moving southwest in the region of Mille Lacs and swinging round to the south, and even to the southeast in the vicinity of St. Croix Falls. The Rainy Lake lobe, which seems to have come partly from the Labrador and partly from the Keewatin center, moved south and southwest over the hills of northern Minnesota (fig. 4). The Red River lobe, the principal division of the Keewatin glacier, often referred to as the Minnesota lobe, advanced southward in the valley of Red River. Although these lobes are described and discussed as somewhat separate glaciers, too much emphasis should not be placed on their separate existence. It would naturally be true that as the Labrador glacier advanced from the northeast it would project farthest where the deepest valleys existed and would have reentrants where the hills caused obstruction to free glacial advance. It therefore seems probable that the Lake Michigan and Lake Superior lobes actually did advance independently over the regions described; but it must also be remembered that with farther advance to the south the lobes in the Great Lakes basins and those on the hills would coalesce until the hilly region was completely covered by one confluent ice sheet. For example, after the Lake Superior lobe had advanced westward from Duluth and the Rainy Lake lobe had advanced over the highland area of northern Minnesota and the international boundary, their farther advance would cause these short lobes to become confluent and form one great ice cap.

DRIFTLESS AREA.

If there was not time enough for two lobes to become confluent before the retreat of the ice, there would be left between them an area where the soil, the ledges, and the drainage bore no evidence of the glacial advance. Such an area might have been formed in northern Minnesota if the Lake Superior lobe and the Rainy Lake lobe had never coalesced. They did coalesce, however, but in one small area at the extreme northeastern part of Minnesota, described by N. H. Winchell [a] and U. S. Grant, [b] the drift is so thin that, although the topography, striated rock surfaces, and scattered foreign bowlders definitely prove glaciation of the area, the fact that the residual soil has not all been removed and the absence of nearly all glacial deposits have led to the description of the locality as "a possibly driftless area." Part of the Marquette district is an area of very thin drift, as near the Mansfield mine, on Michigamme River. Similar areas of thin drift are described as occurring in Canada.

In western Wisconsin and the adjacent parts of Minnesota and Iowa there is a true driftless area, and this was recognized in 1852 or earlier by D. D. Owen [c] and has been studied and fully described by Chamberlin and Salisbury. [d] A portion of the Driftless Area (fig. 68, p. 453) is included in the southwestern part of the region described in this report. Recent studies by Weidman [e] and by Leverett and Alden are somewhat modifying the ideas previously held as to the shape and boundaries of this area, although the main fact of its existence and the assignment of its cause to insufficient time for the reduced supply of ice from the north, retarded by the highlands, to reach this driftless region still stand approved.

RETREATING ICE.

The so-called retreat of the ice sheet was not an actual backward motion, the opposite of the forward motion of the advance, but a melting back of the front of the ice sheet. While the front of the continental ice sheet was retreating from this region, the highlands first emerged from the ice cover because the ice was thinnest above their tops, and valley glaciers or lobes lingered longest in the valleys because it was there that the ice was thickest and, after thinning by ablation, most protected by the load of soil and stones which it was carrying. Accordingly during the retreat the ice front was always lobate. The lobes in the Lake Michigan and Lake Superior basins were much more extensive than those in the northern Minnesota and northern Wisconsin highlands, as the glacial deposits that have been left in the region prove. There were probably slight readvances during the retreat of the ice sheet south of Lake Superior.

[a] Fifteenth Ann. Rept. Minnesota Geol. and Nat. Hist. Survey, 1887, p. 350.

[b] Am. Geologist, vol. 24, 1899, pp. 377–381; Final Rept. Minnesota Geol. and Nat. Hist. Survey, 1899, pp. 421, 437–438.

[c] Geological survey of Wisconsin, Iowa, and Minnesota, 1852.

[d] Chamberlin, T. C., and Salisbury, R. D., The driftless area of the upper Mississippi Valley: Sixth Ann. Rept. U. S. Geol. Survey, 1884, pp. 199–322.

[e] Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 548–565.

A study of these deposits also suggests that the ice lobe which advanced down the Red River valley, moving southward and southeastward in the area discussed in this monograph, came after the Lake Superior and Lake Michigan lobes had retreated for some distance,[a] perhaps into the basins of the present lakes. Moreover, glacial grooves and striæ on the ledges seem to show the same thing. In the St. Croix Dalles region glacial scratches on the rock are associated with the deposits made by the Lake Superior lobe of the Labrador glacier in such a way as to suggest that they were made during a first glacial advance, while striations associated with overlying glacial deposits made by the Red River lobe of the Keewatin glacier differ in direction and were probably made after the first set.[b] The relation of moraines of red and of gray drift near the south boundary of the upper peninsula of Michigan, west of Crystal Falls, suggested the possibility to I. C. Russell[c] that the Chippewa (or Keweenaw) lobe of the Superior glacier was still advancing after the Green Bay lobe of the Lake Michigan glacier had partly retired from the area.

That there were slight readvances of the ice during its general recession is indicated in several places, as in eastern Wisconsin, where red till moraines of the Green Bay and Lake Michigan lobes overlie the earlier moraines of the Wisconsin glaciation. Certain stages of the marginal glacial lakes discussed later also indicate a halt in Lake Michigan in the latitude of Manistee and a subsequent slight readvance. These readvances during the deglaciation of the region, however, do not seem to have been very many or very great, so far as the preliminary studies thus far made give evidence.

CONTRASTED GENERAL EFFECTS OF GLACIATION.

In general the glacial invasion stripped the peneplain of its soil in the area north of Lake Superior, while south of the lake, in the highland region of northern Wisconsin, it removed the soil but left a heavy mantle of glacial deposits. Nevertheless, throughout this area the influence of glaciation on topography was minor, while the effects on soil, drainage, forests, and the subsequent pursuits of man were most profound. What was a hill in this upland area north of the lake before the glacial advance is still a hill; what was a valley is almost without exception still a valley, but it may be marsh or lake, or stony soil, and so useless for agriculture. It may have had a fertile soil before glaciation, or may have contained some evidence of an adjacent body of iron ore, and this the glacier has taken away, leaving as compensation perhaps a sandy soil supporting a splendid pine forest, possibly a ledge from which the location of the ore body may be inferred, perhaps only a clogged valley, a chain of lakes, and broad, loitering stream courses along which the prospector or geologist may travel by canoe, and so reach regions of mineral wealth that otherwise might have lain hidden to this day. Quite in contrast to this pre-Cambrian area, the horizontal Cambrian rocks of the south shore of Lake Superior near Duluth and Ashland and eastward from Marquette to Sault Ste. Marie, the belted plain of Wisconsin and Michigan, and the flat-lying Cretaceous deposits of east-central Minnesota are deeply obscured by glacial drift. Throughout nearly all these areas the rocks were so readily abraded by the ice and the hills were so little higher than the adjacent valleys that the glacial deposits have entirely covered the preglacial topography and molded a new topography of their own. Moreover, the draining of the glacial lakes which occupied the basin of the present Lake Superior and overlapped its shores has permitted streams to produce a peculiar topography of sculptured lake clays.[d]

DESTRUCTIVE WORK OF THE GLACIERS.

Removal of weathered rock.—Glacial erosion removed quantities of weathered rock, including the nonresistant iron ores, perhaps truncating the iron-bearing rocks to a lower level in Canada than in the United States, and hence making the Canadian mines less productive, as

[a] Weidman, Samuel, Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, fig. 21, p. 434, and map in pocket. Berkey, C. P., Jour. Geology, vol. 13, 1905, pp. 35, 39.

[b] Chamberlin, R. T., Jour. Geology, vol. 13, 1905, pp. 249–251.

[c] Ann. Rept. Geol. Survey Michigan for 1906, 1907, pp. 47–52.

[d] Irving, R. D., Geology of Wisconsin, 1873–1879, vol. 3, 1880, p. 69.

Van Hise[a] has suggested. Lawson,[b] however, brings evidence to show that there was no very material reduction of level.

Striæ and roches moutonnées.—The scratches or striæ and the smoothly polished surfaces which were made by the ice advancing over the region are to be found throughout the Lake Superior region wherever there are ledges of hard rock which will preserve them. On the Archean and Algonkian ledges these striæ are exceedingly common. The advance of the glaciers over these ledges modified them, producing the rounded forms known as roches moutonnées. Some of these have longer axes in the direction of ice movement and steep or even precipitous slopes on the lee side, due to a process called plucking, in which large blocks of ice are rasped or torn away by the glacier. In the pre-Cambrian areas these roches moutonnées are exceedingly common, although in the main rather low and not very prominent.

Broadened and deepened valleys.—In certain favorable localities, either where the ice flow is very strong or where the rock is exceptionally weak, glaciers broaden and deepen their valleys. Clements[c] suggests the possibility that in the Vermilion district "glacial erosion was also active in widening and deepening these preglacial valleys, changing V-shaped into U-shaped valleys." The overdeepening of certain parts of the bottoms of valleys results in the production of basins in the solid rock, and these are afterward occupied by lakes. (See Pl. VI, p. 118.) The rock basins of this description are very common in the Lake Superior region, and glacial erosion has probably caused the deepening of many of the lakes in the granite area of northern Minnesota, where it is possible to go all around the lake shores on ledges, demonstrating that the lake basins are lower than the surrounding country. Lake Superior was somewhat deepened by glacial erosion at the time when the ice was advancing through it (Pl. II, p. 86), and Lake Michigan and Green Bay,[d] like the Winnebago Valley, were also somewhat deepened in this way, although, as previously stated, these depressions must have existed before the glacial ice advanced through them.

Glacial erosion also broadened and rounded out the great transverse valley of Portage Lake, which crosses Keweenaw Point at Houghton, as well as many other valleys in the region, especially in the more hilly areas. The overdeepening may be seen west of Houghton, where Huron Creek occupies a hanging valley (Pl. XXX, *B*, p. 434).

The effect of glacial erosion on the Duluth escarpment northwest of Lake Superior, where Thunder, Black, and Nipigon bays occupy submerged hanging valleys, has already been discussed (p. 114).

Glacial rock basins.—The rock-basin lakes occupying depressions produced by glacial erosion are numerous in the areas of pre-Cambrian rocks. (See Pl. VIII, in pocket.) Their character and origin may be inferred from one specific illustration. In the Michipicoten district a series of lake basins entirely rimmed by rock has been studied by Coleman,[e] who concluded that these basins have been formed by chemical action and are not due to glacial erosion.

The writer visited the Michipicoten district during the summer of 1907 and after a study of these rock basins came to a conclusion different from that of Coleman. For a number of reasons it seems probable that Hematite Mountain, at whose base is the Helen iron mine and one of the rock basins, was the seat of a local glacier that probably came into existence as the ice was advancing over southern Ontario and lingered as the ice sheet was retreating, because of the height of the hill (1,700 feet). The north and northwest slopes of the hill would receive less sunlight and heat than the south slope and the snow and ice would therefore linger there longest. The local glacier would naturally be on that side. The shape of the depression in which the Helen mine is situated is such as to suggest that it is a glacial cirque (fig. 61), and the rock basin is of exactly the kind which is made by small glaciers in their cirques. A

[a] Van Hise, C. R., Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 411–412.

[b] Lawson, A. C., Bull. Geol. Soc. America, vol. 1, 1890, p. 169.

[c] Clements, J. M., Mon. U. S. Geol. Survey, vol. 45, 1903, p. 43.

[d] Winchell, N. H., Am. Jour. Sci., 3d ser., vol. 2, 1871, pp. 15–19.

[e] Coleman, A. P., Rock basins of Helen mine, Michipicoten, Canada: Bull. Geol. Soc. America, vol. 13, 1902, pp. 293–304; Univ. Toronto Studies, 1902, pp. 5–6, 26; Rept. Bur. Mines Ontario, vol. 15, pt. 1, 1906, pp. 187, 188; Econ. Geology, vol. 1, 1906, p. 522.

ledge separates it from an adjoining rock basin a little farther down (a normal glacial rock basin relation of which many examples are known) and a rather marked hanging valley (Pl. XXIX, *A*) connects the depression in which these two lakes are situated with a lower trunk valley in which lies still another lake (fig. 61). The existence of this hanging valley indicates glacial erosion in the region. The glacial striæ in the upper part of the valley, which occasioned one of Coleman's difficulties in believing this a glacial rock basin, are oblique to the trend of the valley, as would be natural during the higher stages of the continental glacier, but the lower striæ run in the proper direction for the later stages of a local glacier. Ice would naturally excavate

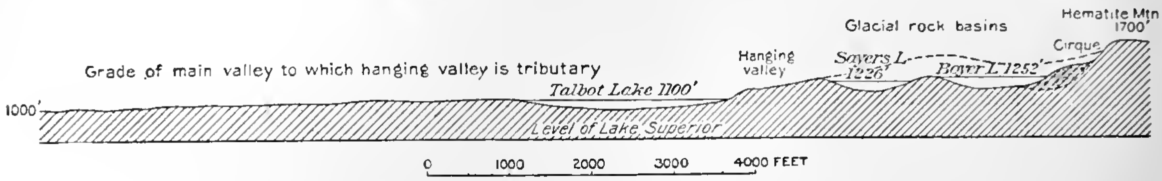


FIGURE 61.—Sketch showing the glacial cirque, the rock basins, and the hanging valley near the Helen mine, Michipicoten.

along the zone of weak iron-bearing rocks, which were possibly somewhat prepared for the excavation by chemical action of the sort that Coleman suggests.[a]

The real crux of the determination of these lake basins as of chemical or glacial origin lies in the fact that the iron ore remaining in the basins is found in just that locality where a small glacier in a cirque would protect it, although removing the rest of the iron ore, whereas if a chemical origin is thought plausible, the selective chemical action in preserving the ore at just this point and removing it elsewhere in the basin must be accounted for.

TRANSPORTING WORK OF GLACIERS.

It is well established that the deposits carried by the glaciers have been worn by the ice from the ridges over which the ice sheet advanced and that in any place where glaciers have been the rocks brought by them are apt to be of an entirely different sort from the ledges which underlie them, although a large part of the material in the drift may be of local derivation. This transportation of foreign material was early observed in this region, though explained by Bigsby[b] as due to "an earthquake sea wave" or "loaded icebergs." When rocks of a distinctive kind are found in an area where no similar rocks normally occur and the striæ indicate that the glaciers moved in the proper direction to carry these rocks, it may be considered demonstrated that glacial ice has moved the material from one place to the other. The early students lacked this conception of moving glaciers. Devonian limestone with fossils was thus brought into the Michipicoten district from a locality some 150 miles to the northeast, and iron ore was thus transported in the upper peninsula of Michigan.[c] Cambrian or Silurian limestone pebbles[d] from ledges in Manitoba seem to have been brought to the Lake of the Woods region of old crystalline rocks by a later movement of the Keewatin glacier after the chief northeast-southwest movement of the Labrador ice sheet. Many fragments of the granites and gneisses of the Archean and the porphyrites and quartzites and jaspers of the Lake Superior region were transported by the glaciers and are now found in the region of horizontal Paleozoic rocks to the south, fragments of this kind coming from both the north and the south shores of Lake Superior. It is sometimes an aid to the iron prospector to study the stones in the glacial drift in order to determine where possible ledges of iron-bearing formations may be found. The most notable case of glacial transportation of iron ore is that of the 30,000-ton mass south of the Fayal mine, on the Mesabi range, which Leith[e] describes as being entirely inclosed in the glacial drift and hence evidently transported bodily from the ledges to the north.

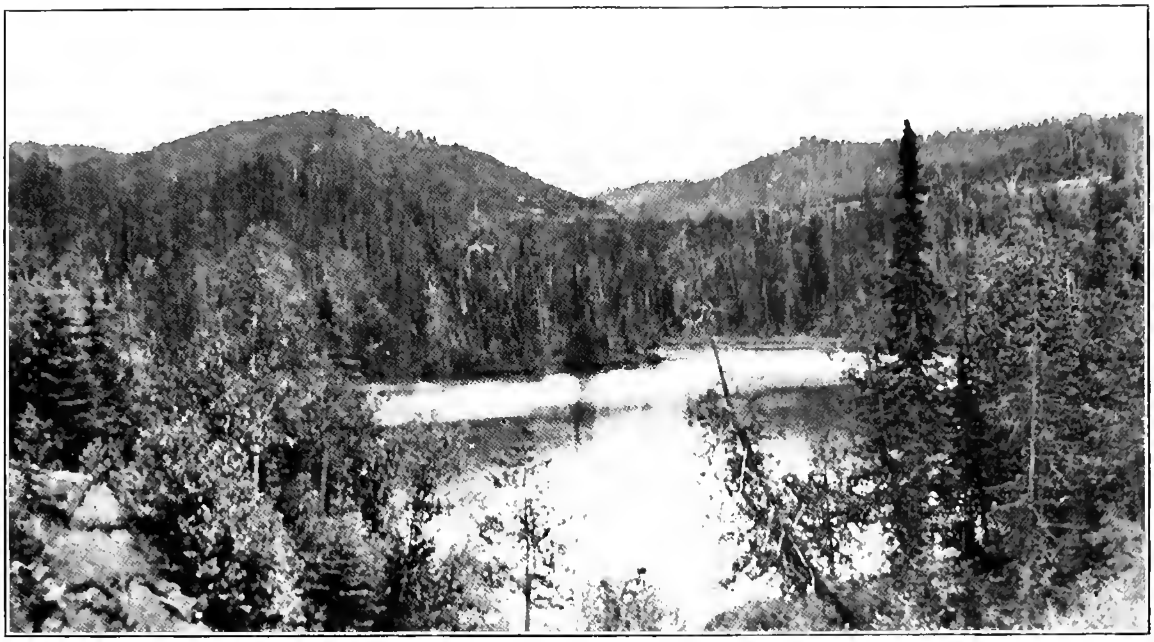
[a] Coleman, A. P., Rept. Bur. Mines Ontario, vol. 8, pt. 2, 1899, pp. 156–157

[b] Bigsby, J. J., On the erratics of Canada: Quart. Jour. Geol. Soc., vol. 7, 1851, pp. 215–238.

[c] Brooks, T. B., Geol. Survey Michigan, vol. 1, 1873, pp. 76–79.

[d] Lawson, A. C., Geol. and Nat. Hist. Survey Canada, vol. 1, 1885, p. 132cc.

[e] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, p. 263.



A. HANGING VALLEY NEAR HELEN MINE, MICHIPICOTEN.

Talbot Lake in foreground. See page 432.

B. LAKE CLAY OVERLYING STONY GLACIAL TILL IN MOUNTAIN IRON OPEN PIT, MESABI RANGE, MINN.

See page 443.

Among the distinctive materials which are found in the glacial drift are diamonds and native copper. The copper is of course traceable to the copper-bearing rocks of northern Wisconsin and Michigan and Michipicoten Island, but the source of the diamonds is not known.[a]

CONSTRUCTIVE WORK OF GLACIERS.

GROUND MORAINE.

Much of the material carried by the ice sheet is ground finer and finer until it is reduced to clay, and this clay with the included stones of various sizes which were not ground up so fine forms the most widespread of the deposits left by the glaciers. It is generally called till or bowlder clay and was formerly known as unmodified glacial drift. It reached its present position simply by being dropped from the melting ice, and forms the great mantle of ground moraine and parts of the ridges of terminal or recessional moraines. The present thickness varies with the former thickness of the ice, the amount of such débris which was contained in the ice, and the amount of erosion by running water either in connection with the melting ice or subsequently. This glacial till is found with varying thicknesses in every part of the Lake Superior region, overlying the Archean, Algonkian, Paleozoic, and Cretaceous rocks, being entirely absent or represented only by scattered stones in some rock ledges, and covering other areas and completely obscuring the bed rock by an overburden 200 to 300 feet thick.

The type of topography produced by the glacial till in the ground-moraine areas depends largely on whether enough of it accumulated to bury the preglacial topography or not. Many hills in the glaciated area still have the form of their bed-rock cores or are merely thinly veneered with the bowlder clay. Many valleys also are only partly filled by the till (fig. 55, p. 364) and remain as valleys, though not now as deep as before the glacial advance. On the other hand, more commonly the topography was so mild before the glacial advance and the accumulation of glacial deposits was so thick that an entirely new topography is modeled by the ice. (See Pls. XI, p. 180, and XXXI, *A*, p. 436.) This topography is generally of the "moderately rolling," "undulating or rolling," and "flat or undulating" types described by Warren Upham and others.[b]

DRUMLINS.

A class of till, or unassorted ground moraine, which deserves special mention is the drumlin. Drumlins in only one or two areas within the field of this report have yet been described, but they doubtless exist at numerous other points. The drumlins of the Lake Superior region are lenticular hills of bowlder clay or till, varying in shape from that of half of an egg that has been bisected lengthwise to that of half of a cigar cut in two in the same way. They characteristically have one rather steep side and one gentle slope, the steep slope being on the side from which the ice came. The long axis of the drumlin is invariably parallel to the direction of the latest ice movement.

Three areas of drumlins in Michigan have been described. The first is in the Menominee district,[c] where the drumlins are found over an area of about 150 square miles and have an average height of about 40 feet. The second area is also in the upper peninsula of Michigan, including Les Cheneaux Islands and a portion of the adjoining mainland on the north shore of Lake Huron.[d] The third drumlin area is in the Grand Traverse region,[e] in the northwestern part of the southern peninsula of Michigan.

[a] Salisbury, R. D., Notes on the dispersion of drift copper: Trans. Wisconsin Acad. Sci., Arts and Letters, vol. 6, 1886, pp. 42–50. Hobbs, W. H., Emigrant diamonds in America: Ann. Rept. Smithsonian Inst., 1901, pp. 359–366; Am. Geologist, vol. 15, 1894, pp. 31–35; Jour. Geology, vol. 7, 1899, pp. 375–388. Farrington, O. C., Correlation of distribution of copper and diamonds in the glacial drift of the Great Lakes region: Proc. Am. Assoc. Adv. Sci. vol. 58, 1908, p. 288.

[b] Final Rept. Geol. and Nat. Hist. Survey Minnesota, text accompanying county maps.

[c] Russell, I. C., The surface geology of portions of Menominee, Dickinson, and Iron counties, Mich.: Ann. Rept. Geol. Survey Michigan for 1906, 1907, pp. 8–91.

[d] Russell, I. C., A geological reconnaissance along the north shore of Lakes Huron and Michigan: Ann. Rept. Geol. Survey Michigan for 1904, 1905, pp. 39–150.

[e] Leverett, Frank, Science, new ser., vol. 21, 1905, p. 220; Water-Supply Paper U. S. Geol. Survey No. 183, 1907, pp. 333–335.

Geologists have not thoroughly agreed as to the origin of drumlins. Two theories have been held. One holds that the drumlins are constructed under the ice by the accumulation of material there, the material being derived by the ice sheet from the land from which it is advancing and the drumlins being built somewhat like bars in a river. The alternate hypothesis ascribes drumlins to a destructive action, the ice sheet being supposed to carve drumlins from a preexisting mass of till laid down by a previous ice sheet. The drumlins of the first two areas described seem to have been formed by the destructive process, as very decisive evidence by Russell proves, but Leverett thinks that some of the drumlins in the Grand Traverse region are constructional rather than destructional.

ESKERS.

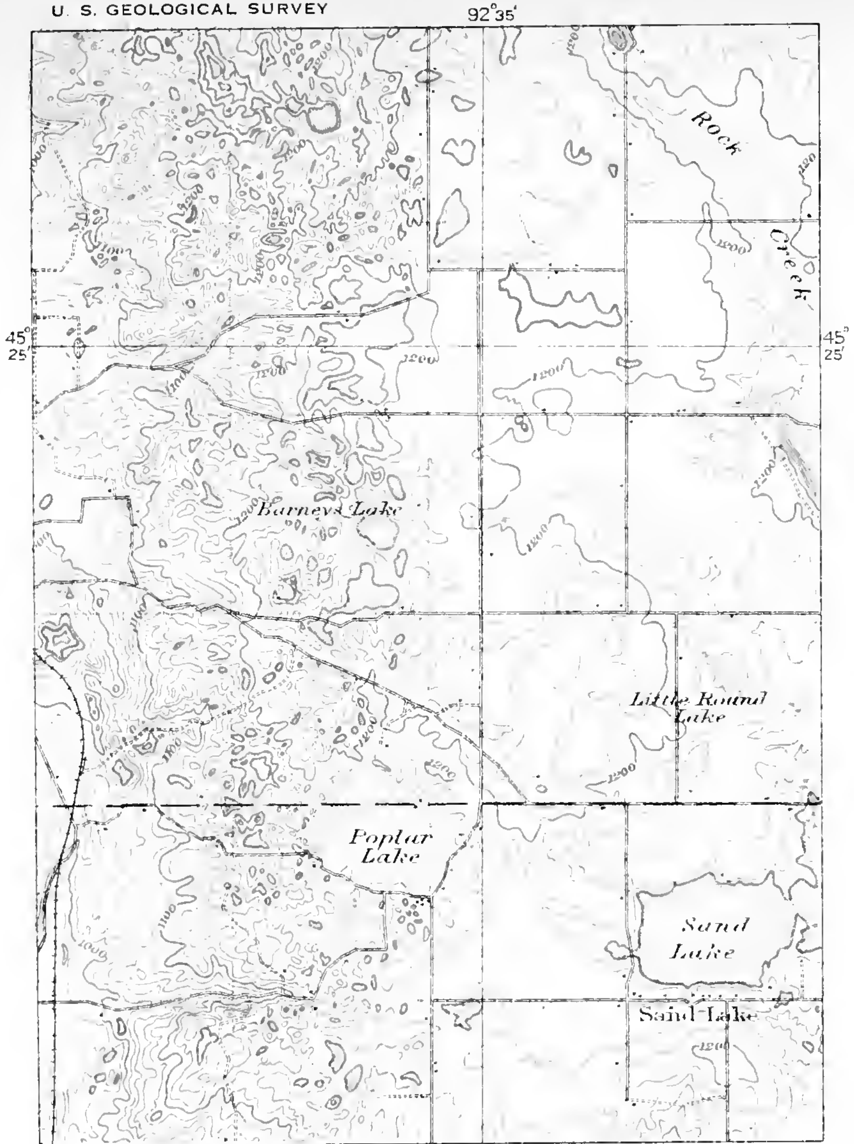
Another glacial feature to be described, the esker, is a fossil stream course formed in or under the ice by a stream flowing in a tunnel and depositing its load of sediment, which is preserved on the surface as a low winding ridge after the ice has melted away. Eskers in many parts of the Lake Superior region, as in northeastern Minnesota [a] and the Menominee district,[b] have been described. Russell describes them as low, serpentine gravel ridges in the valleys between the drumlins. They are doubtless also present in many other areas. They are mentioned here rather than with the other stratified drift deposits, like outwash plains, because in this area they are commonly associated with the ground moraine rather than with the outwash of the valleys.

TERMINAL MORAINES.

The deposit piled up at the end of the ice tongue or lobe is called a terminal moraine, and the name is applied not only to the deposit made at the farthest advance of the ice but also to those made at any point where the ice halts. The latter are also sometimes called recessional moraines. The only terminal moraines in the Lake Superior region which mark the farthest advance of the ice lie around the borders of the Driftless Area, but recessional moraines are more abundant. Some of them, so far as mapped, are shown in figure 68 (p. 453). These recessional moraines may be made up of two rather different kinds of material—the glacial till, or unmodified drift, and the drift which is assorted and stratified by running or standing water. A terminal or recessional moraine in the Lake Superior region usually consists of a series of ridges or knolls (Pl. XXX, *A*), in general constituting a long, narrow zone of hilly country, which may be in a single ridge, but is more commonly an irregular belt of ridges and valleys. The characteristic terminal moraine is made up largely of knobs and kettles. The belts of terminal moraine range from several hundred yards to several miles in width but are rarely over 4 or 5 miles wide and generally a mile or less. A great terminal moraine of course indicates that the edge of the ice remained at one point for a considerable length of time. During this time, if the glacier was moving, it would be constantly bringing material up to this point, dropping the material there, and perhaps, by slight readvances, shoving ahead the material which had previously been deposited by the melting ice, and all this material would be subject to constant removal or rearrangement by the running water that issued from the ice as the glacier was melting. These terminal moraines are therefore made up of a mixture of unmodified till and stratified sand, gravel, and clay deposited by running water, with variations of the two as the ice may have advanced, or as the water may have cut channels in the deposits, or as portions of the ice may have been buried beneath the deposits made by the melting of the upper ice layers or laid down by the streams. The subsequent melting of these buried ice blocks has caused the glacial drift to slump down, forming broad hollows and steep-sided pits. This is the general origin of the kettles which are found in terminal moraines.

[a] Elftman, A. H., Am. Geologist, vol. 21, 1898, p. 97.

[b] Russell, I. C., The surface geology of portions of Menominee, Dickinson, and Iron counties, Mich.: Ann. Rept. Geol. Survey Michigan for 1906, 1907, pp. 8-91; Am. Geologist, vol. 35, 1905, pp. 177-179; Science, new ser., vol. 21, 1905, pp. 220, 221.



From St. Croix Dalles (Wis.-Minn.) sheet

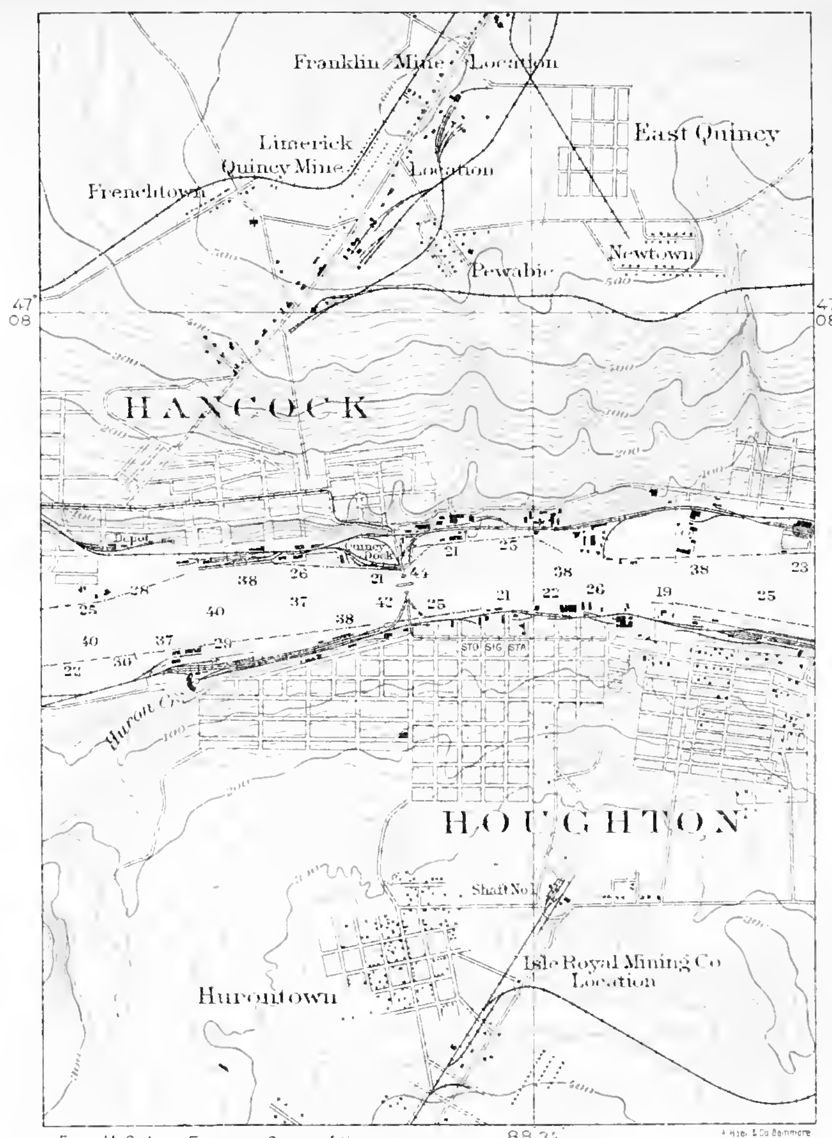
A

TERMINAL MORAINE AND OUTWASH PLAIN TOPOGRAPHY IN GLACIATED AREA OF WESTERN WISCONSIN

Scale 1:62500

2 Miles

Contour interval 20 feet



From U. S. Army Engineers Survey of the Northern and Northwestern Lakes

B

GLACIATED VALLEY OF PORTAGE LAKE ON KEWEENAW POINT IN MICHIGAN WITH HANGING VALLEY OF HURON CREEK. THE LOWER PART OF HOUGHTON IS ON A TERRACE OF GLACIAL LAKE NIPISSING

Scale 1:30000

1 Mile

Contour interval 20 feet

KAMES.

Kames, or irregular hummocks of waterworn sand and gravel, are present throughout the moraine belts of the Lake Superior region, many of them at the borders of valleys, as if formerly at the margin of an ice sheet whose melting has caused the edges of marginal terraces to slump down into irregular hummocks and kettles. Russell describes irregular hillocks of rounded kame gravels in the Menominee area and ascribes them to accumulation beneath wells, or moulins, in the ice sheet, where streams on or in the glacier fell vertically and deposited their load.

RECESSIONAL AND INTERLOBATE MORAINES.

The recessional moraines formed at temporary terminal points of the ice sheets during the Wisconsin stage are seen from the map (fig. 68, p. 453) to be definitely related to the larger lowland and highland areas, and it is by a study of these moraines that some of the conclusions as to the behavior of the different ice lobes in the Lake Superior region have been reached.

As the ice retreated from the maximum stage of a confluent ice cap and once more resolved itself into lobes, some very distinctive deposits were formed between the adjacent lobes, and these are called interlobate moraines. An example of the moraines of this kind is found in the interlobate (kettle) moraine of eastern Wisconsin, which was accumulated between the Green Bay lobe and the Lake Michigan lobe. Other interlobate moraines were formed between the Chippewa lobe and the Superior lobe in Bayfield and Douglas counties, Wis., west of Ashland, and between the Superior and the Rainy Lake lobes in northeastern Minnesota.

DRAINAGE OF DRIFT-COVERED AREAS.

The accumulation of till over this great area has modified the drainage, and one of the most prominent effects of this accumulation is the destruction of mature or submature preglacial drainage and the superposition of young drainage on the drift, causing gorges, waterfalls, and the great numbers of lakes and swamps for which the region is noted. (See Pl. XXII, in pocket.) These lakes and swamps are due to a common cause—interference with the free run-off of rain by the irregular deposition of the drift. Among the most common kinds of lakes and swamps or muskegs (Pl. XXXI, *B*) are those which are produced by the accumulation of water in shallow depressions in the undulating or mildly irregular till sheet. As the material of the till was largely clay, it would naturally be difficult for the water to escape through it. Another common cause of lakes is the accumulation of a greater thickness of the glacial till in one part of the valley than in another, producing an obstruction to drainage. Many of the streams were also forced out of their preglacial courses by the deposits of glacial till, and numerous rapids and waterfalls are due to this displacement. Clements[a] has described Deer River, Michigan (Pl. XXII), as typical of a stream with associated swamps and lakes in a till-covered area and has outlined the life history of such a drainage system. The normal type of preglacial drainage of the entire Lake Superior region is illustrated in Plate XXXI, *A*, showing part of the Driftless Area. Plate XXXI, *B*, shows the young drainage of the glacial drift which now covers the greater part of the region.

DIFFERENCES BETWEEN YOUNGER AND OLDER DRIFT.

There is evidence in the central United States which has been interpreted as indicating that the glacial period, instead of being simple, was decidedly complex. It is thought that the ice did not advance from the Labrador and Keewatin centers once and retreat once, but that instead it underwent a series of oscillations so that glacial deposits were laid down under or in front of the ice, the ice retreated from them, and then the weathering and erosional agencies acted upon these deposits. This is the reason why the lakes among the older glacial deposits are largely either filled or drained, the till-veneered hillsides are cut by streams, the stones in the drift are weathered and disintegrated, and the soluble constituents have been leached out of the soil by percolating water. After all this had taken place the glaciers are thought to have readvanced and covered the older drift with a sheet of new till, etc., which in some places extends

[a] Clements, J. M., Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 32-36; Am. Geologist, vol. 17, 1896, pp. 126-127.

farther out than the older drift and in others has left a broad zone of it exposed. This fresh, unweathered, young till forms a decided contrast to the older drift.

Only the extreme southwestern part of this region contains any of what has been interpreted as older drift. In the greater part of the region the drift seems to be solely the work of the Wisconsin ice sheet. The drift near the borders of the Driftless Area has been ascribed to two or three earlier glacial epochs, but most of the Lake Superior region furnishes no evidence whatever of more than one glacial advance, either in the deposits or in the topography.

EFFECT OF NUNATAK STAGES ON DISTRIBUTION OF DRIFT.

In spite of the lack of detailed studies in a large part of this region, it seems probable that the behavior of the ice in retreating can be somewhat discriminated. When an ice sheet covers an irregular land surface, there are two ways in which it may retreat. It may disappear gradually from the lowlands and linger longest in the upland regions, as is the case in the Rockies, in Norway, in Alaska, and in Switzerland to-day. It does this, however, only where the elevated areas are high enough to become centers of local glaciation and to supply new ice. The contrasting condition is found where the highland areas are not sufficiently elevated to retain snow through the summers and therefore to supply ice. Where the latter condition prevails, the glacier does not continue to be active up to the very time of its extinction, as in the Rocky Mountains at present, but becomes stagnant because there is no fresh supply of ice. When an ice sheet becomes stagnant, the high areas are first exposed by melting, because over them the ice is thinnest, and they rise out of the ice sheet as nunataks. These nunataks gradually increase in size, and eventually the ice shrinks until it is found only in the valleys, where it was thickest.

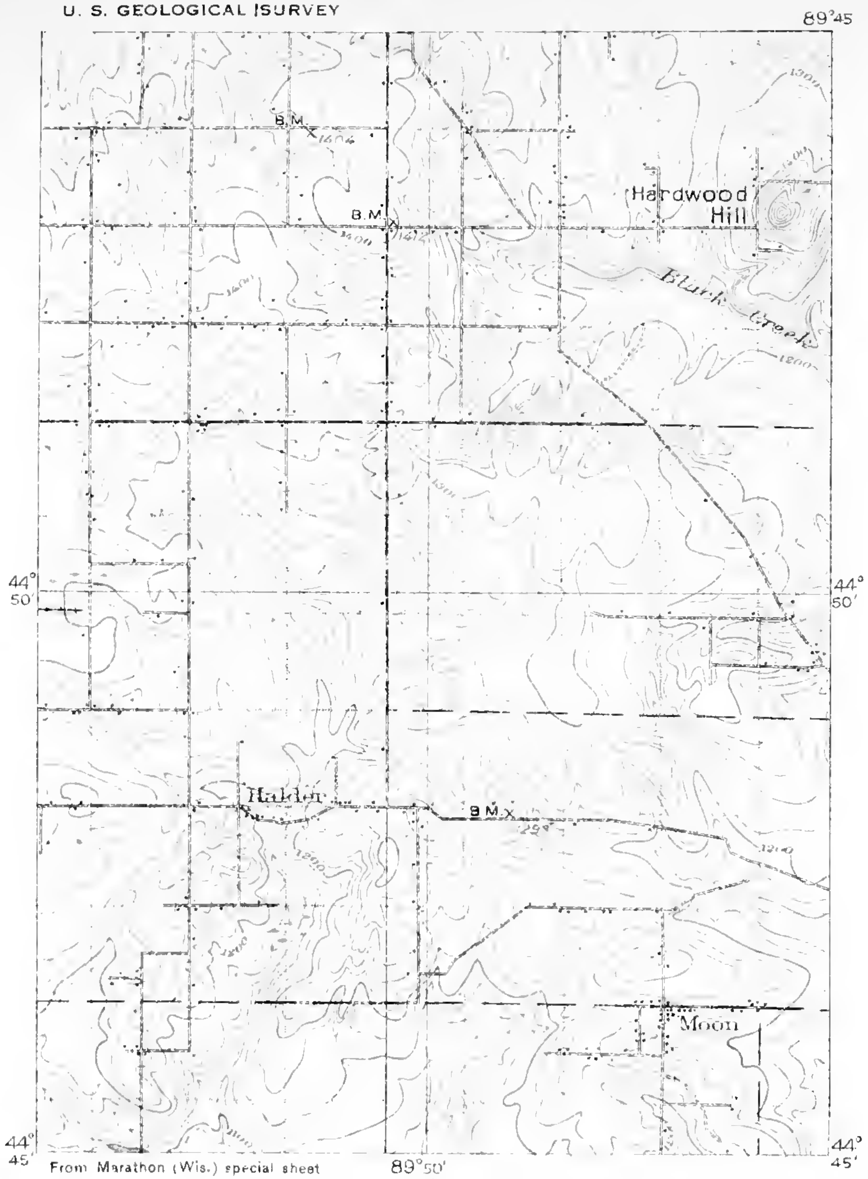
The conditions just described seem to have prevailed in parts of the Lake Superior region. Northwest of Lake Superior the Giants Range was a nunatak (figs. 60 and 62), emerging in the interlobate area between the Rainy Lake glacier and the Lake Superior glacier. These lobes gradually retreated to the Lake Superior basin and to the valley of Red River, respectively, marginal lakes being formed as described in another section (p. 441). North and northeast of Lake Superior, in Ontario, the conditions may possibly have been similar, the ice shrinking away from an interlobate area near the Height of Land and occupying the basin of Lake Superior largely as a stagnant mass.

South of Lake Superior, however, the highland area seems to have had a somewhat different history. The ice from the Chippewa and Keweenaw lobes, which advanced over the highland region of northern Wisconsin and somewhat down its southward slope, probably retreated northward over the same slope without the emergence of the northern Wisconsin highland as a nunatak area, although the Porcupine Mountains were probably uncovered as a nunatak region about the time the glacier became lobate in the valleys east and west of Keweenaw Point. The Huron Mountains seem also to have first emerged as a nunatak area,[a] lying between the Keweenaw and Green Bay lobes. Some of the earliest drift deposits were developed about these emerging nunataks.

VARIATION OF DEPOSITS WITH SLOPES.

When a glacier is retreating—that is, melting back faster than the ice advances, or melting back with no advance, as in a stagnant ice sheet—two rather different kinds of deposits are made in association with two diverse topographic conditions. One kind is formed where the land slopes away from the ice, allowing a free run-off of the glacial streams which are fed by the melting ice. The other kind is formed where the land slopes toward the ice and the drainage from the ice is detained in a glacial lake until it rises to a sufficiently high level to flow over a neighboring divide. The first condition was well exemplified by the Chippewa-Keweenaw lobe as it retreated from the highland region of northern Wisconsin, when its streams flowed freely away, carrying great quantities of gravel, sand, and clay that were deposited in outwash plains

[a] Davis, C. A., Ninth Rept. Michigan Acad. Sci., 1907, pp. 132-135.



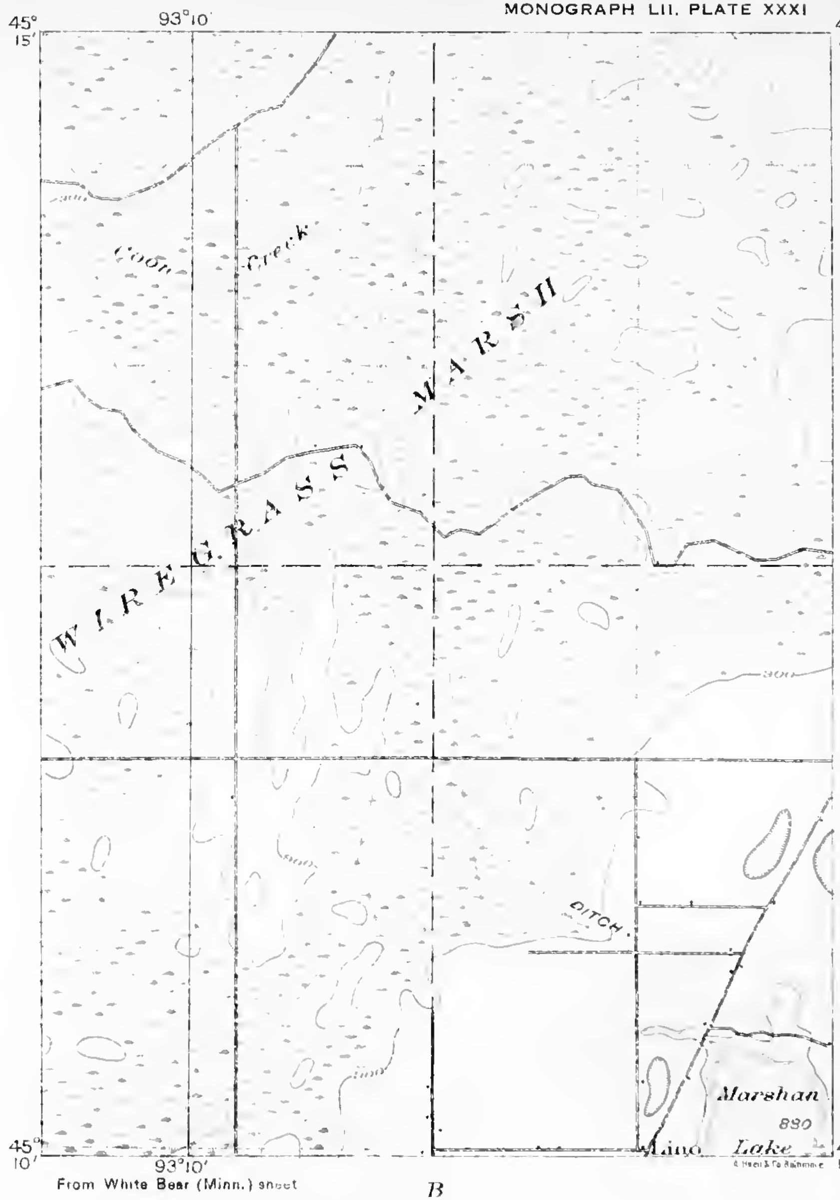
A

CHARACTERISTIC DRIFTLESS AREA TOPOGRAPHY IN NORTHERN WISCONSIN, SHOWING NORMAL MATURE DRAINAGE

Scale 1:125000

0 1 2 3 4 Miles

Contour interval 20 feet



B

CHARACTERISTIC MUSKEG AND GROUND MORAINE TOPOGRAPHY IN GLACIATED AREA OF MINNESOTA, SHOWING POST GLACIAL YOUNG DRAINAGE

Scale 1:62500

0 1 2 Miles

Contour interval 20 feet

or valley trains, a number of which cross the Driftless Area of Wisconsin. At later stages such outwash gravels are likely to be so dissected by stream erosion that terraces are formed at higher levels than the present stream. This is believed to be the origin of the terraces in the valley of Wisconsin River near Wausau, in that of the St. Croix near the Dalles, and along several other stream courses of the region.

OUTWASH DEPOSITS.

When several streams flowing out side by side build up a broad plain of the same kind as the valley trains, but not confined to a valley, the deposit is called an outwash plain (Pl. XXX, *A*). Outwash plains of this type are found in the Upper Peninsula of Michigan, in Ontario, in Minnesota, and in northern Wisconsin. Weidman [a] has described some of them as "alluvium" and believes that these deposits are associated with (*a*) uplift of the land, rejuvenating the streams and causing intrenchment; (*b*) lowering of the land, permitting aggradation, during which these so-called alluvial deposits were laid down; and (*c*) later uplift, permitting reintrenchment of the streams, and terrace cutting. The age of this alluvium he is inclined to place as perhaps pre-Iowan, between his "Second" and "Third" drift sheets. It may be pointed out that the alluvium is in places directly associated with terminal moraines, and Weidman has not brought forward evidence to show that it extends beneath them or is plowed up by them. After short field studies by the writer it seems more probable that nearly all of this material is normal outwash.

In view of some of the most recent conclusions concerning the conditions that determine stream work, it may be conceived that the volume and load of the streams have varied, rather than the grade. The advance of ice sheets, with increased supply of water, would perform the same work of intrenchment as the uplift postulated by Weidman, if indeed this intrenchment is not preglacial. Later the increased load of the streams, supplied with débris from the melting ice, would necessitate aggradation and the formation of outwash deposits, exactly similar to Weidman's alluvium and such as are known in association with existing ice fronts the world over. Still later the diminution of the débris furnished to the streams by melting ice would result in their relief from overloading and in a return to processes of intrenchment and terrace cutting. More than this, Weidman's alluvium, where supposedly overriden by the ice depositing the "Third" drift in the Wisconsin River valley, seems to lack entirely the broad truncation and grooving characteristic of gravels overridden and eroded by ice, as they are known in Alaska. Again, Weidman has not shown that the terraces are gullied or the drift in them weathered and leached as it should be if they are pre-Wisconsin in age. Lastly, if these so-called alluvial deposits are not outwash and mostly of Wisconsin age, it may be asked, What became of the water and débris from the melting Wisconsin ice sheet?

I. C. Russell [b] described a series of interesting outwash deposits in the valley of Menominee River (Pl. XXVI, in pocket). They lie in a series of steplike levels associated with moraines, marking receding stages of the border of the Green Bay lobe. The angular turns of Menominee River seem also to be related to these receding stages.

At Grantsburg, Wis., in the valley of the St. Croix, C. P. Berkey [c] has studied a series of laminated red and gray clays, judged to have been formed in a glacial lake whose deposits overlie Wisconsin till. He reaches the conclusion that the clays were derived from the melting of an oscillating ice sheet and estimates a greater length of time than is usually thought of since the retreat of the ice, on the theory that each of the laminæ represents a year of melting interrupted by freezing and supply of finer sediment. He has also compiled an excellent sketch map [d] showing the relation of recessional moraines west and south of the end of Lake Superior in Wisconsin and Minnesota.

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[a] Weidman, Samuel, Bull. Wisconsin Geol. and Nat. Hist. Survey, vol. 16, 1907, pp. 418–421, 425, 477, 497–498, 501, 504, 506, 514–547, 569–571, 609–610, 622–624.

[b] Ann. Rept. Michigan Geol. Survey for 1906, 1907, p. 65.

[c] Jour. Geology, vol. 13, 1905, pp. 35–44.

[d] Idem, fig. 1, p. 43.

PITTED PLAINS.

There is one phase of the building of outwash gravel deposits or valley trains which deserves special mention. In numerous places these gravel deposits are deeply pitted. Such pits or kettles are well developed, for example, near Negaunee, in the Marquette district; all through the valley of Michigamme River; in the Perch Lake district (Pl. XXI, in pocket); in the Crystal Falls district, between Randville and Witbeck (Pl. XXII, in pocket); in the valley of Menominee River south of Iron Mountain (Pl. XXVI, in pocket); in the lowland region of the northern peninsula of Michigan, east of Marquette; in the Michipicoten district of Canada; and doubtless elsewhere. As the glaciers in these regions retreated small tongues or isolated blocks of ice were buried beneath the gravels of the glacial streams. Subsequently, when these detached ice blocks melted, the gravel layers slumped and the kettles which pit the surface of the gravel plain were formed. Many of the gravel kettles contain lakes (Pl. XXX, *A*, p. 434) and a considerable number of the small lakes of northern Michigan and Wisconsin are of this origin.

LOESS.

In the southwestern part of the area is a fine clayey or sandy material called loess, formed possibly from the rock flour carried by the streams flowing from the retreating glaciers or transported by winds. Its distribution within this area is not well known as yet.

VALLEY LAKES DUE TO VARIATION IN STREAM LOAD.

There is a striking contrast between the streams that were the outlets of marginal glacial lakes and the streams that flowed directly from the ice, the former being relatively clear streams and the latter being heavily loaded with sediment. Accordingly it was possible for Chippewa River, with its heavy load of glacial material, supplied directly by the melting ice, to build its outwash plain right across Mississippi River in western Wisconsin in spite of the fact that the volume of the Mississippi was probably much larger, so that it should have been able to carry away the sediment supplied by a small tributary like the Chippewa. Many of the streams feeding the upper Mississippi were, like the outlets of Lake Agassiz, Lake Nemadji, and Lake Duluth, outlets of glacial lakes in which the sand, gravel, and clay had all been strained out. Accordingly the small Chippewa, with its heavy load, aggraded at its confluence with the Mississippi and was able to dam back the Mississippi itself in a narrow, lakelike expansion more than 25 miles long, called Lake Pepin (Pl. II, p. 86).

Farther up the Mississippi, on the Wisconsin-Minnesota boundary near St. Paul, the process just outlined was reversed, the main stream having more load as well as more volume than its tributary, the St. Croix (Pl. II). Accordingly the Mississippi outwash plain and more recently the modern flood plain have retarded the outflow of the St. Croix, so that a lake is formed in its valley from the mouth, where a modern sandbar surmounts the flood plain, to a point about 30 miles upstream, the head of the present Lake St. Croix.

Similar valley lakes on the Minnesota side of the Mississippi have been described by Winchell.[a] During the summer of 1908 the writer observed a similar series of lakes in the tributary valley mouths on the Wisconsin shore of the Mississippi. These are in the Driftless Area. They were formed during glacial time by the greater building up of the main glacier-fed Mississippi (through outwash) than of its rain-fed tributaries. The assumption by Winchell of a long, narrow ice tongue in the Mississippi Valley, however, seems to the writer unnecessary. The outwash itself, carried by the great volume of water from the melting glaciers and not by the more slender stream of the modern Mississippi, could perfectly well account for these glacial materials in the Driftless Area and for the shallow lateral lakes, like Waumandee Lake in Wisconsin, across the river from Winona, and numerous unnamed ponds and swamps in side valley mouths.

[a] Winchell, N. H., Bull. Geol. Soc. America, vol. 12, 1901, pp. 127-128.

DISTRIBUTION OF GLACIAL DRIFT.

The detailed work on the distribution of the morainic deposits in this region has not covered anything like the whole area. It is of interest to note that the first man to present a correct explanation of the glacial phenomena in America, Louis Agassiz,[a] was one of the first to make observations in the Lake Superior region, as did James Hector,[b] Sir William Logan,[c] J. J. Bigsby,[d] J. W. Foster and J. D. Whitney,[e] E. Desor,[f] D. D. Owen,[g] J. G. Norwood,[h] C. Whittlesey,[i] B. F. Shumard,[j] G. M. Dawson,[k] C. T. Jackson,[l] W. A. Burt,[m] and many other early observers who observed many of the facts of transported bowlders and soil, waterworn materials, smoothed and striated rocks, etc., without recognizing or being willing to accept their glacial origin, as Agassiz and some others had done.

The Pleistocene deposits of the Ashland region, Penokee range, etc., in Wisconsin, were early described by R. D. Irving,[n] who distinguished the glacial drift and the lacustrine clay and showed their distribution on his map. E. T. Sweet [o] briefly refers to the unstratified glacial deposits, the moraines, and the stratified drift (lake clays) farther west, in Bayfield and Douglas counties. T. C. Chamberlin [p] made a report based on notes of Moses Strong,[p] concerning the glacial features in the upper St. Croix district, including the striæ, the kettle moraine, the bowlder clay, and the "barrens." The glacial deposits, lakes, morainic belts, etc., in the upper Flambeau Valley of Wisconsin are described by F. H. King.[q] The glacial deposits in eastern Wisconsin are described by T. C. Chamberlin.[r] The glacial features of an area in the upper Wisconsin Valley are briefly described by T. C. Chamberlin from notes by A. C. Clark.[s] R. D. Irving [t] described and mapped the glacial deposits in central Wisconsin and part of the Driftless Area. The glacial phenomena of all Wisconsin are reviewed by T. C. Chamberlin,[u] who has also correlated the glacial features of the southern part of the Lake Superior area in Minnesota, Wisconsin, and Michigan.[v] Samuel Weidman has recently done detailed work over an area of about 7,200 square miles in north-central Wisconsin, and has published descriptions [w] of the terminal moraines, the ground moraine, the older drift, etc. He has also surveyed the glacial geology of a nearly equal area west of this, within the region discussed in this monograph, but his report on it is not yet published. C. P. Berkey[x] and R. T. Chamberlin[y] have each discussed the glacial geology of a small area near the St. Croix Dalles. The detailed mapping of the glacial deposits of the south half of the Green Bay glacier by W. C. Alden, of the United States Geological Survey, not yet published, extends up to the south boundary of the area here discussed.

The glacial deposits in Michigan were examined in the early surveys by T. B. Brooks,[z] Carl Rominger,[aa] and others. More recently A. C. Lane[bb] has described the glacial deposits on

[a] Agassiz, Louis, Lake Superior, its physical character, vegetation, and animals, 1850, pp. 395–416.
[b] Quart. Jour. Geol. Soc., vol. 17, 1861, p. 393.
[c] Geology of Canada, 1863, pp. 888–893, 904–908, 912–913, and plate in atlas showing superficial deposits.
[d] On the erratics of Canada; Quart. Jour. Geol. Soc., vol. 7, 1851, pp. 215–238.
[e] Report on the geology and topography of a portion of the Lake Superior land district, vol. 1, 1850, pp. 186–218.
[f] Idem, vol. 2, 1851, pp. 232–247.
[g] Report of a geological survey of Wisconsin, Iowa, and Minnesota, 1852, pp. 32, 36, 141–145, etc.
[h] Idem, pp. 298, 329–330, 348, etc.
[i] Idem, pp. 426–429, 435–436, 462–466, etc.
[j] Idem, pp. 515, 517, etc.
[k] Geology and resources of the region in the vicinity of the forty-ninth parallel, 1875, pp. 217–254.
[l] House Ex. Doc. No. 5, 31st Cong., 1st sess., pt. 3, 1849, pp. 388–389.
[m] Idem, p. 820.
[n] Geology of Wisconsin, 1873–1879, vol. 3, 1880, pp. 211–214, Pl. XX.
[o] Idem, pp. 352–356.
[p] Idem, pp. 382–387, Pl. XXXVII.
[q] Idem, vol. 4, 1882, pp. 611–613.
[r] Idem, 1873–1877, vol. 2, 1877, pp. 199–246.
[s] Idem, 1873–1879, vol. 4, 1882, pp. 717–721.
[t] Idem, 1873–1877, vol. 2, 1877, pp. 608–635.
[u] Idem, 1873–1879, vol. 1, 1883, pp. 261–298.
[v] Terminal moraine of the second glacial epoch: Third Ann. Rept. U. S. Geol. Survey, 1883, pp. 315–330, 381–393.
[w] Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 433–513.
[x] Am. Geologist, vol. 20, 1897, pp. 355–369.
[y] Jour. Geology, vol. 13, 1905, pp. 238–256.
[z] Geol. Survey Michigan, vol. 1, pt. 1, 1873, pp. 72, 76–79.
[aa] Idem, vol. 1, pt. 3, 1873, pp. 15–20; vol. 4, 1881, pp. 1–2, 40–41.
[bb] Idem, vol. 6, pt. 1, 1898, pp. 183–184, 193.

Isle Royal and has published some brief notes on the glacial deposits of parts of Keweenaw Point.[a] Besides this he has written a short description and published a glacial map of the deposits in the Lower Peninsula,[b] the northwestern part of which comes within the area of this report, from published and unpublished data by Messrs. Gordon, Leverett, Sherzer, and Lane. He also treats the drift in his summary of the surface geology of Michigan.[c] I. C. Russell has studied the glacial features of the south border of the Upper Peninsula from St. Mary River to a point west of Crystal Falls. His map shows the distribution of the moraines in this region, and his work has been continued by C. A. Davis [d] west of Marquette and south of the Huron Mountains. Frank Leverett has studied in detail the glacial deposits there and in the eastern lowland portion of the Upper Peninsula, but has published no report as yet except a brief review.[e]

The glacial deposits north and northeast of Lake Superior in Ontario are not known in detail, though A. B. Willmott,[f] A. P. Coleman,[g] E. S. Moore,[h] and J. M. Bell,[i] have made observations in the Michipicoten district. Coleman also briefly refers to the glacial deposits near Lake Nipigon,[j] as does E. S. Moore [k] to those in the Windegokan district east of Lake Nipigon [k] and W. H. Collins [l] to those west of Lake Nipigon.

Northwest of Lake Superior the glacial phenomena in the Lake of the Woods region have been described by G. M. Dawson,[m] and the glacial features there and in the Rainy Lake region have been treated fully by A. C. Lawson.[n]

To the east, north of the international boundary, the glacial geology of Hunters Island has been described by W. H. C. Smith [o] and that of the area covered by the Seine River and Lake Shebandowan map sheets by William McInnes.[p]

In Minnesota the glacial deposits have been studied extensively by Warren Upham, N. H. Winchell, U. S. Grant, J. E. Todd, A. H. Elftman, and others. Their discussions are found in the annual reports of the Minnesota Geological Survey and in the volumes of the final report, including a series of detailed county maps and descriptions. This is the most detailed series of studies of the glacial deposits thus far made within the area here considered, though without sufficient correlation. H. V. Winchell and U. S. Grant have described some of the glacial phenomena in Minnesota, near Rainy Lake.[q]

In a preliminary report[r] Warren Upham has described the moraines of northeastern Minnesota and published a map of part of the Lake Superior area. The location of the chief morainic deposits on this map seems to have been accurate, but there have been some differences of opinion as to the interpolation between morainic belts and the correlation and interpretation of the moraines. Upham indicated by his map that the ice all retreated northward, no special influence being exerted by the Lake Superior basin, the valley of Red River, or the highlands of northern Minnesota and the international boundary. But this would mean that the Mesabi, Itasca, and Leaf Hills moraines had the ice on the wrong side, as is proved by the superposition of lake clay on glacial till south of the Mesabi range, a relation that would not exist if the ice had retreated northward over the range. (See figs. 62, p. 443; 68, p. 453; and Pl. XXIX, *B*, p. 432.) J. E. Todd [s] subsequently pointed out this discrepancy and A. H.

[a] Proc. Lake Superior Min. Inst., vol. 12, 1907, pp. 101-104.

[b] Water-Supply Paper U. S. Geol. Survey No. 30, 1899, Pl. II, pp. 58-67, 75-77.

[c] Ann. Rept. Geol. Survey Michigan for 1907, 1908, pp. 97-143.

[d] Ninth Rept Michigan Acad. Sci., 1907, pp. 132-135.

[e] Sixth Rept. Michiga Acad Sci., 1904, pp. 100-110; Water-Supply Paper U. S. Geol. Survey No. 160, 1906, pp. 29-53, with contour map; Water-Supply Paper U. S. Geol. Survey No. 183, 1907, pp. 4-6.

[f] Rept. Bur. Mines Ontario, vol. 7, 1898, pp. 204-205.

[g] Idem, vol. 15, pt. 1, 1905, pp. 192-193.

[h] Idem, p. 206.

[i] Idem, vol. 14, pt. 1, 1905, p. 288.

[j] Idem, vol. 16, pt. 1, 1907, p. 135.

[k] Idem, pp. 147-148.

[l] Summary Rept. Geol. Survey Canada, 1906, pp. 103-104, 108.

[m] Quart. Jour. Geol. Soc., vol. 31, 1875, pp. 607-608.

[n] Geol. and Nat. Hist. Survey Canada, vol. 1, new ser., pt. CC, 1886, pp. 25-26, 130-140; vol. 3, pt. F, 1890, pp. 10, 20-21, 163-176.

[o] Geol. Survey Canada, new ser., vol. 5, pt. 1, 1893, pp. 71G-74G.

[p] Idem, vol. 10, 1899, pp. 51H-54H.

[q] Twenty-third Ann. Rept. Minnesota Geol. and Nat. Hist. Survey, 1895, pp. 68-69.

[r] Twenty-second Ann. Rept. Minnesota Geol. and Nat. Hist. Survey, 1894, pp. 31-54.

[s] Am. Geologist, vol. 18, 1896, pp. 225-226; Am. Jour. Sci., 4th ser., vol. 6, 1898, pp. 469-477 (with map).

Elftman [a] has discussed it further and published a revised map of the moraines northwest of Lake Superior.

The geologists of the United States Geological Survey have referred briefly to the glacial deposits,[b] and their work is cited more specifically in other parts of this report. On only two of their geologic maps [c] are glacial deposits separately shown (Pls. XVII and XXII, in pocket), though a special map [d] of a third region shows the distribution of the recessional moraines, and there are detailed maps for the Marquette district.

The map of the Marquette district (Pl. XVII) gives a separate color to "undivided Pleistocene" without specifically stating of what this consists. The areas so mapped are those in which no ledges whatever are found because of the thickness of the glacial drift and modern stream and swamp deposits. Accordingly it is evident that these areas do not include all the Pleistocene deposits of the district, but merely the places where they are continuous and thick, completely obscuring the older rocks. Pleistocene deposits are found throughout the district, but in other places are discontinuous or very thin. The undivided Pleistocene of the Marquette area, which is confined chiefly to the lowland south and east of Marquette, includes, where mapped, glacial till, morainic deposits, stream-assorted glacial outwash deposits, beaches of higher levels of Lake Superior, and lake-bottom clays, besides small areas of modern swamp accumulations, like peat and marl, and stream deposits.

The undivided Pleistocene of the Crystal Falls area (Pl. XXII) where mapped in the Michigamme River valley west of Floodwood and farther south near Channing and Sagola includes glacial till, recessional moraines, flat sandy outwash-plain deposits, and various swamp and stream deposits.

On the sketch map (fig. 68, p. 453) it has been thought wise to distinguish three facts concerning the distribution of the drift and the terminal moraines—(1) the distribution of the outermost moraine, whether of the last glacial advance or of an earlier one; this is the boundary of the Driftless Area; (2) the boundary of the Wisconsin stage of glaciation, the latest stage; (3) some of the more prominent recessional moraines, so far as their location is known. The locations assigned to the more important recessional moraines inside the border of the terminal moraine of the Wisconsin stage are of varying degrees of accuracy, because, although the recessional moraines in Minnesota are fairly well known and well mapped, those in Wisconsin, Michigan, and Ontario have been mapped only in small areas. In fact, comparatively little is known of the episodes accompanying the withdrawal of the ice sheet from the portions of the Lake Superior region not lying in Minnesota, save in regard to the association of the ice with the marginal lakes that were the predecessors of Lake Superior and Lake Michigan.

MARGINAL LAKES.

In places where the land slopes toward the ice so that glacial lakes are formed, deposits of a quite different type from the outwash are accumulated, and deposits of this kind were formed in the glacial lakes now to be described.

While the ice sheet was retreating into the basin of Lake Superior marginal lakes were formed between the ice front and the adjacent higher land. Such lakes were of course formed also during the advance of the glacier, but the evidence of them was later destroyed. An early nunatak, already referred to as rising through the ice, was the long, narrow Giants Range (figs. 4, p. 87; 5, p. 88; 62, p. 443), which had been completely buried by the glacier, but because it stood highest in the ice was the first to emerge after the ice became stagnant and began to melt. The emergence of this range divided the ice sheet into two separate glaciers—the Keewatin or western continental glacier (Rainy Lake or Red River or Minnesota lobe) and the

[a] Am. Geologist, vol. 21, 1898, pp. 91-109.

[b] Mon. U. S. Geol. Survey, vol. 36 (Crystal Falls district), 1899, pp. 29-30, 332-333; vol. 43 (Mesabi district), 1903, pp. 22, 24, 191-194, 199; vol. 45 (Vermilion district), 1903, pp. 39, 425-430; vol. 46 (Menominee district), 1904, p. 500; Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 25-26; Menominee special folio (No. 62), Geol. Atlas U. S., 1900, p. 12.

[c] Van Hise, C. R., Bayley, W. S., and Smyth, H. L., The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, atlas, sheets 4, 25-39. Clements, J. M., Smyth, H. L., and Bayley, W. S., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, Pl. III.

[d] Clements, J. M., The Vermilion iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 45, 1903, fig. 23, p. 427.

Laurentian glacier (Lake Superior lobe), the two probably coalescing some distance to the northeast, perhaps north and east of Gunflint Lake. The Lake Superior lobe filled all of the Lake Superior basin, extending down over part of the Archean area of northern Wisconsin and southwestward beyond Carlton, Minn. The Minnesota or Red River lobe extended north and west from the Giants Range.

GLACIAL LAKE AGASSIZ.

In the valley of Red River, where the Red River lobe of the Keewatin glacier probably retreated some time after the Lake Superior lobe had gone back, the topographic conditions were such that a great marginal glacial lake was formed. These conditions consisted in the presence of a broad valley with gently sloping sides and a slight slope toward the north, and of a low divide between its headwater region and the headwaters of the Mississippi. Until the ice had retreated up to this low divide, which was in the vicinity of Bigstone and Traverse lakes, northwest of St. Paul, near latitude 45° 30′, the streams from the melting Red River glacier had a free outflow to the south (glacial River Warren) and built up valley-train deposits of the kind already described. As soon as the ice had retreated to this divide, however, an entirely different condition was introduced. The ice sheet was now retreating down the valley and the waters emerging from it were temporarily detained in a marginal glacial lake. With successive stages of retreat of this glacier the lake became enlarged, although probably continuing to overflow southward through the valley into Mississippi River until some lower outlet to the northeast, whose location is as yet unknown, had been uncovered. To this great glacial lake (fig. 65, p. 446) the name Lake Agassiz has been given. Warren Upham has described the lake and its abandoned, tilted shore lines, etc., in a monograph [a] that contains a full bibliography of earlier publications on the lake. The whole lake as commonly shown on maps probably never existed at one time. It is not definitely known to have been contemporary with glacial Lakes Duluth and Chicago, as the sketch map (fig. 65) shows it for convenience.

The features associated with the several stages of Lake Agassiz were beaches and lake-bottom clays. The beaches are found in the Lake Superior region as far east as Red Lake and Rainy Lake,[b] northwest of Lake Superior; the lake clays overspread all the areas below these beaches and form the fertile lowland in the wheat lands of the Red River valley in Minnesota, North Dakota, and Manitoba.

MARGINAL GLACIAL LAKES.[c]

Before or during the early stages of Lake Agassiz in the area just north of the Giants Range the glacial Lakes Norwood, Dunka, Elftman, and Onnamani were the first ones held between the east end of the Giants Range and the Rainy River lobe of the Red River glacier, outflowing southward and cutting channels across the Giants Range. (See fig. 4, p. 87; 5, p. 88; Pl. II, p. 86.) The present Lake Vermilion is a small remnant of the last of these glacial lakes. Glacial Lake Nicollet [d] was held in by the Red River glacier and the encircling land. Leech, Cass, and Winnibigoshish lakes are remnants of it. To the north glacial Lakes Big Fork, Beltrami, and Thompson were small marginal stages of glacial Lake Agassiz. Rainy Lake and Red Lake probably occupy parts of the basin of Lake Thompson and of the later Lake Agassiz, as do also the Lake of the Woods, etc. All these glacial lakes were held between a northwestward-retreating ice front and the Height of Land, overflowing southward to the Mississippi drainage basin.

South of the Giants Range the Superior lobe similarly held up glacial lakes, the first notable one being a long, narrow marginal lake, as yet unnamed, parallel to the Giants Range (fig. 62). This lake received the drainage from glacial lakes north of it, as described by Leith,[e] and in

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[a] The glacial Lake Agassiz: Mon. U. S. Geol. Survey, vol. 25, 1896.

[b] Lawson, A. C., Report on the geology of the Lake of the Woods region, with special reference to the Keewatin (Huronian?) belt of the Archean rocks: Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1885, vol. 1, new ser., 1886, pp. 139-140CC; Report on the geology of the Rainy Lake region: Idem for 1887-88, vol. 3, new ser., 1890, pp. 169-176F.

[c] Winchell, N. H., Bull. Geol. Soc. America, vol. 12, 1901, pp. 109-128.

[d] Not to be confused with glacial Lake Jean Nicolet in Wisconsin.

[e] Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 193-194.

it were deposited the lake clays that overlie the stony drift in most of the open-pit mines on the Mesabi range. The relation of stony till and lake clay shown in Plate XXIX, *B* (p. 432), is explained by the halt of the ice front south of the Giants Range and the building of the Mesabi moraine (fig. 62, *a*), after which a withdrawal of the ice toward the south made possible the formation of the glacial lake and the deposition of the clay overlying the till (fig. 62, *b*).

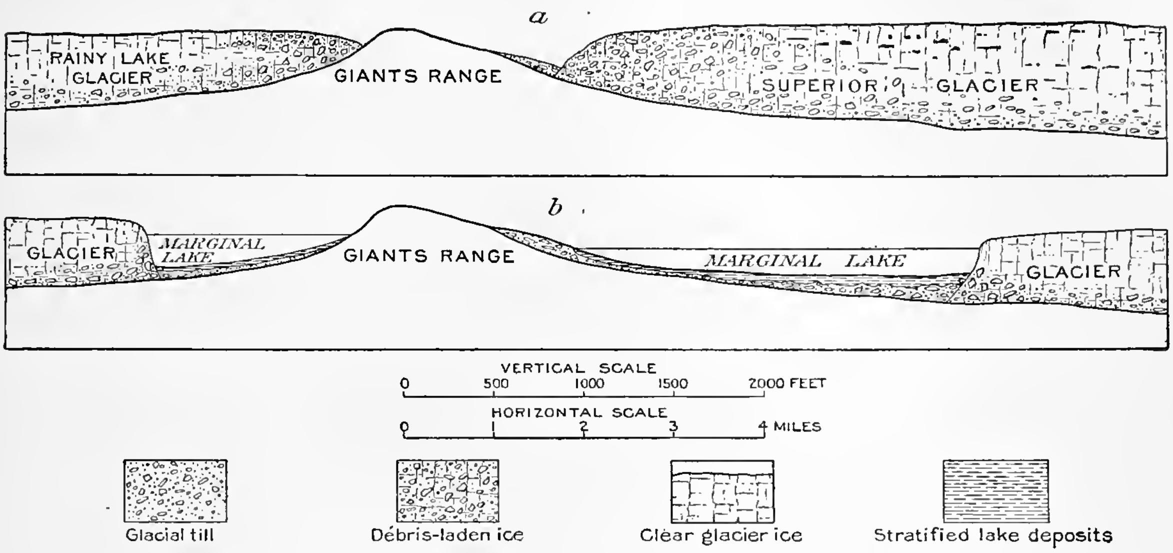


FIGURE 62.—Sketch showing the origin of the drift deposits overlying the ore in the Mesabi iron range.

With farther retreat of the Lake Superior glacier southeastward, the unnamed marginal lake mentioned above was drained and a new glacial lake, Lake Upham, was formed, its southernmost ice barrier being near the upper bend of the present St. Louis River, while the gabbro highland to the east, the granite range to the north, and the morainic highland to the west and south held it in. Lake Upham had an elevation of about 1,300 feet and its bottom forms the flats traversed by the Duluth, Missabe and Northern Railway in the great muskeg area where the railway is so straight. At about this same time glacial Lake Aitkin was formed farther west. The obstruction on the site of Mille Lacs produced glacial Lake Issati. Afterward glacial Lake St. Louis was formed in the St. Louis Valley, draining out over a low col near Barnum and Carlton, at an elevation of about 1,135 feet, and having an area of about 40 square miles.

Many glacial lakes, including Lake Minnesota, were formed in southern Minnesota in association with the Red River lobe. Lake Agassiz, already referred to, was similarly formed in the Red River valley at a little later stage, and glacial Lake Jean Nicolet [a] occupied Green Bay and the Fox River valley in Wisconsin, draining westward into Wisconsin River at Portage. The present Lake Winnebago lies in its basin.

LAKE NEMADJI.[b]

Glacial Lake Nemadji (fig. 63) was formed between the ice barrier of the Lake Superior lobe on the northeast and east and the higher land west of Lake Superior in Minnesota. This lake, which was about 65 feet lower than Lake St. Louis and may have had a slightly greater area, drained through another col near Barnum and Pickering, southwest of Carlton, into the Mississippi.

As the ice retreated still farther to the northeast [c] there were changes in the levels and in the outlets of the glacial lakes that lie between ice dams and the surrounding land. The first

[a] Upham, Warren, Am. Geologist, vol. 32, 1903, pp. 105-115, 330-331.
[b] Winchell, N. H., Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 4, 1899, pp. 2-3, 18-20.
[c] F. B. Taylor (A short history of the Great Lakes: Studies in Indiana geography, 1897, chapter 10, pp. 1-21) has written a review of the various lake stages and the outlets, etc., associated with the different positions of ice fronts and levels of the land.

consequence of the retreat of the ice barrier would be that lower valleys across the hills to the south or east might be exposed, and as a result of this the waters of the lake would find a way out through the new divide and the lake would fall to a new level. The earliest glacial lakes in northern Wisconsin, like the predecessor of Lake Gogebic and the great marginal lake in the Ontonagon Valley,[a] probably began to exist before or during the Lake Nemadji stage.

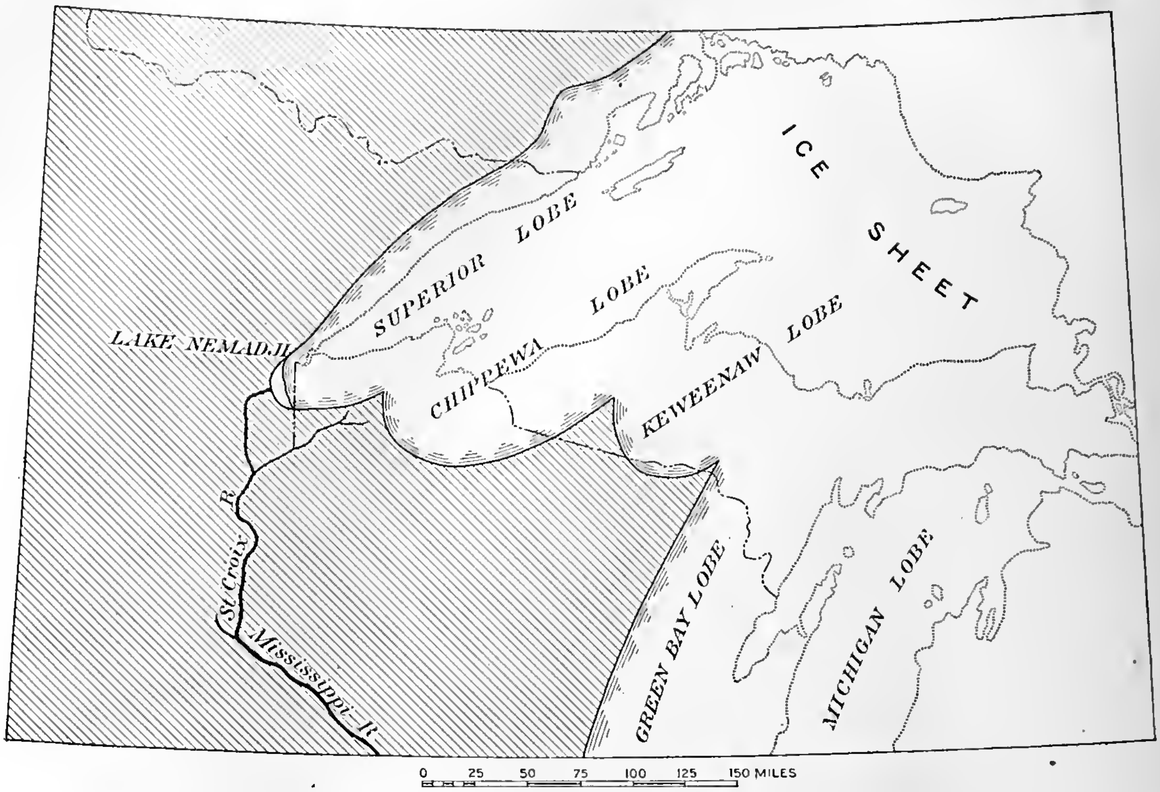


FIGURE 63.—Glacial Lake Nemadji.

LAKE DULUTH.

As the ice retreated northeastward, after the Lake Nemadji stage, it soon retired to a point far enough to the northeast to expose the col now crossed by the Chicago, Minneapolis, St. Paul and Omaha Railway. As a result the outlet near Carlton was abandoned and the waters of this lake outflowed directly southward through the St. Croix to the Mississippi (fig. 64) through a channel[b] 419 feet above the present Lake Superior, between the headwaters of the Brule and those of the St. Croix. Exactly where the ice front of the Lake Superior glacier stood at this stage can not be stated, but it probably halted at several points east of the Apostle Islands and perhaps as far east as Keweenaw Point, the other margin resting against the north shore of Lake Superior at several points in Minnesota, smaller marginal lakes being held on each shore between the ice and the land in Minnesota, Wisconsin, and Michigan.

The great glacial lake of this stage is called Lake Duluth,[c] although Upham[d] had previously named it the West Superior glacial lake. It is evident that this lake existed for a long time, and there are three kinds of deposits which indicate that this was so. One kind consists of the elevated beaches which are still found along the hillsides at the level of the St. Croix outlet and which are so broad and well developed on the escarpment face above Duluth that the Boulevard

[a] Lane, A. C., Summary of the surface geology of Michigan: Ann. Rept. Geol. Survey Michigan for 1907, 1908, pp. 141–142.

[b] The elevation of this channel is given as 1,070 feet by Warren Upham (Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, p. 55; Final Rept. Geol. and Nat. Hist. Survey Minnesota, vol. 2, 1888, pp. 642–643). The altitude of the summit in this channel is stated by Leverett to be 1,021 feet, as shown in a profile in House Doc. 330, 54th Cong., 1st sess., 1896.

[c] Taylor, F. B., Studies in Indiana geography, 1897, fig. 1, p. 10.

[d] Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1894, pp. 54–55.

Drive follows one or two of them for miles. This shore can be traced from a point east of Ashland westward to Brule River and on the other side around the head of the lake to a point some distance east of Duluth. Similar beaches or terraces in the Lake Superior basin were observed early in the exploration of the region [a] and were explained as wave-wrought forms.

The second class of deposits indicating that the glacial lake at Duluth existed for a long time comprises the deltas that were built where streams flowed into the lake at the level of the Boulevard beaches, as at Thompson east of St. Louis River, on Tischers Creek, and on Chester Creek at Duluth.[b]

The third class of these deposits consists of the lake clays, which without question accumulated in later periods as well as in this, but which would of course have formed to a considerable depth when the ice front stood across the lake and was discharging icebergs with glacial material, and when streams from the hills to the north, south, and west contributed their load of sediment.

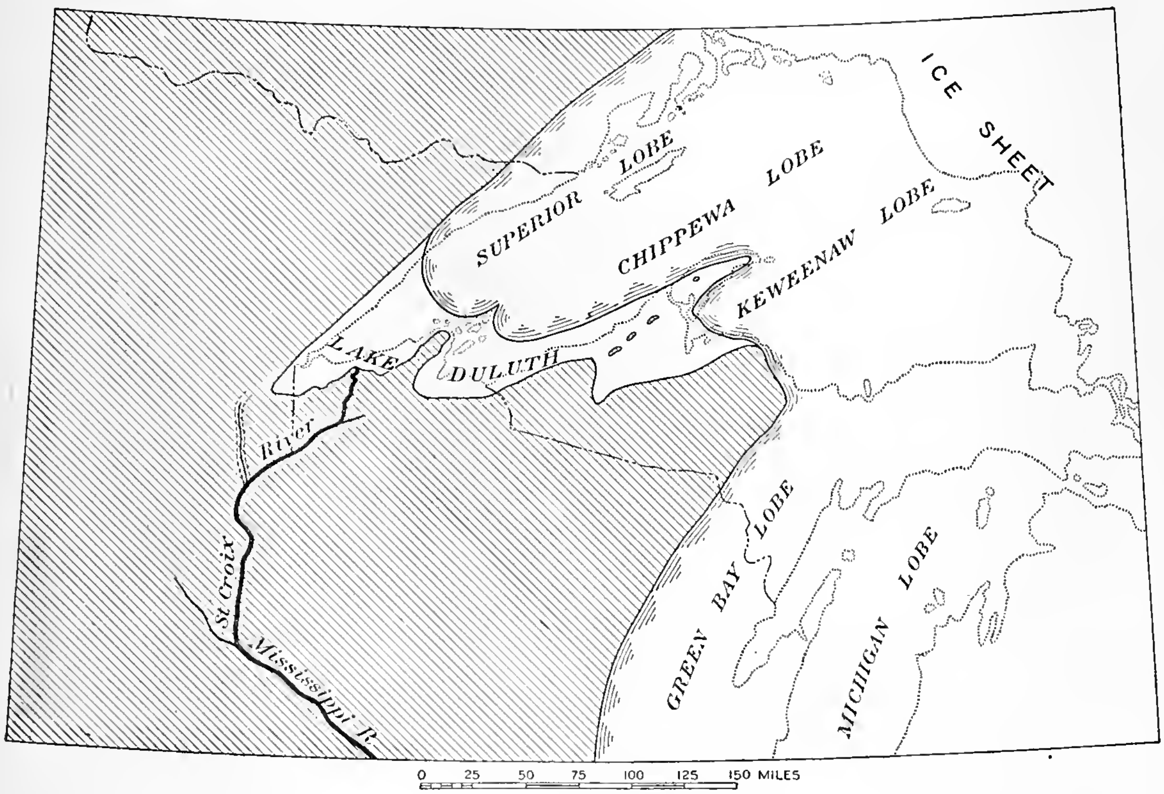


FIGURE 64.—Glacial Lake Duluth.

INTERMEDIATE GLACIAL LAKES.

As would naturally be expected, with the continued retreat of the Lake Superior and Lake Michigan ice lobes, the lake levels were falling lower and lower. One of the next levels at which there was a notable stand of the ice was when the waters of the western Lake Superior basin escaped past Chicago through Illinois River to the Mississippi. This was probably some time after the early Lake Duluth stage (fig. 65). Whether there were intermediate outlets between the two stages referred to is not known, but it seems probable that the ice in retreating northeastward gradually exposed the highland of northern Wisconsin and Michigan so that

[a] Logan, W. E., Report on the geology of the north shore of Lake Superior: Geol. Survey Canada, 1847, p. 31. Hubbard, Bela, House Ex. Doc. No. 1, 31st Cong., 1st sess., pt. 3, 1849, pp. 910-911. Foster, J. W., and Whitney, J. D., Report on the geology and topography of a portion of the Lake Superior land district, vol. 1, 1850, pp. 194-197, 211-213. Desor, E., idem, vol. 2, 1851, pp. 248-255, 268-270. Whittlesey, Charles, idem, pp. 270-273. Agassiz, Louis, Lake Superior, 1850, pp. 60, 66, 100-101, and frontispiece.

[b] Upham, Warren, Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, pp. 65-66.

eventually the waters from the enlarged Lake Duluth abandoned the St. Croix outlet for some lower ones in northern Wisconsin and Michigan, and still later outflowed southward along the margin of the ice sheet into Lake Jean Nicolet, in eastern Wisconsin, which drained into Wisconsin and Mississippi rivers. Still later the drainage went into the enlarged Lake Chicago. It is known that there were a number of intermediate stages due either to lowering of the ice barrier, to discovery of lower outlets, or to tilting of the land, because the beaches preserved on the hillsides below the upper Lake Duluth beach indicate other stands of the lake waters for considerable periods of time. The beaches associated with these intermediate stages are found at several levels below the Boulevard Beach, as shown in the table (p. 451).

It seems likely that some of the intermediate stages, like the Lake Duluth stage, were of considerable duration, because the beaches that were built are broad, the cliffs that were cut are well marked, and good-sized deltas were formed at the mouths of the streams. Of these deltas that of Dead River at Forestville near Marquette and those of Swedetown and Huron creeks near Houghton are good examples.[a] The fine material carried beyond the deltas into

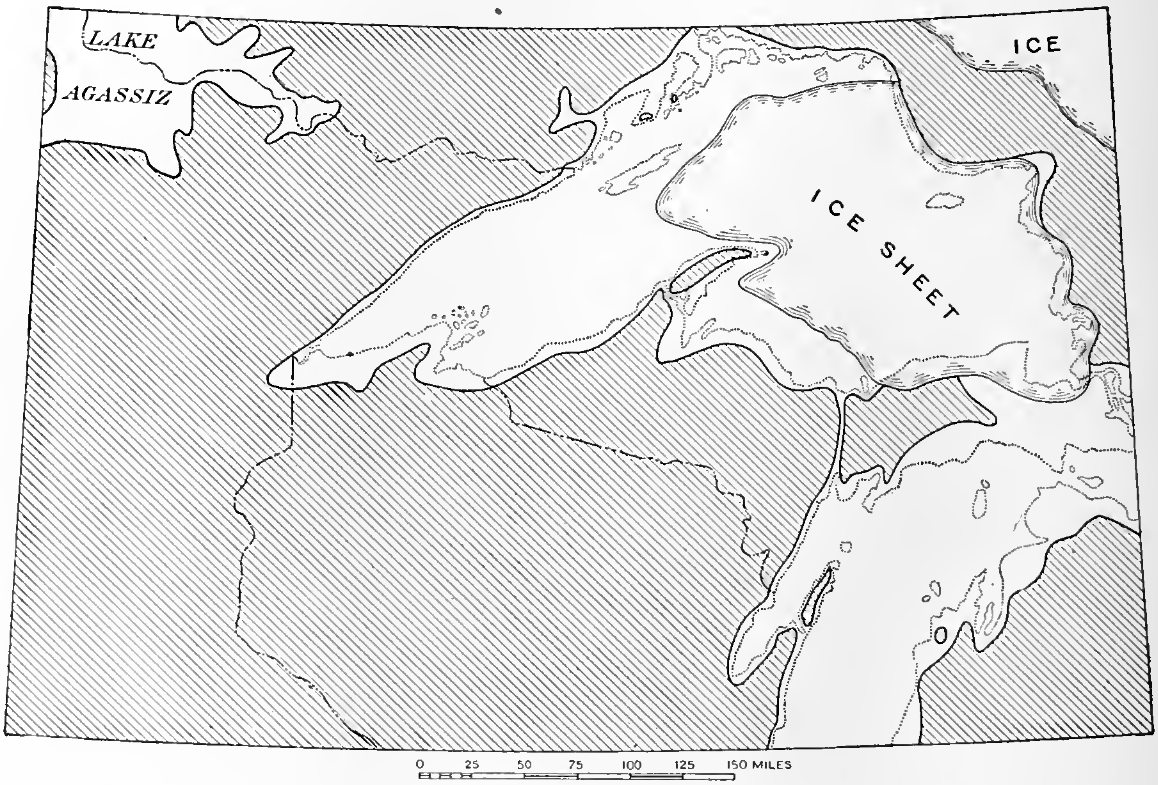


FIGURE 65.—Hypothetical intermediate stage with the expansion of glacial Lake Chicago and the later stage of glacial Lake Duluth; part of glacial Lake Agassiz near the northwest corner. An isolated stagnant ice block is shown in the Lake Superior basin.

the lake formed thick deposits of glacial clays, of which some are now exposed and others are still below lake level.

LAKE ALGONQUIN.

After the episode of the Chicago outlet the glacial barrier continued to retreat to the northeast, and the glacial lake, which came into existence gradually, occupied all of the basin of the present Lake Superior, its waters covering parts of the peninsula of upper Michigan west of Marquette and being confluent with those in the basins of the present Lakes Michigan and Huron (fig. 66). This is called the Lake Algonquin stage. At this time the ice barrier stood east of North Bay in the Ottawa Valley, and had retreated from Lake Superior north of the Height of

[a] Lane, A. C., Summary of the surface geology of Michigan: Ann. Rept. Michigan Geol. Survey for 1907, 1908, p. 142.

Land. Possibly there was a stagnant isolated ice block in the Lake Superior basin at this time or just before. During the Lake Algonquin stage, which of course came after a series of intermediate stages in which Lakes Chicago and Duluth were enlarged as recorded by the successive beach levels one below the other, the waters deserted the outlet past Chicago to Illinois and Mississippi rivers because lower outlets were uncovered to the east. Lake Algonquin had two such outlets. The first led past Port Huron through the present Lake St. Clair and Lake Erie into glacial Lake Iroquois, which covered more than the basin of the present Lake Ontario; the second outlet also led into Lake Iroquois through the Trent River valley from Georgian Bay. There were several oscillations with one or both of these outlets running during the Algonquin stage. The Lake Iroquois waters flowed eastward through Mohawk River to Hudson River and New York Harbor. All around the Lake Superior basin the strongest Lake Algonquin beaches are well-marked shore lines elevated high above the waters of the present lake. At this stage glacial lakes probably occupied the Kaministikwia and Nipigon River valleys, including all the basin of the present Lake Nipigon.

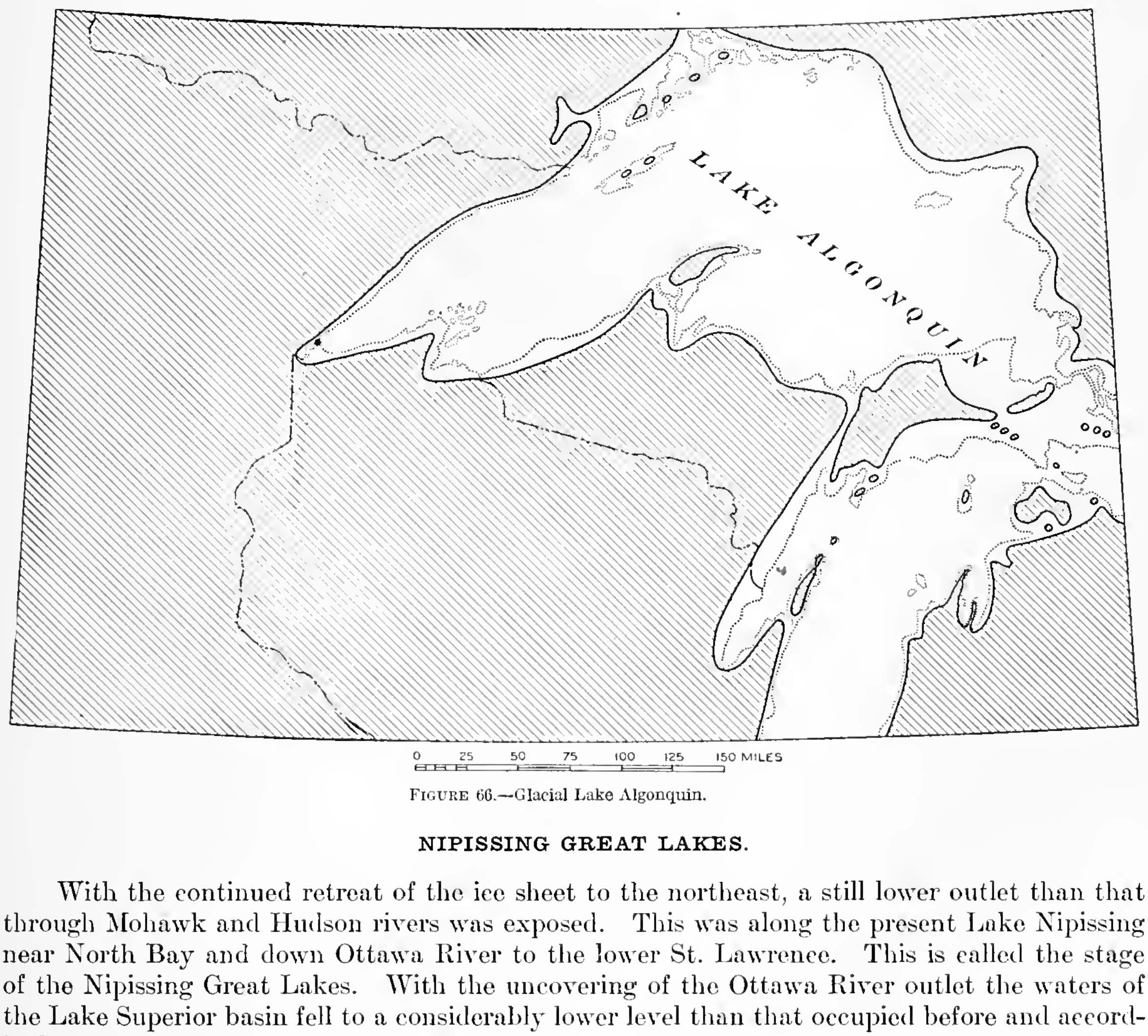


FIGURE 66.—Glacial Lake Algonquin.

NIPISSING GREAT LAKES.

With the continued retreat of the ice sheet to the northeast, a still lower outlet than that through Mohawk and Hudson rivers was exposed. This was along the present Lake Nipissing near North Bay and down Ottawa River to the lower St. Lawrence. This is called the stage of the Nipissing Great Lakes. With the uncovering of the Ottawa River outlet the waters of the Lake Superior basin fell to a considerably lower level than that occupied before and accordingly regions about the shores of Lake Superior which had been submerged or had groups of islands were wholly uncovered. The largest area of this sort was the lowland east of Marquette, in the Upper Peninsula of Michigan (fig. 67). Rominger, who described the superficial deposits of this region,[a] was somewhat at a loss to explain the mixture of ground moraine, reces-

[a] Rominger, Carl, Geol. Survey Michigan, vol. 1 1873, pp. 15–20.

sional moraines, assorted drift, and lake clay with which the region is covered as a result of its occupation first by ice, then by melting ice fronts, and later by glacial lakes.

One notable change was the temporary abandonment of the outlet from Lake Huron past Detroit to Lake Erie. Lake Erie continued to drain into Lake Ontario, which may have been an arm of the sea, while Lakes Superior, Michigan, and Huron (the Nipissing Great Lakes) drained independently to the Ottawa. Another marked change was the disconnection of the Lake Nipigon basin so that Lake Nipigon at this time first assumed somewhat its present form and was independent of Lake Superior. Isle Royal, the site of several small islets at the Algonquin stage, assumed form as one large island of nearly its present area. All about the lake shore the waters stood at lower levels. The beaches built at the Nipissing stage seem to be the largest that were formed at any time in the history of the Lake Superior basin. These beaches are so broad and the cliffs cut by the Nipissing waves are so high that it has been inferred that this stage of the lake was continued for a very long time—longer, in fact, to judge from the strength

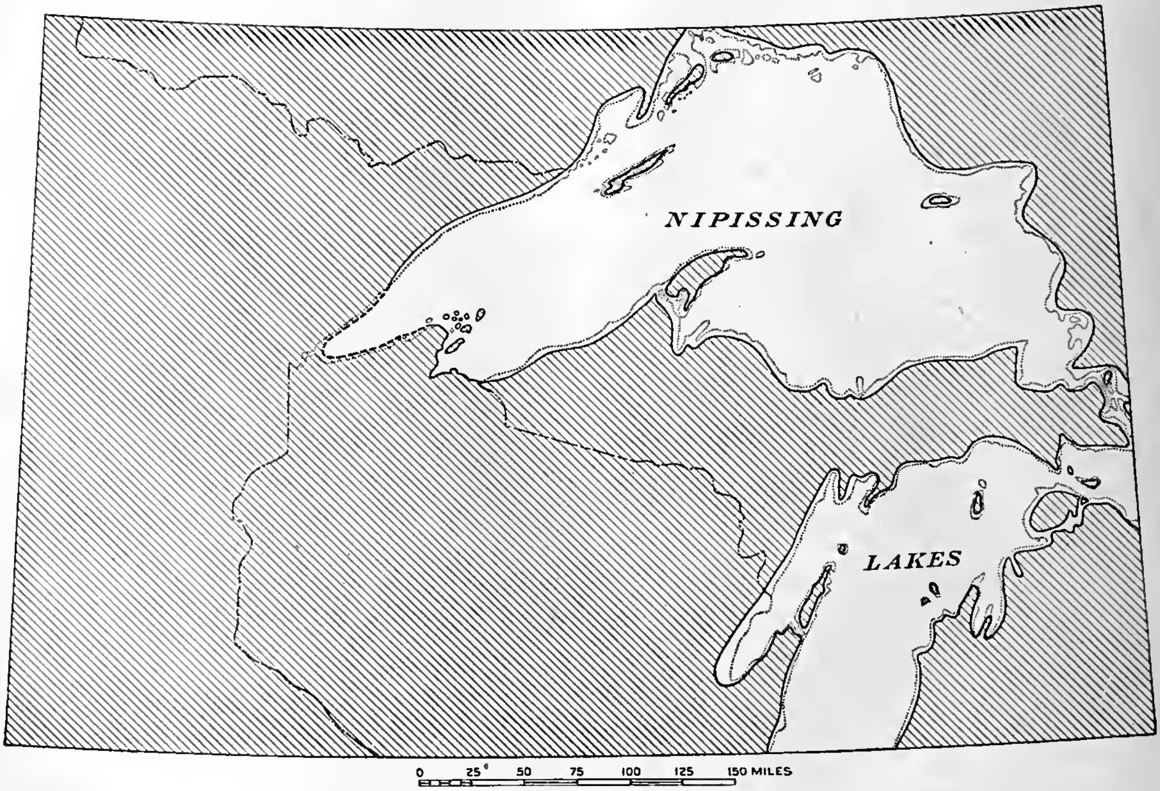


FIGURE 67.—Part of Nipissing Great Lakes.

of the shore lines, than the present level of Lake Superior has been maintained as yet, though postglacial gorges are cut back much farther at the present level than they were at the Nipissing stage.

EFFECT OF TILTING ON GLACIAL LAKES.

Up to this point in the history of the Lake Superior basin the lake waters fell every time a lower outlet was exposed by the northeastward retreat of the ice sheet. For some time before this there had been going on a broad warping which was producing an uplift of the region to the north or a sinking of the region to the south. The evidence of this disturbance is found in the fact that the beaches of the glacial lakes, which must have been originally horizontal in position, for the waters of the lake were horizontal, are now inclined from north to south at a slight angle. It was not until after the close of the Nipissing stage that this warping of the lake basin had any very profound effects, except to produce a fanlike splitting of glacial-lake shore lines and to cause temporary oscillations in the outlets of the Algonquin and Nipissing stages. During and after the Nipissing stage, however, the tilting became sufficient to bring about a new and rather dramatic change in the history of the glacial lakes. It has been stated that the lake levels had fallen because lower and lower outlets toward the northeast were exposed by the ice sheet (figs. 63–66). The normal result of such a series of changes would be the establishment of a permanent outlet of the Great Lakes along the line of greatest depression between the uplands of New England and the Adirondacks on the one hand and the Height of Land of Canada on the other. The Lake Nipissing and Ottawa River outlet was so situated; but after the occupation of this outlet for what may have been a longer time than the present St. Lawrence outlet has been occupied, to judge from the strength of the beaches, as already stated, the uplift of the land toward the north became sufficient to raise the Nipissing-Ottawa Valley to a higher level than another valley farther south, and the latter valley became the outlet of the Great Lakes. The three upper Great Lakes at this time, instead of draining through Lake Nipissing to Ottawa River or through Trent River and Georgian Bay to Lake Ontario, were once more turned southward and drained through Lake St. Clair past the present site of Detroit into Lake Erie, whence the waters of the four upper lakes once more passed over Niagara Falls to Lake Ontario and down the St. Lawrence by the present route. The amount of tilting necessary to accomplish this result was not very great, although that it was greater than the previous tilting is proved by the fact that in places these lower beaches are more highly inclined than any above them. That it did not affect the whole region is shown by the horizontality of some of the beaches.

This tilting has continued up to the present time and is still going on, as is proved by several kinds of evidence. One proof is found in the fact that on the south side of Lake Superior and the other Great Lakes the waters are being canted into bays and river mouths, so that what were formerly valleys are now becoming bays and estuaries (Pl. II, p. 86), as noted in northern Wisconsin by the land surveyor G. R. Stuntz[a] in 1869. In these southern rivers the lake water extends backward far enough to make river navigation possible for some distance, as from Duluth 17 miles up St. Louis River to Fond du Lac; but in all except the largest rivers on the north side of the lake the water cascades down in falls and rapids almost directly into the basin of the lake itself. The lower courses of many rivers on the south side of Lake Superior are so broad that it requires a double line to represent them on the map, whereas on the north side of the lake practically all the rivers are so narrow that they are represented by a single line. This canting of the lake waters into the river valleys on the south side of the lake has had a very important effect in connection with man's occupation of the region, by producing good harbors, and of such harbors that at Duluth and Superior is the best (figs. 69, p. 457, and 70, p. 458; Pl. V, *A*, p. 112), having been protected by the subsequent building of great sandbars. To the submergence of old stream valleys during this tilting are due the Apostle Islands, which have been briefly described by Whittlesey[b] and Irving.[c]

PRESENT POSITION OF RAISED BEACHES.

The effect of the tilting of this elevated shore line has been to submerge some of the beaches of the former lakes, so that the Nipissing shore line, for example, is elevated many feet above the level of Lake Superior on the north shore of the lake, whereas on the south shore it is now submerged in places by the lake waters. It has been estimated that the shore line of the Nipissing stage in Lake Superior is 25 feet below the present water surface at Duluth and that this shore line appears above the present water surface at Beaver Bay, beyond which it rises with an average slope of about 7 inches to the mile.[d]

Numerous observations and notes on these abandoned strands were made by pioneers in the region. Some of these by Sir William Logan, Foster and Whitney, Bela Hubbard,

[a] Stuntz, G. R., Some recent geological changes in northeastern Wisconsin: Proc. Am. Assoc. Adv. Sci., vol. 18, 1870, pp. 205–210.
[b] Whittlesey, Charles, Geological survey of Wisconsin, Iowa, and Minnesota, 1852, pp. 437–438.
[c] Irving, R. D., Geology of Wisconsin, 1873–1879, vol. 3, 1880, pp. 72–76.
[d] Taylor, F. B., Am. Geologist, vol. 15, 1895, p. 307.

W. A. Burt, Agassiz, Desor, Whittlesey, and others have already been alluded to. None of these furnish very specific data or contain more than scattered observations. A. C. Lawson,[a] however, made a very painstaking study and instrumental measurement of these elevated shore lines on the northern shore of Lake Superior, and concluded that these strands were horizontal and were formed in a great lake, held in by a land barrier that was progressively lowered by warping. He rejected the idea of an ice barrier. Subsequently F. B. Taylor[b] pointed out that Lawson and also Warren Upham,[c] who supported Lawson's conclusion as to the horizontality of these shore lines, though recognizing the glacial-lake condition, had not sufficiently considered the possibility that the shore lines observed from point to point along the shore of Lake Superior were inclined instead of being horizontal. By field study Taylor demonstrated that the shore lines which Lawson interpreted as horizontal were indeed inclined at a small angle, and pointed out conclusively that they were formed in a glacial lake whose barrier was an ice dam to the east.[d]

These raised beaches on the north shore of Lake Superior, especially in the Michipicoten district, have also been studied by A. B. Willmott[e] and by A. P. Coleman,[f] who has noted very many more shore lines than were measured by Lawson. Near Lake Nipigon Coleman has also measured many new shore lines,[g] and a number were noted by C. R. Van Hise and J. M. Clements[h] in a trip around northern Lake Superior in 1901. Observations on the raised beaches in northern Lake Michigan, Green Bay, and western Lake Huron have been made by Taylor,[i] Russell,[j] Goldthwait,[k] and others.

The writer took a hasty trip around the north shore of Lake Superior from Duluth to Sault Ste. Marie in 1907 and visited a number of the localities described by Lawson. Although feeling that Lawson's observations in general were most thorough and accurate, he believes that the conclusion suggested by Taylor is fully warranted and that at least the lower beaches of this region show a decided tilt to the south and southwest. In evidence of the tilting and the long duration of the Nipissing stage established by Taylor, he found that near Duluth and northward from that city to Beaver Bay the mouths of the small postglacial gorges contain no bed rock but are uniformly either filled with gravel deposits or occupied by the waters of the lake, as at Lester Creek, north of Duluth. Northeast of Beaver Bay most of the small stream valleys are found to have no gorges extending down to or below the present lake level, but instead the streams flow over the bare rock surface of the hillside. An especially good illustration of this is Current River, northeast of Port Arthur, Ontario. Good evidence was found that the Nipissing shore line dips under the lake at Beaver Bay, Minnesota.

It has been shown by G. K. Gilbert[l] that the canting of the lake basins is still in progress, and his estimate of the rate of tilting is that the north end of a south-southwest line 100 miles long in the Great Lakes region would in a century be tilted 0.42 foot above the south end. This amount of tilting, of course, is small, but it would be sufficient to divert the waters of Lake Superior again, just as they were once diverted from the Nipissing Valley to the St. Lawrence Valley, turning them southward to Chicago River, where the waters would once more flow southward rather than over Niagara and through the St. Lawrence. More recent studies

[a] Sketch of the coastal topography of the north side of Lake Superior: Twentieth Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1893, pp. 230-282.

[b] The Nipissing Beach on the north Superior shore: Am. Geologist, vol. 15, 1895, pp. 304-314.

[c] Am. Jour. Sci., 3d ser., vol. 49, 1895, p. 7; Twenty-second Ann. Rept. Geol. and Nat. Hist. Survey Minnesota, 1894, pp. 54-66; Bull. Geol. Soc. America, vol. 6, 1895, pp. 21-27.

[d] Taylor, F. B., Am. Geologist, vol. 15, 1895, pp. 304-314; vol. 20, 1897, pp. 111-128.

[e] Rept. Bur. Mines Ontario, vol. 7, 1898, p. 193.

[f] Idem, vol. 8, pt. 2, 1899, pp. 150-156; vol. 9, 1900, pp. 175-176; vol. 11, 1902, p. 184; vol. 15, pt. 1, 1906, pp. 193-199.

[g] Idem, vol. 16, pt. 1, 1907, p. 135.

[h] Unpublished MS.

[i] Taylor, F. B., The abandoned shore lines of Green Bay: Am. Geologist, vol. 13, 1894, pp. 316-327; A reconnaissance of the abandoned shore lines of the south coast of Lake Superior: Idem, p. 365; The highest old shore line on Mackinac Island: Am. Jour. Sci., 3d ser., vol. 43, 1892, pp. 210-218; The Munuscong Islands: Am. Geologist, vol. 15, 1895, pp. 24-33; The great ice dams of Lakes Maumee, Whittlesey, and Warren: Idem, vol. 24, 1899, pp. 6-38.

[j] Russell, I. C., Ann. Rept. Michigan Geol. Survey, for 1904, 1905, pp. 83-93; idem for 1906, 1907, Pl. III.

[k] Goldthwait, J. W., Abandoned shore lines of eastern Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey No. 17, 1907, pp. 43-119; Jour. Geology, vol. 14, 1906, pp. 411-424; Bull. Illinois Geol. Survey No. 7, 1908, pp. 54-68; Jour. Geology, vol. 16, 1908, pp. 459-476.

[l] Modification of the Great Lakes by earth movement, Nat. Geog. Mag., vol. 8, 1897, pp. 233-247; Recent earth movement in the Great Lakes region: Eighteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1898, pp. 601-647.

by J. W. Goldthwait[a] indicate that the abandoned shore lines in the southern part of the Lake Michigan basin are horizontal. The axis of tilting runs south of Green Bay. The effect of the presence of this hinge line will be to postpone very much the time before the tilting can be sufficient to divert the drainage of Lake Superior and the other Great Lakes to the Chicago outlet.

A series of observations as to the fluctuating level of Lake Superior have been made by Capt. J. H. Darling, of the United States engineer office, at Duluth, who comes to the conclusion that so far as evidence from two stations nearly on an east-west line, Duluth and Marquette, for eighteen years indicates, there is no adequate proof of a change in the level of the present water surface. It seems possible to the writer, however, that this fact of no variation at two points, one almost directly west of the other, would indicate that the axis of tilting runs nearly east and west in the Lake Superior basin, as it seems to run in Lake Michigan.

One of the great unsolved problems of the glacial-lake history in the Superior and upper Lake Michigan basins concerns the stages intermediate between Lake Duluth and Lake Chicago or Lake Algonquin. Between the time of the St. Croix outlet and the Hudson River outlet Lake Duluth must have had an outlet to Lake Chicago through a series of lakes and straits, including Portage Lake on Keweenaw Point, the possible marginal channel east of Marquette in the Au Train and Whitefish valleys to Green Bay,[b] and perhaps a channel through Sturgeon Bay in the Door Peninsula of Wisconsin. Nothing conclusive can yet be said as to the halts of the ice front or the time of shifting from the St. Croix outlet to the temporary initial Lake Algonquin outflow past Chicago, a stage which preceded the double outlets to Lake Iroquois and thence to the Hudson. Further observation, however, will settle these questions.

Another interesting possibility, at present merely a hypothesis, is that which supposes stagnant ice in the deep eastern part of the Superior basin with retreat southward from the Height of Land, instead of northward toward it as has always been inferred. No evidence known to the writer disproves this possibility and certain unusually high beaches in the Marquette and Michipicoten districts suggest it. It is possible that this stagnant mass may have become completely detached from the retreating ice sheet. At the beginning of this withdrawal marginal lakes of high level were formed in the Michipicoten district, just as Lakes Omini and Kaministikwia were formed earlier on the northwest side of the lake.

The following table shows some of the present altitudes of the abandoned shore lines, the discrepancies in elevation in the same beach proving the tilting and indicating how the warping varied from the earlier to the later stages and from one part of the region to another. Not all the higher isolated beaches are listed, and some of the correlations are tentative.

Elevations above Lake Superior (602 feet) of some of the abandoned beaches.

	Glacial Lake Duluth (or highest early lake recorded).	Glacial Lake Algonquin.	Nipissing Great Lakes.	Sault stage.
Duluth	532-535, 510-515, 470-475	410-415	-25	
Beaver Bay		314(?)	0	
Isle Royal	467-498	203-315, 380	30	
Port Arthur	482	400-450	60	
Nipigon			90	28
Jackfish		418	105-110	33
Peninsula Harbor		410	110-115	40-45
Michipicoten	728, 843, 470			
Old Woman River	315, 534, 543	212-265	85-148	10-34
Root River		414		
Sault Ste. Marie		412	49	
Grand Marais			35	
Munising			25	
Marquette	590	338		
Huron Mountains		260, 240, 235, 335	25	
L'Anse	590	338	20	
Ontonagon Valley	718			
Houghton		410	25	
Lac La Belle			40	
Porcupine Mountains	561			
Kimball	570			
Iron River	510			
Maple Ridge	535			
Brule-St. Clair outlet	419			
Duluth	470-535			

[a] Bull. Wisconsin Geol. and Nat. Hist. Survey No. 17, 1907, p. 42; Jour. Geology, vol. 14, 1906, pp. 411-424, vol. 16, 1908, pp. 459-476.

[b] Winchell, N. H., Am. Jour. Sci., 3d ser., vol. 2, 1871, p. 19.

Elevations above Lake Michigan (580 feet) of some of the abandoned beaches.

	Glacial Lake Algonquin.	Nipissing Great Lakes.
Sault Ste. Marie	412-434	49
Detour	....	51
Cedarville	....	40
St. Ignace	....	45
Munuscong Islands	280	....
Mackinac	200	45
Cooks Mills	170	....
Ensign	120	....
Garden Bluff	120	30
Fayette	130	....
Burnt Bluff	125	30
Escanaba River	140	24
Gladstone	120	20
Ford River	100	....
Pine Ridge	110	....
Birch Creek	50	....
Rock Island	99	....
Washington Island	95	20
Deaths Door Bluff	79	....
Ephraim	62	....
Egg Harbor	51	....
Graceport	....	20
Sturgeon Bay	40	....
Wilcox	41	....
Sawyer	38	....
Clay Banks	....	20
Little Suamico	31	....
Dykesville	29	....
Cormier	28	....
Two Rivers	26	18

GLACIAL LAKE DEPOSITS.

The deposits laid down in the glacial lakes differ from the deposits now being made in the Great Lakes in the rapidity of accumulation and in the character of materials laid down in water which was fed by melting ice and in which icebergs floated. The deposits made in these glacial lakes were predominantly clay, although sands and gravels were laid down near the lake shores. Great thicknesses of these clays were accumulated at the west end of Lake Superior during the Nemadji, Duluth, and Algonquin stages and acquired a prevailing red color by derivation from the Keweenawan rocks. These clays form a distinctly different soil from that found in the region not covered by marginal lakes. Well borings near Ashland and Superior, Wis., show thicknesses of 100 to 150 feet or even more of red clay, in places with a little blue clay, generally without any stones, overlying what is reported as sand and "hardpan," the latter possibly glacial till. The total thickness of clay and sand in one boring is 193 feet and in others is over 200 feet. West of Duluth and Superior and extending eastward from Superior on the south shore of the present lake, these thick lake clays, overlying the horizontal Cambrian sandstone, form a plain which appears horizontal though sloping imperceptibly northward.[a] This plain has been cut by postglacial streams into a series of rather deep, steep-sided gullies, which necessitate the building of a great number of bridges by the railroads: for example, the Duluth, South Shore and Atlantic between Ashland and Duluth and the Northern Pacific and Great Northern between Duluth and Carlton, Minn. The highways extending east and west across this region, where the streams generally flow from south to north, are continually going up and down hill in crossing ridges and valleys. West of Duluth and south of Fond du Lac, Minn., these gullies are of very great depth, some as deep as 200 feet, so that the railroads swing far southward in order to cross the gullies near their heads, reducing the number and height of the bridges which must be built. The bridges on the Great Northern Railway are in striking contrast with those on the Northern Pacific, both in their number and in their height above the streams, the latter railway crossing nearer the headwaters of the streams. The flat plain of these clays is not especially suited for agriculture and has not been cleared. The clays were covered with timber, but have been devastated by fire and at present constitute a rather desolate country that is traversed in the first hour of the ride from Duluth to St. Paul.

[a] Grant, U. S., Bull. Wisconsin Geol. and Nat. Hist. Survey No. 6, 1901, p. 6.

North of Duluth, as previously indicated, the ice retreated southward toward the Lake Superior basin, and between the Mesabi range and Lake Superior the area of flat-lying lower Huronian rocks was the bed of a great glacial lake, called Lake Upham, which gradually increased in size as the ice retreated, and in which great quantities of clay were accumulated. The interference with drainage in this lake-clay plain has brought about the great prevalence of muskegs along the Duluth, Missabe and Northern Railway, which pursues an almost mathematically straight course for over 25 miles because of the levelness of the lake-bottom plain. Nearly all of this distance is through muskeg swamps, interrupted here and there by low gravel ridges, which are believed to be portions of recessional moraines built at temporary halts of the ice during this southward retreat and later partly submerged by the accumulation of lake clay. The bed of glacial Lake Agassiz is similar in nature.

THE FOUR PLEISTOCENE PROVINCES.

GROUNDS FOR DISTINCTION.

In review of the conditions prevailing in the Lake Superior region as regards minor topography and soil, it may be stated that this region includes four distinctive provinces—(1) the Driftless Area, (2) the area of the older drift sheets, (3) the area overlain by the till and the

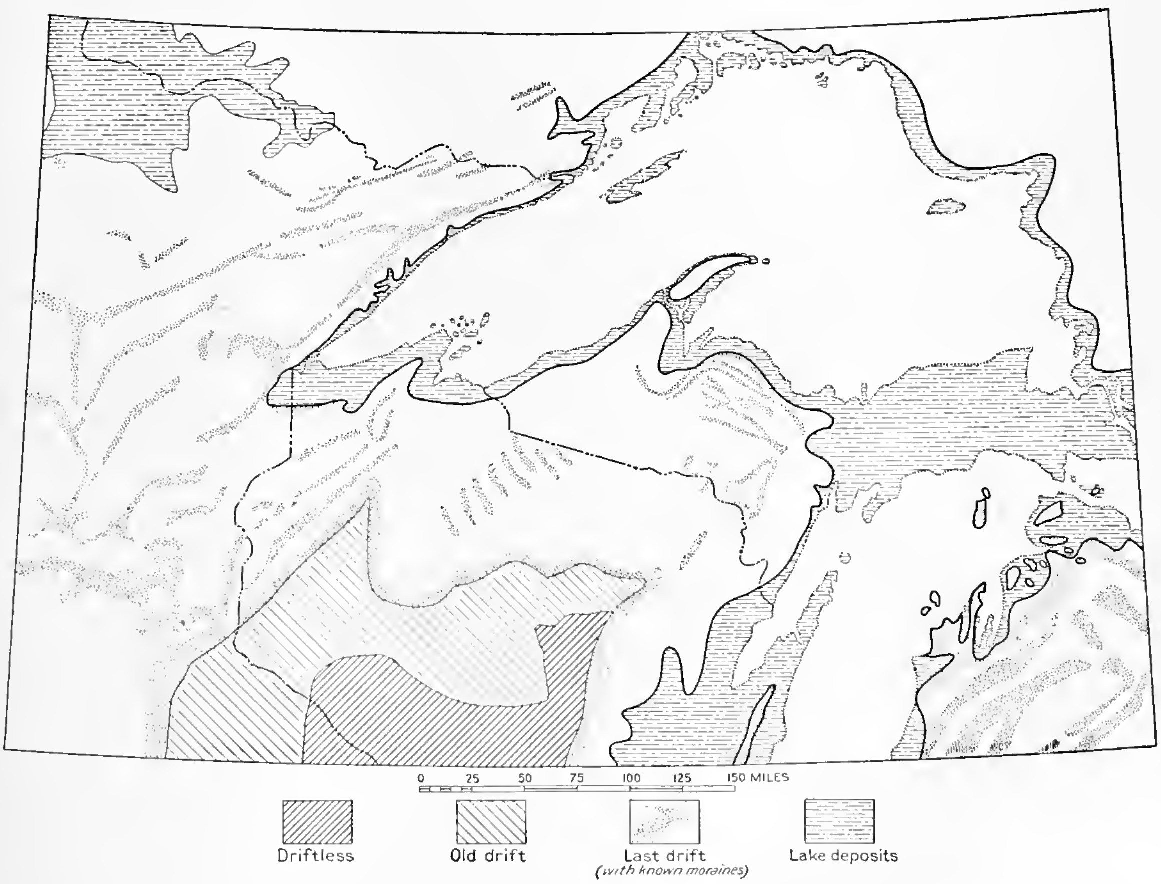


FIGURE 68.—Sketch map showing Driftless Area and regions of older drift, last drift, and lake deposits.

assorted glacial deposits of the last (late Wisconsin) stage of glaciation, and (4) the area where glacial-lake deposits predominate. (See fig. 68.) These provinces are bounded respectively by the terminus of the outermost of the older drift deposits, by that of the glacial lobes of the Wisconsin stage, by the border of the highest shore lines of the great glacial lakes in the Lake Superior and Lake Michigan basins, and by the highest shore of Lake Agassiz. Not all the glacial lobes, and by no means all the glacial lakes, were contemporaneous, so the map should not be understood as representing conditions that were produced at any one time. It merely represents four groups of areas within each of which the average conditions are strikingly similar and which contrast with one another.

DRIFTLESS AREA.

In the Driftless Area the minor topographic conditions are intimately related to the underlying rock. The drainage is mature (Pl. XXXI, *A*). The valleys are cut almost entirely by streams. Resistant rocks make prominent ledges with castellated forms, and weak rocks are worn to insignificant relief. Waterfalls and rapids in the streams are rare. Lakes are absent. The soil consists of the materials of the underlying rock or of some adjacent material from a source uphill from its present location. It usually grades downward with coarser and coarser fragments to the undecayed ledge from which it has been derived by disintegration. It is a typical local or residual soil.

AREA OF OLDER DRIFT.

The province of older drift includes the regions adjacent to the Driftless Area where deposits were left by one or more of the earlier glacial advances before the Wisconsin. The topography and soil of this province are contrasted with that of the Driftless Area on one hand and with that of the area of Wisconsin glaciation on the other. The preglacial topography is partly obscured. The valleys are due in part to inequalities in glacial accumulation as well as to stream cutting. The streams may have rapids or waterfalls, though these are rarer than in the region of latest drift. Lakes are rather rare, and many lakes and swamps have been filled and drained. The glacial topography has slumped down to a softened outline. The soil is distinctly a transported soil, containing foreign fragments quite different in composition from the underlying bed rock, overlying it unconformably as glacial soils always do, and not grading into it. This soil, however, contrasts with the soil of the area of youngest drift, which is fresh and unweathered. Indeed, the soils of the areas of older drift are leached of their soluble constituents to some extent by the action of percolating ground water, although the degree of solution is naturally less than in the Driftless Area. This might be called a modified, transported soil.

AREA OF LAST DRIFT.

As already described, the minor topography in the province of latest drift is of the various kinds characteristic of a region overridden by glaciers. The province has a mildly irregular surface, covered by the till or ground moraine, which in some places completely mantles the ledges (Pls. XXIX, *A*, p. 432; XXXI, *B*, p. 436), in others covers them thinly (Pls. V, p. 112; XVI, in pocket), and in still others is almost absent (Pls. IV, *B*, p. 90; XVII, in pocket). It contains drumlins, terminal and recessional moraine deposits (Pl. XXX, *A*, p. 434), and the many assorted glacial deposits like the outwash. These minor topographic forms and the transported soil, which is fresh and still retains its soluble constituents, make up the surface of the great province of the Wisconsin drift, which includes the greater part of the Lake Superior region. The important feature about this province is its contrast with the adjacent areas, where there is either no drift or the older drift or where even this youngest drift is overlain by glacial-lake deposits. The contrast with the topography of the older drift has already been emphasized and may be dismissed with the statement that here the irregularity is greater and the aspect of the topography is distinctly fresher. The young streams have cut relatively insignificant courses in the latest drift, except along the largest rivers, and the lakes and swamps mostly exist as at the close of the glacial period, though some are partly filled.

AREAS OF GLACIAL-LAKE DEPOSITS.

The fourth Pleistocene province includes not the areas covered by the numerous small inland lakes, but the area formerly occupied by the larger glacial lakes which overspread the margins of Lake Superior and Lake Michigan and extended some distance northward from Duluth, as well as the bed of the large glacial Lake Agassiz.

In this province the deposits consist chiefly of assorted glacial drift of lacustrine types, showing a predominance of clay and silt, although in the region between Marquette and Sault Ste. Marie sandy deposits cover large areas. The minor topography in this province contrasts strikingly with everything else in the whole Lake Superior region. In places there is an exceedingly smooth, monotonous surface of lake clay or sand covered with muskegs or forests, with insignificant stream valleys, as south of the Mesabi range, in Minnesota, and in the eastern part of the northern peninsula of Michigan; elsewhere there is a similar clay or sandy surface which stands at a high enough level above the present lake for streams to have cut deep, steep-sided gorges and gullies in the clays, as west and south of Duluth. The soils of this lake-bottom plain vary greatly in character, being in some places exceedingly fertile, as in the valley of Red River and on the bed of the extinct Lake Agassiz; in others sandy, originally supporting an excellent forest, as in the eastern part of the northern peninsula of Michigan; and in still others of the clayey character which is here fertile and there sterile, as near Superior, at the head of the lakes, and around Green Bay and Lake Winnebago. The distribution of these varieties of soil has not yet been determined in the greater part of the Lake Superior region.

POSTGLACIAL MODIFICATIONS.

Since the retreat of the ice normal processes have begun to work upon the region. These are chiefly the atmospheric agencies that accomplish weathering and denudation, including the chemical work of air, of surface water, and of ground water; the work of vegetation and animals; and the erosive and constructive work of streams and waves. The most notable results thus far accomplished are the modification of the glacial drift and the bed rock by weathering and by stream work and the work of lakes in their beds and on their shores.

MODIFICATIONS ON THE LAND.

The modification of the glacial deposits since the retreat of the Wisconsin ice sheet has been exceedingly slight. Weathering has done relatively little, not even erasing delicate glacial striæ except on the more friable rocks.

The deposits of older drift, however, as described by Samuel Weidman[a] and others, seem to have been much more modified since their formation. The older drift now contrasts with the last drift in showing a greater amount of modification by stream action and very much less relief. Its composition has been changed, the more soluble constituents of the clay in the till and of certain of the bowlders having been leached out by percolating water. Streams have filled or drained the many shallow lakes which may have existed in inequalities in the older drift sheets, and swampy areas are much less prevalent.

The Wisconsin drift sheet, which covers the greater part of this region, contrasts strikingly with the older drift in standing at a higher elevation, in being essentially unmodified by streams and in having relatively few of its lakes and swamps filled or drained. Many of the shallower lakes, however, have probably been converted into swamps by silting up and by encroaching vegetation. Doubtless many of the muskeg areas of the Lake Superior region were previously areas of shallow water. Hall has estimated that in northern Minnesota the shallow glacial lakes, whose numbers have probably been greatly exaggerated, are being extinguished at a rate of about sixty a year.[b] The outwash deposits are in places the only ones that have been very much modified by stream work, and the change in these consists principally of the cutting of terraces,[c] as in the lower St. Croix district of western Wisconsin and along Wisconsin, Chippewa, Mississippi, and other rivers. The greater part of these terraces were probably developed during and at the end of the glacial period, when the streams carried much more water from the melting of the retreating ice sheet. There has been considerable postglacial stream gullying, especially in the lake deposits. The composition of the glacial drift of Wisconsin age has

[a] Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 435–488.
[b] Hall, C. W., The geology and geography of Minnesota, 1903, pp. 178, 181–183.
[c] Wooster, L. C., Geology of Wisconsin, 1873–1879, vol. 4, 1882, pp. 134–138.

remained essentially unchanged in the comparatively brief time since the retreat of the ice. Alluvial deposits are present and are being formed constantly, but are confined largely to the valleys. As already stated, however, part of what Weidman[a] discusses as alluvial material is certainly glacial outwash.

MODIFICATIONS IN AND AROUND THE GREAT LAKES.[b]

Since the Nipissing stage, as already stated, the waters of Lake Superior have been markedly fluctuating in level, occupying lower and lower points on the north shore of Lake Superior and higher and higher points on the south shore of Lake Superior and the shores of the adjacent parts of Lakes Michigan and Huron, as the warping of the earth's surface in this region gradually tilted the water southward. This tilting has caused a gradual postglacial emergence of the northern coast and a gradual submergence of the southern coast. In northern Michigan, for example, A. C. Lane has observed dead trees now standing out in the waters of Lake Superior.

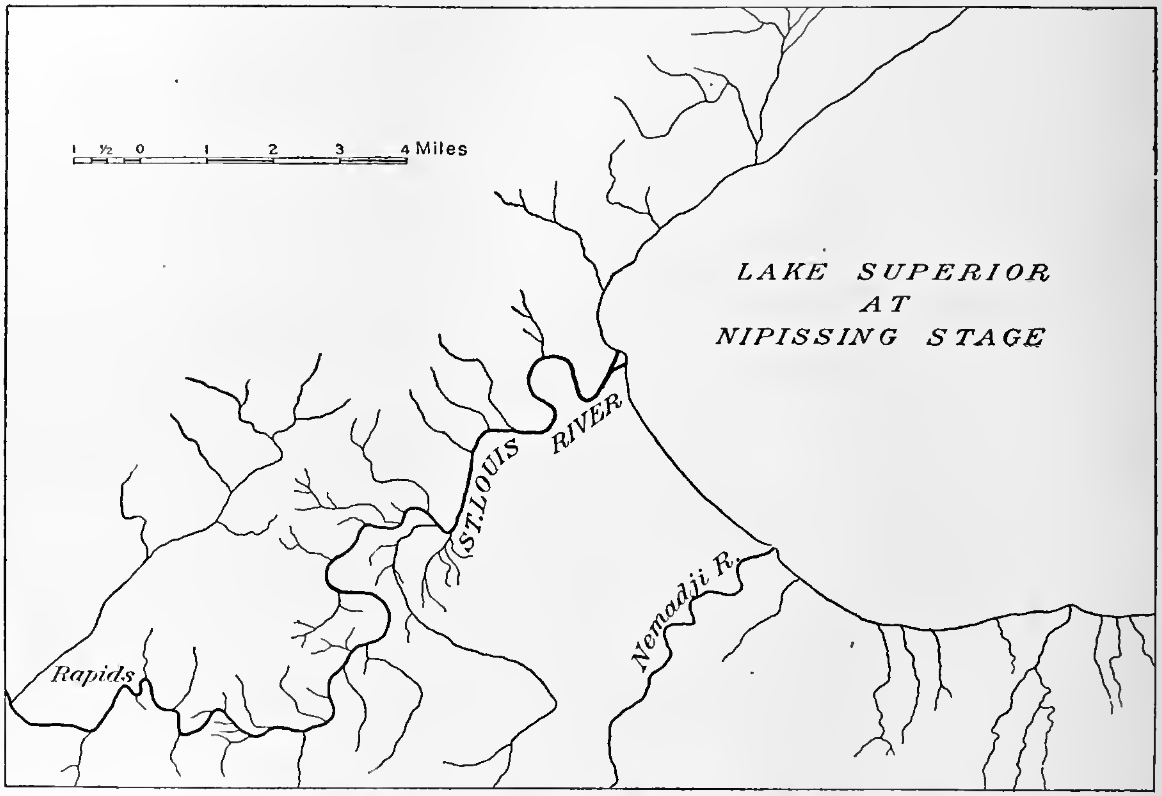


FIGURE 69.—St. Louis River at the stage when it cut its valley and emptied directly into Lake Nipissing.

Although the recent beach levels have not all continued to be occupied by the lake waters at exactly the same level, some rather distinctive shore deposits of the normal type have been built up. On the headlands cliffs have been cut, and of these cliffs those on the south shore of Lake Superior in the Pictured Rocks region[c] are famous. Because of the character of the Lake Superior sandstone, the attack of the waves upon it has developed overhanging cliffs

[a] Weidman, Samuel, Bull. Wisconsin Geol. and Nat. Hist. Survey No. 16, 1907, pp. 514–547.

[b] Édouard Desor was the first to describe the Lake Superior shore features (Foster, J. W., and Whitney, J. D., Geology of the Lake Superior and district, vol. 2, 1851, pp. 256–268), as Charles Whittlesey (idem, pp. 270–273) did for Lake Michigan. In 1880 R. D. Irving described the coast in the Ashland region (Geology of the eastern Lake Superior district: Geology of Wisconsin, 1873–1879, vol. 3, 1880, pp. 70–72). I. C. Russell has described some recent changes on the north shores of Lakes Huron and Michigan (Ann. Rept. Michigan Geol. Survey for 1904, 1905, pp. 102–105). A. C. Lawson has described the modern cliffs, beaches, etc., of the north shore of Lake Superior (Twentieth Ann. Rept. Minnesota Geol. and Nat. Hist. Survey, 1893, pp. 197–230), discussing the shore contours and the coastal profiles in the various kinds of rocks. G. L. Collie (Bull. Geol. Soc. America, vol. 12, 1901, pp. 197–216) has done some work on the modern shore lines of the south coast of Lake Superior in Wisconsin. G. K. Gilbert used many illustrations from Lake Superior and northern Lake Michigan in his Topographic Features of Lake Shores (Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 75–123).

[c] Foster, J. W., and Whitney, J. D., op. cit., pp. 124–129, plates.

and caves, as well as isolated stacks and, still farther out in the lake, reefs. The attack of the waves upon Cambrian sandstone, upon the Keweenawan lavas, and upon the Algonkian and Archean rocks has produced different styles of coastal topography, and the cliffs cut in the glacial drift are different from all others. On the north shore of Lake Superior the relative position and resistance of certain dikes and sills have modified the shore topography, as was long ago described by Agassiz.[a] Logan[b] carried the idea of coast control by dikes still further—further, indeed, than Irving[c] thought justified. The bold north coast forms a striking scenic contrast to the mild south shore of Lake Superior, as Irving[d] has pointed out.

Between the headlands beaches have been formed, and these beaches are of the usual sand and gravel and bowlder type, associated with spits, hooks, bars, and sand dunes. In places where such beaches have been built across the mouths of valleys or bays and separated them from the lake, ponds have been held in, as on the south shore of Lake Superior or the

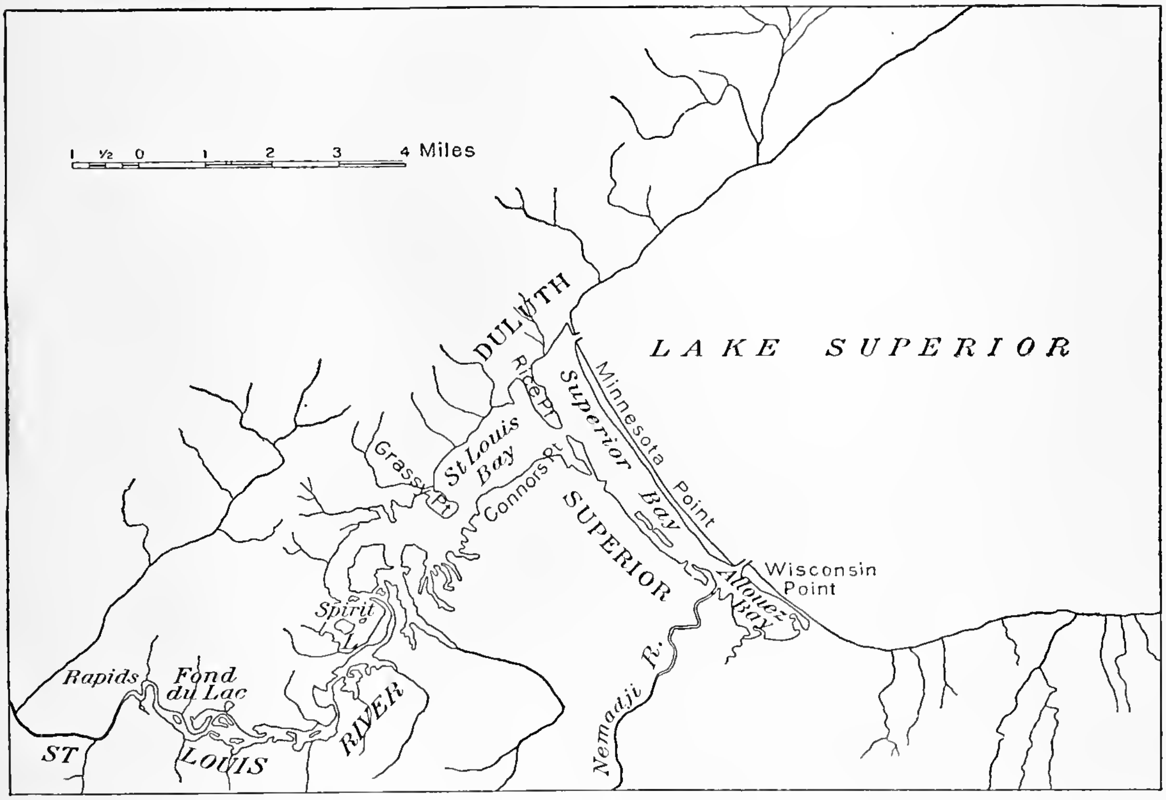


FIGURE 70.—The present St. Louis River, which has been converted into an estuary by post-Nipissing tilting. The figure also shows the two sets of sand spits which have been built.

east shore of Lake Michigan near Grand Traverse Bay, where some very large ponds of this sort are found. Elevated examples of these ponds were observed by C. R. Van Hise and J. M. Clements in 1901 on the north shore of Lake Superior, along the Black Bay coast, forming a peculiar type of lakes associated with the raised beaches.[e] In the Michipicoten district a bar of this kind was thrown across the bay now occupied by Wawa Lake at the time of one of the higher lake stages, as described by A. P. Coleman.[f] The modern and abandoned beaches, cliffs, caves, and skerries on Isle Royal have been described by Lane,[g] and the older and modern beaches at Pigeon Point, Minn., by Bayley.[h]

[a] Agassiz, Louis, Lake Superior, its physical character, vegetation, and animals, 1850, pp. 420–425.
[b] Logan, W. E., Geology of Canada, 1863, p. 72.
[c] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 336–337.
[d] Idem, pp. 250–251.
[e] From unpublished field notes.
[f] Rept. Bur. Mines Ontario, vol. 15, pt. 1, 1906, p. 196; Univ. Toronto Studies, Geol. Series, 1902, p. 5.
[g] Lane, A. C., Geol. Survey Michigan, vol. 6, pt. 1, 1898, pp. 184–186.
[h] Bayley, W. S., Bull. U. S. Geol. Survey No. 109, 1893, p. 15.

Among the striking shore deposits of Lake Superior now being formed are the two great bars or spits which extend across the head of Lake Superior at Duluth—Minnesota Point and Wisconsin Point. (See figs. 4, p. 87, and 70, p. 457.) Their ends are separated by a narrow channel which formed the only entrance to the Bay of Superior until the Government dredged the canal near the Duluth shore. These bars have a total length of about 10 miles (Minnesota Point 6½ miles, Wisconsin Point 3¼ miles) and a width varying from a little over an eighth of a mile to less than a hundred yards (Pl. V, *A*, p. 112). They have been built up above the water by a combination of two causes. The first and more important is the interference of the shallowing lake bottom with the passage of waves, causing waves to be overturned on the site of the present Minnesota and Wisconsin points. The overturning stirred up the deposits at the bottom of the lake and caused the waves to heap up material at this locality. The continued accumulation of material along this narrow line gradually built up a deposit that approached the surface of the water and was augumented by the deposits of the second kind, namely, the materials derived from the shores of the lake, which were transported outward along the submerged embankment, under the influence of the shore currents. The combination of these two agencies soon carried the spits a great distance out from the lake shores, and they were eventually built up above water for a greater part of the distance and finally connected, except for a narrow outlet.

Drill holes put down near the Government canal at Duluth and at the newer jetties between Wisconsin Point and Minnesota Point have shown that the points are built upon a base of fine lake clay, overlain near the shore by very coarse material, which a short distance out is replaced by fine sand. On the Minnesota side no pebbles are found on the present beach at a greater distance from the shore than three-quarters of a mile, showing that the contribution of the coarse along-shore drift in the middle of the point is not very great and that the larger part of the material is washed up by the waves, although probably augmented by the material drifted along the beaches. The higher parts of these points, which rise 20 or 30 feet above the lake level, consist of very fine sand, built up into sand dunes by the wind, and upon these dunes evergreen trees have been able to grow.

About a mile back from Minnesota and Wisconsin points another pair of points (Rice Point and Connors Point) has been built, separating St. Louis Bay, where most of the ore boats are loaded, from Superior Bay. These were doubtless formed as spits at an earlier date, in an exactly similar manner to the outer spits, though they have never been connected.

Still farther up St. Louis River there are projections from the sides of the valley, like Grassy Point and others, in some respects similar to these points but probably of an entirely different origin. It seems probable that in the post-Nipissing tilting of the lake waters into the valleys the St. Louis Valley, which had been rather deeply cut in the lake-clay plain and which had developed to the stage of a flood plain with a meandering stream (fig. 69), has been drowned, so that portions of the spurs on the valley sides now emerge from the water and resemble bars (fig. 70). Farther up the St. Louis the deposits in the vicinity of Spirit Lake and above to Fond du Lac form a very characteristic drowned flood plain.

Smaller bars, similar to these at Duluth, have been formed in several bays on the shores of Lake Superior, especially on the south shore, where the rocks are weak and easily supply material for the waves and currents to move. The most notable of these spits is Chequamegon Point,[a] near Ashland, and there are numerous smaller ones, as on Au Train Island. In Grand Traverse Bay, Lake Michigan, a great hook is formed by the curving of a similar spit.

It is a rather notable fact that almost none of the streams flowing into Lake Superior have been able to build deltas. Naturally the streams on the south side of the lake, like St. Louis River, could not build deltas fast enough to keep up with the gradual submergence of the region in connection with the tilting of the land. On the north shore, however, there seem to be special conditions which prevent the building of deltas by several large streams. Nipigon River would not build a delta because it is a relatively clear stream, having been strained of all sediment

[a] Collie, G. L., Bull. Geol. Soc. America, vol. 12, 1901, pp. 206-207.

before it flows out of Lake Nipigon. This is also true of Michipicoten River and of a great number of smaller streams which at present carry rather small amounts of sediment because they flow through so many lakes. The Kaministikwia, at Fort William, has the only delta of any notable size in Lake Superior, and this seems to have been formed mostly at an earlier time, relatively little sediment being carried by the Kaministikwia at present.

Of the offshore deposits less is known specifically. As already suggested, these deposits are accumulating more slowly than when melting glaciers furnished both water and sediment in greater quantities and when stones dropped by floating icebergs differentiated the silts from those now going down. Coarse deposits like gravel and sand predominate near the beaches and the river mouths, and rocky accumulations are probably growing near the cliffs. In deep water fine clay and silt predominate, as the detailed soundings of the Lake Survey charts show. The several areas of sand, clay, etc., on the lake bottom show appropriate relationships to the rocks and the glacial deposits of the adjacent shores, the drainage basins, the lake currents, etc. Deposition here contrasts with the postglacial weathering, erosion, transportation, and slighter deposition on the land.

SUMMARY OF THE PLEISTOCENE HISTORY.

The Pleistocene epoch in the Lake Superior region witnessed four rather different sets of conditions—(1) in preglacial time, when the topography was much as it is now except for certain valleys that have since been deepened by glacial erosion, broad areas that have been covered by glacial drift, and an entire contrast of drainage; (2) in the time of advancing glaciers, when the land was gradually being covered and eroded by an ice sheet, drainage was being modified, and plants and animals were being driven out; (3) in the time of retreating glaciers, when from an extreme stage of glaciation with nothing uncovered except the Driftless Area the present topography was revealed by the gradual melting of a largely stagnant ice sheet, with the several marginal lake stages, etc., and the attendant warping of the earth's crust; (4) in the present stage of modification of glacial deposits, building of stream and lake deposits, return of plants and animals, and a general attempt to restore the normal conditions that were prevalent before the interruption by glaciation.

CHAPTER XVII. THE IRON ORES OF THE LAKE SUPERIOR REGION.

By the authors and W. J. Mead.

HORIZONS OF IRON-BEARING FORMATIONS.

The ages and names of the iron-bearing formations of the Lake Superior region are as follows:

Brown ores associated with Paleozoic and Pleistocene deposits (Spring Valley, Wis.).
Cretaceous detrital ores of the western Mesabi district of Minnesota.
Clinton ores of the Silurian of Dodge County, Wis.
Algonkian system:
- Keweenawan series: Titaniferous gabbros of Cook and Lake counties, Minn.
- Huronian series:
  - Upper Huronian (Animikie group):
    - Biwabik formation of the Mesabi district of Minnesota.
    - Animikie group of the Animikie district, Ontario.
    - Ironwood formation of the Penokee-Gogebic district, Michigan and Wisconsin.
    - Vulcan formation of the Menominee and Calumet districts, Michigan.
    - Vulcan iron-bearing member of the Crystal Falls, Iron River, and Florence districts, Michigan and Wisconsin.
    - Gunflint formation of the Gunflint Lake district, Canada, and Vermilion district, Minnesota.
    - Bijiki schist of the Marquette district, Michigan.
    - Deerwood iron-bearing member of the Cuyuna district, Minnesota.
  - Middle Huronian:
    - Negaunee formation of the Marquette district, Michigan.
    - Freedom dolomite of the Baraboo district, Wisconsin.

Archean system.
- Keewatin series:
  - Soudan formation of the Vermilion district, Minnesota.
  - Helen formation of the Michipicoten district, Ontario.
  - Unnamed formation of Atikokan district, Ontario.
  - Several nonproductive formations in Ontario.

The ores of these horizons fall into natural groups on the basis of general characters and origin as follows:

(1) The ores of the Lake Superior pre-Cambrian sedimentary iron-bearing formations, including practically all the ores produced from the Lake Superior region.

(2) Titaniferous magnetites constituting magmatic segregations in Keweenawan gabbros. Nonproductive.

(3) Magnetic ores representing pegmatite intrusions in basic igneous rocks. Doubtfully represented by Atikokan and certain nonproductive Vermilion ores.

(4) Residual or bog ores of the Paleozoic at Spring Valley, in northwestern Wisconsin. Slightly productive.

(5) The Clinton ores of the Paleozoic in Dodge County, southeastern Wisconsin. Slightly productive.

GENERAL DESCRIPTION OF ORES OF THE LAKE SUPERIOR PRE-CAMBRIAN SEDIMENTARY IRON-BEARING FORMATIONS.

INTRODUCTION.

The ores of the pre-Cambrian sedimentary type comprise 99 per cent of the productive ores of the region. They occur in the Keewatin series, the middle Huronian, and the upper Huronian (Animikie group). The following table shows the percentage of ore which has been mined from these rocks, by districts, from the opening of mining in the district to the close of 1909:

Percentages of ores mined from pre-Cambrian sedimentary rocks in Lake Superior region to close of 1909.

District.	Per cent of total to close of 1909.	Per cent of 1909 shipments.	Geologic horizons.					
			Keewatin series.		Middle Huronian.		Upper Huronian.	
			Per cent of total to close of 1909.	Per cent of 1909 shipments.	Per cent of total to close of 1909.	Per cent of 1909 shipments.	Per cent of total to close of 1909.	Per cent of 1909 shipments.
Minnesota:								
Mesabi	43.57	66.41					43.57	66.40
Vermilion	6.49	2.61	6.49	2.61				
	50.06	69.02						
Michigan:								
Gogebic	11.48	7.90					11.48	7.90
Marquette [a]	20.45	9.99			19.91	9.21	.54	.78
Menominee [b]	14.71	10.80			.24	.37	14.47	10.43
	46.64	28.69						
Wisconsin:								
Florence	1.17	.67					1.17	.67
Penokee	2.07	1.62					2.07	1.62
Baraboo	.06				.06			
	3.30	2.29						
Total	100.00	100.00	6.49	2.61	20.21	9.58	73.30	87.80

[a] Including Swanzy district.

[b] Includes Iron River and Crystal Falls districts.

A comparison of the total production from each of the geologic horizons with the production for 1909 shows that in the past the Keewatin and middle Huronian iron-bearing formations were more productive relatively than they are now; and that the upper Huronian is increasing its proportion. A further increase in percentage of the upper Huronian ores is probably to be looked for.

Notwithstanding the fact that the iron-bearing formations are contained in three different groups, separated by great unconformities, they are remarkably similar in their lithology, making it possible to discuss them essentially as a unit. These formations are unique among most of the sediments of the globe with which we are familiar. The early geologic conclusions relating to their structure were based on the assumption that formations so peculiar were developed at one and the same time, an assumption which of course led to much confusion in the interpretation of the stratigraphy of the region.

An attempt is made under the following headings to summarize the salient features of the ores of the region as a whole. In earlier chapters the ores of the several districts are separately discussed.

KINDS OF ROCKS IN THE IRON-BEARING FORMATIONS.

In the simplest terms the iron-bearing formations of the Lake Superior region consist essentially of interbanded layers, in widely varying proportions, of iron oxide, silica, and combinations of the two, variously called jasper or jaspilite, where anhydrous and crystalline

(Pls. XXXII and XXXIII), and ferruginous chert[a] (Pl. XXXIV, *A*, *B*), taconite, or ferruginous slate (Pl. XXXIV, *C*), where softer and more or less hydrous. These rocks become ore by local enrichment, largely by the leaching out of silica and to a less extent by the introduction of iron oxide. There are accordingly complete gradations between them and the iron ores. Many of the intermediate phases are mined as lean siliceous ores. In the following descriptions, therefore, the ores are not in all cases sharply differentiated from the iron-bearing rocks. Local phases of the iron-bearing formations are amphibolitic and magnetitic cherts and slates (Pl. XXXV), cherty iron carbonates (Pl. XXXVI), ferrous silicate or greenalite rocks (Pl. XXXVII), pyritic quartz rocks, and detrital iron-bearing rocks derived from older iron-bearing formations. All these phases are found in each district, but in considerably varying proportions. One of the most significant variations with reference to the origin of the ore is in the relative abundance of greenalite rocks and siderite.

CHEMICAL COMPOSITION OF THE IRON-BEARING FORMATIONS.

The average iron content of all the original phases of the iron-bearing formations for the region, not including interbedded slates, as shown by all available analyses, is 24.8 per cent. The average iron content of the ferruginous cherts and jaspers, from which there has been but little leaching of silica, as shown by all available analyses, is 26.33 per cent. The amphibole-magnetite phases of the formations show approximately the same percentage. The average iron content of the formations, as shown by all available analyses, different phases, including the ores, being taken in proportion to their abundance, is 38 per cent for the Lake Superior region. (See table, p. 491.) A comparison of this figure with 24.8 per cent for the original siderite and greenalite (see pp. 167, 527) and 26.33 per cent for the ferruginous cherts and jaspers from which silica has not been removed (see pp. 181, 238) will show what has been accomplished in the secondary concentration of the ores. It is possible, however, that the ores have in part been derived from the richer phases of the iron-bearing formations. So far as this is true, the secondary concentration accomplished has been less than the comparison of these figures might indicate.

RATIO OF ORE TO ROCK IN THE IRON-BEARING FORMATIONS.

It may again be noted that the iron ores, though important commercially, form but a very small percentage of the rocks of the iron-bearing formations. The deposits are very large, but are relatively insignificant as compared with the great adjacent masses of ferruginous cherts and jaspers making up the bulk of these formations.

The percentages of iron ore to rock, by weight (see p. 492 for depths), calculated from estimates of tonnage given on other pages, are as follows:

Proportions of ore to rock, by weight, in the iron-bearing formations of the Lake Superior region.

	Per cent.
Marquette district	0.110
Penokee-Gogebic district	.165
Menominee and Crystal Falls districts	.183
Mesabi district	2.000
Vermilion district	.062

STRUCTURAL FEATURES OF ORE BODIES.

It will be shown later that the iron ores are the result of subsurface alterations of richer layers of the iron-bearing rocks and are localized at places in these layers where these alterations have been most effective, particularly where the ordinary ground waters are converged within

[a] Chert, as defined in the text-books, is an amorphous and hydrous variety of quartz, but in the field the term has been very generally applied to siliceous bands, such as those found in limestone, with little regard to their microscopic or chemical characteristics. Some of the so-called cherts and limestones are very fine grained or amorphous. The cherts of the iron-bearing formations are similar in every respect to those of the limestones. They show the same irregularity of texture, interlocking of quartz grains, and in places very fine grains. However, it can not be said that any of the so-called chert in the Lake Superior region has been found to be truly amorphous and hydrous

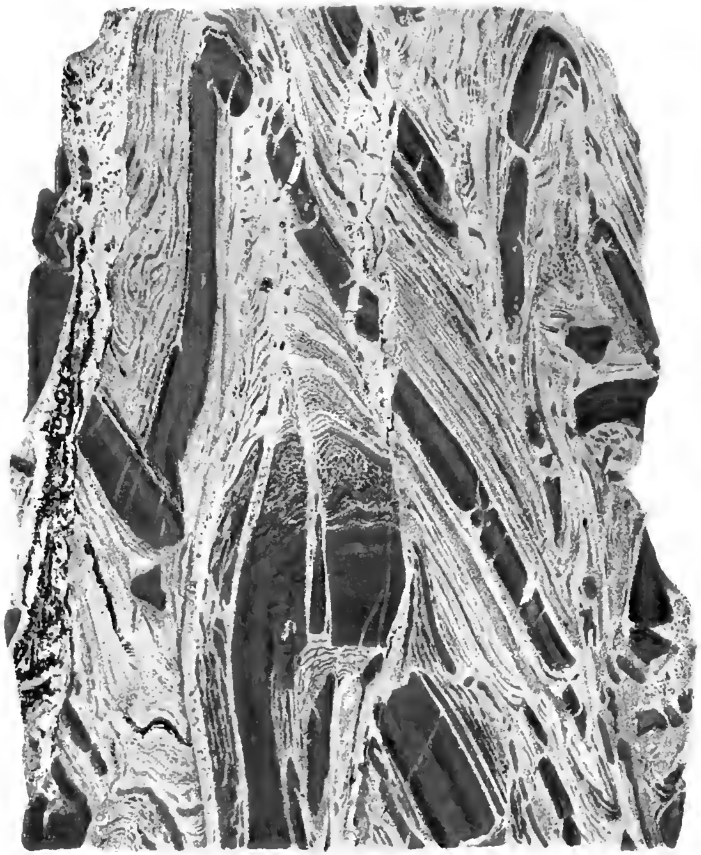
PLATE XXXII.

PLATE XXXII.

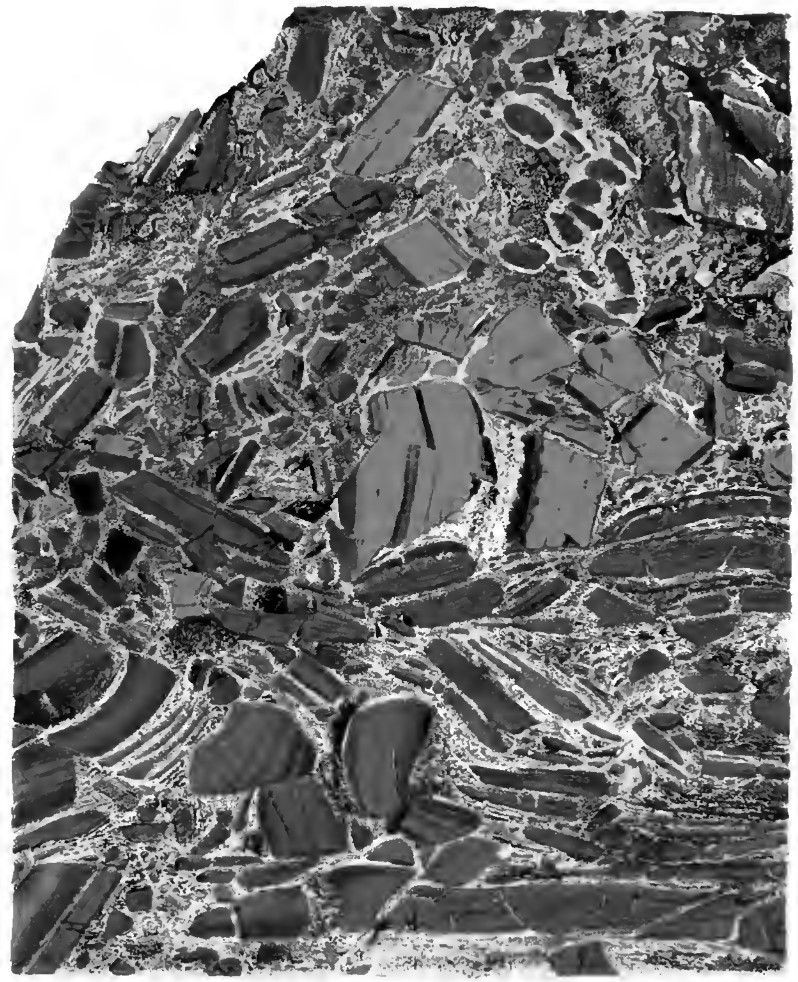
Jaspilite.

A. Folded jaspilite from Jasper Bluff, Ishpeming, Marquette district, Michigan. The illustration beautifully shows the secondary infiltration of iron oxide and deformation by combined fracture and flow. By close observation iron oxide of three different ages may be seen. The oldest is the dark-gray hematite. Intersecting this is the more brilliant steel-gray hematite and magnetite, and cutting both of the former are other veins of brilliant hematite and magnetite. The history of the rock seems to be briefly as follows: Banded hematite and jasper was bent by folding, probably while the rock was deep seated. During this folding the hematite was mashed. In a later stage, when the rock was more rapidly deformed near the surface, fracturing occurred. This gave the conditions for the first infiltration of iron oxide, and later, when the rock was perhaps still nearer the surface, further deformation resulted in new fractures. Finally, the crevices thus formed were filled with the latest iron oxide.

B. Brecciated jaspilite from Jasper Bluff, Ishpeming, Marquette district, Michigan. The illustration gives evidence of the history as shown by *A*. However, during the final process the layers of jasper, which were bent at the earlier stage, were broken through and through, producing a breccia. The same evidences are seen of three stages of iron oxide as in *A*. The less brilliant gray is the earliest-mashed hematite; the intermediate gray represents a first infiltration; after this there was shattering; and finally the breccia was cemented by brilliant steel-gray hematite and magnetite.



(A)



(B)

JASPILITE FROM MARQUETTE DISTRICT, MICHIGAN

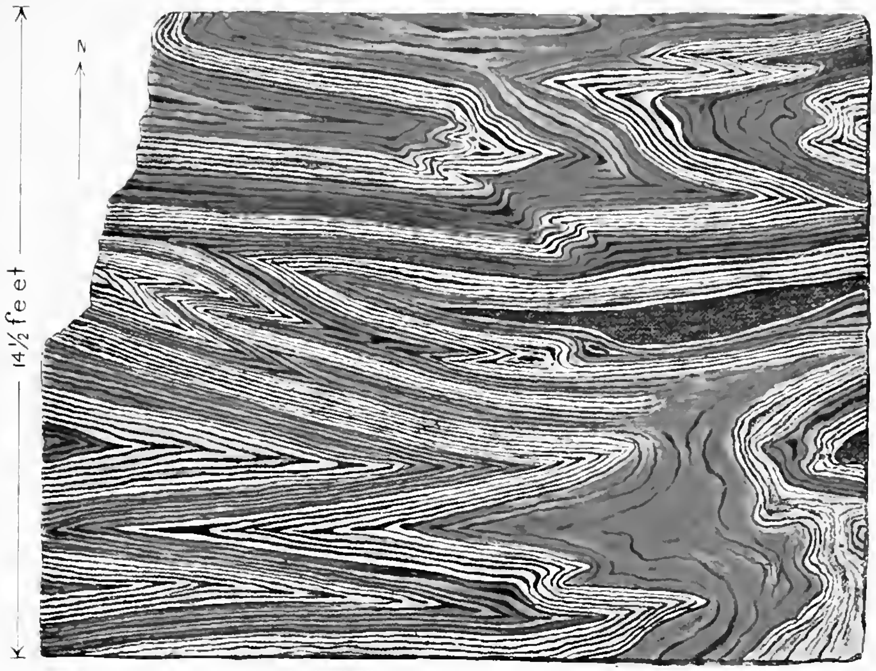
PLATE XXXIII.

PLATE XXXIII.

Jaspilite and hematitic chert.

A. Folded and brecciated jaspilite of the Soudan formation, Vermilion district, Minnesota. (After Clements.)

B. Hematitic chert from Negaunee, Marquette district, Michigan. The bands of chert are so broken by movement that they are in some places difficult to follow. Many of the fragments have roundish outlines, due to their partial solution and replacement by iron oxide. The material illustrated is frequently found very close to the ore bodies. If a portion of the remaining silica were removed and iron oxides introduced in its place, it would become iron ore. The hematite is soft and the material illustrated is therefore called soft-ore jasper by the miners.



(A)

(B)

(A) FOLDED AND BRECCIATED JASPILITE OF THE IRON-BEARING SOUDAN FORMATION, VERMILION DISTRICT, MINNESOTA.

(B) HEMATITIC CHERT FROM NEGAUNEE, MARQUETTE DISTRICT, MICHIGAN

PLATE XXXIV.

PLATE XXXIV.

Ferruginous chert and slate of iron-bearing Biwabik formation.

A. Gray ferruginous chert (specimen 45027) from Chicago mine, in sec. 4, T. 58 N., R. 16 W. Mesabi district, Minnesota. Natural size. This is one of the characteristic aspects of the ferruginous cherts of the iron formation. Under the microscope iron oxide and chert can be seen still marking the shapes of the greenalite granules. Described on pages 168–170.

B. Ferruginous chert (specimen 45588) from Mahoning mine, Mesabi district, Minnesota. Natural size. The rock shows interbanding of chert with iron oxide. Described on pages 168–170.

C. Banded ferruginous slate (specimen 45594) from Penobscot mine, 298 feet below ferruginous chert. Mesabi district, Minnesota. Natural size. Described on pages 170–171.

FERRUGINOUS CHERT AND SLATE OF IRON-BEARING BIWABIK FORMATION
MESABI DISTRICT, MINNESOTA

PLATE XXXV.

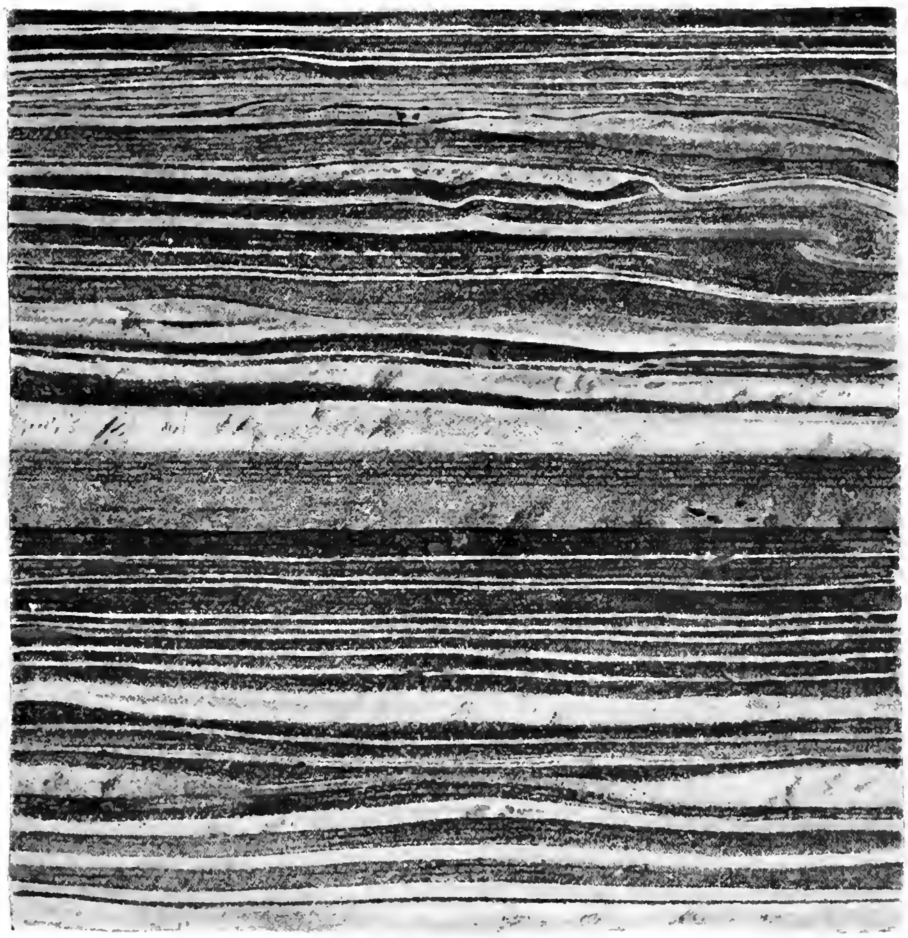
PLATE XXXV.

Ferruginous chert and schist.

A. Amphibole-magnetite chert (specimen 48571) from Republic, Mich. Note coarsely crystalline anhydrous character as compared with ferruginous cherts and jaspilites. For discussion of origin, see pages 545 et seq.

B. Sideritic magnetite-grünerite schist from sec. 13, T. 47 N., R. 27 W., Marquette district, Michigan. The different bands consist mainly of grünerite, hematite, magnetite, and quartz, in varying proportions. The darker-colored bands contain much of the iron oxide. In the lighter bands grünerite is abundant. In all the layers there is a sufficient amount of residual siderite to show that from this mineral and silica the grünerite formed, and from the grünerite, with partial or complete oxidation, the magnetite and hematite developed. Most of the hematite is of the specular variety, but in places blood-red flecks of hematite may be seen, and parts of the specimens are stained by limonite. This is doubtless the result of weathering. Natural size.

(A)



(B)

(A) AMPHIBOLE-MAGNETITE CHERT FROM REPUBLIC, MICHIGAN.

(B) SIDERITIC MAGNETITE-GRUNERITE SCHIST FROM MARQUETTE DISTRICT, MICHIGAN

PLATE XXXVI.

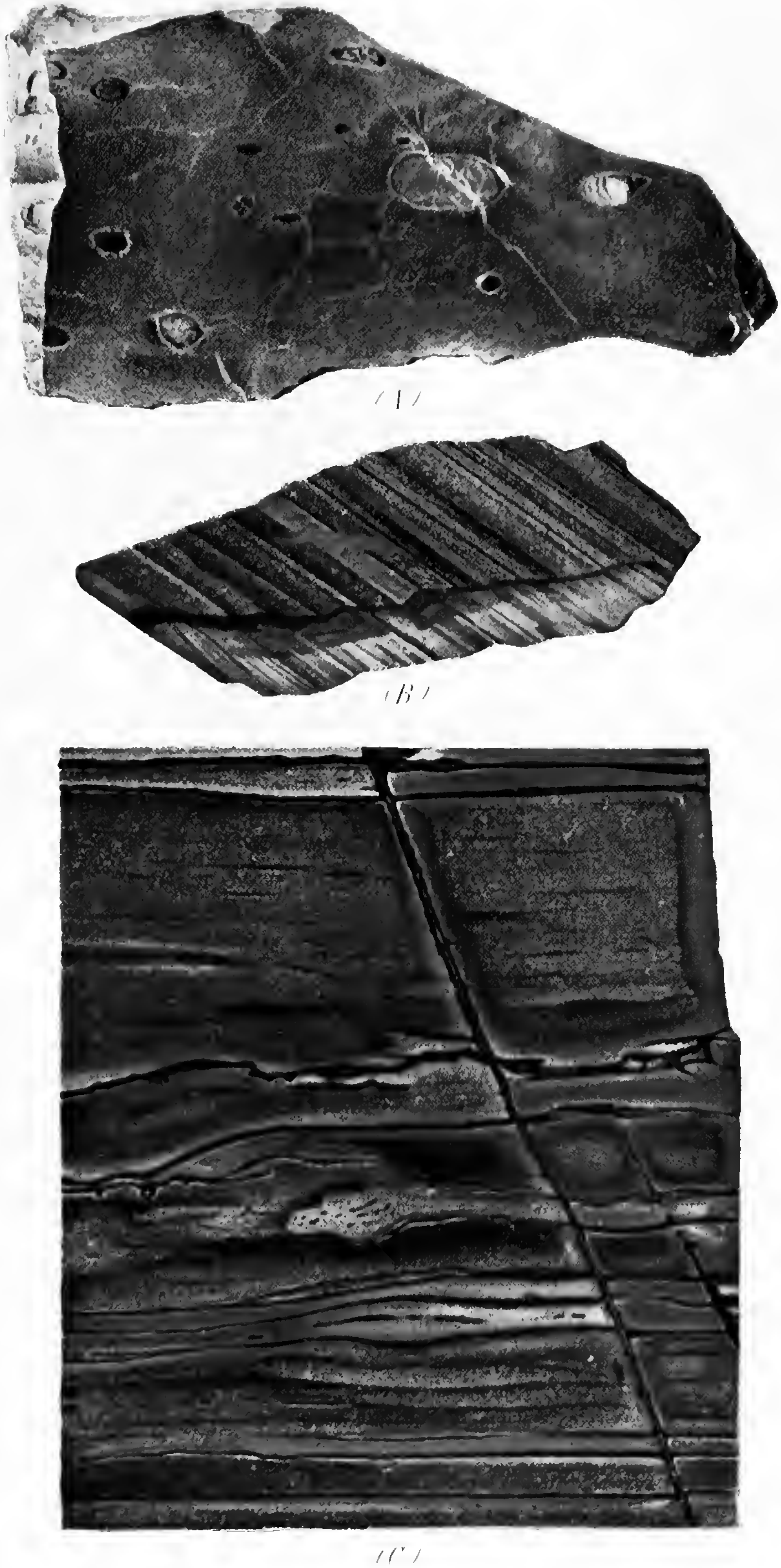
PLATE XXXVI.

Jaspery filling in amygdules and cherty siderite.

A. Jaspery filling in amygdules from ellipsoidal basalt of the Crystal Falls district, Michigan. (Specimen 47554.)

B. Cherty siderite from sec. 19, T. 47 N., R. 27 W., Marquette district, Michigan. This is one of the purest cherty siderites found in the Marquette district. The gray material consists almost wholly of very finely crystalline and opaline silica and of siderite. The bluish-gray layers contain some silica, the greenish layers some siderite. On the weathered surface the siderite is entirely decomposed and in place of it is hematite and limonite. The beginning of the same kind of alteration may be seen to affect some of the siderite belts quite to the center of the specimen. As examined in thin section the secondary limonite is found to be in pseudomorphous areas after the siderite. Between the unaltered siderite and that which is completely decomposed there is every gradation, different granules showing all stages of the transformation. Natural size.

C. Cherty siderite from sec. 13, T. 47 N., R. 46 W., Penokee district, Michigan. (See Mon. U. S. Geol. Survey, vol. 19, 1892, Pl. XXI, fig. 4.) The original cherty siderite of the Penokee district is represented perfectly by the grayish-green material. Its very close similarity to that of the Marquette siderite represented in *B* is noticeable. The beginning of the transformation of the siderite to limonite and hematite is beautifully shown. The transitions between the two are clearer than in *B*. The processes of change begin along the bedding planes and along intersecting veins. These two together make two sets of nearly right-angle planes, which doubtless are shearing planes. The veins are entirely filled with limonite and hematite and therefore are minute layers of ore. The changes along the bedding illustrate the beginning of the process which results in the formation of the iron-ore deposits. It is noticeable that, as a result of the alterations, the original banding of the rock is emphasized, although the emphasizing bands are not so regular as the original sedimentary laminæ. This emphasizing of the original banding of the iron-bearing rocks by metasomatic changes is a general law for the iron-bearing formations of the entire Lake Superior region. Natural size.



(A) JASPERY FILLING IN AMYGDULES FROM ELLIPSOIDAL BASALT OF THE CRYSTAL FALLS DISTRICT, MICHIGAN.

(B) CHERTY SIDERITE FROM MARQUETTE DISTRICT, MICHIGAN

(C) CHERTY SIDERITE FROM PENOKEE DISTRICT, MICHIGAN.

PLATE XXXVII.

PLATE XXXVII.

Greenalite rock.

A. Greenalite rock (specimen 45647) from locality near Duluth, Missabe and Northern Railway track, 1 mile south of Virginia, Mesabi district, Minnesota. Granules of greenalite, but little altered, stand in a matrix of chert. Described on pages 165–168.

A'. Portion of surface of specimen shown in *A*, slightly magnified to show greenalite granules to better advantage.

B. Interbanded greenalite and slate rock (specimen 45176) from 100 paces north 500 paces west of southeast corner of sec. 22, T. 59 N., R. 15 W., Mesabi district, Minnesota. Natural size. The black portion of the rock is slate and the green portion is made up of greenalite granules lying in a matrix of chert. Greenalite is characteristically associated with slaty layers in the iron-bearing formation; indeed it is due to their protection that greenalite has been retained in comparatively unaltered form. Described on pages 165–168.

(A)

(B)

(C)

GREENALITE ROCK FROM MESABI DISTRICT, MINNESOTA

the formation, owing to various structural conditions. Rarely are the original layers of iron formation rich enough to be mined when they have suffered only minor secondary concentration. Because of secondary concentration the ores are usually in the upper parts of the formations and always extend to the surface, though they may reach depths of 2,000 feet or more. It may readily be conceived that there are a great variety of structural conditions which determine the circulation of the altering waters and therefore the localization and shapes of the ore deposits within the formations. Such structural features are joints, faults, folds, intersection by igneous rocks, impervious sedimentary layers within or below the iron-bearing formations, and area of exposure.

The structural features of the ores are described principally in the detailed descriptions of the ores of the several districts, but some of the more salient features of the structural relations are summarized below.

The development of ore within the richer layers of the iron-bearing formations depends on their accessibility to altering solutions from above, and the largest result is given by a wide area of exposure of the formations, which is in turn a function of the dip. The flat-lying iron-bearing formation of the Mesabi district exposes a greater surface to concentrating agents than the steeply dipping formation of the Gogebic district, of similar thickness and character, with the result that the proportion of the formation altered to ore is much greater in the Mesabi district. A comparison of the actual areas of the different iron-bearing formations with their total shipments to date and with their probable reserves shows a close relation between area and amount of ore developed.

Of more immediate and practical importance in relation to the distribution of the ores are the structural conditions, such as impervious basements and fractures, which determine the location of ores within a given area of the iron formation.

Impervious basements for the ore body may be formed (1) by the intersection of the footwall quartzite with an igneous dike, as in the Gogebic district; (2) by irregular intrusive masses of basic igneous rock, as in the Marquette district; (3) by dolomite, as in the Menominee district; (4) by slate, as at the lower horizons of the Negaunee formation in the Marquette, Crystal Falls, Iron River, and Florence districts, and at the upper horizon of the Vulcan formation in the Menominee district; (5) by slate layers within the iron-bearing formation, locally developed in the Gogebic and Mesabi districts; and (6) by granite, as in the Swanzy district of Michigan and very locally in the Mesabi district. Most of these basements have the configuration of pitching troughs.

The ores are likely to be closely associated with fractures in the iron-bearing formation which give access to altering solutions, as is particularly well illustrated by certain of the deposits of the Mesabi district and by parts of the deposits of the Gogebic district which pass through faults in the impervious basement, and indeed is illustrated to a greater or less extent by practically all the iron deposits of the region.

The relative importance of the several structural features of the ore deposits varies widely from place to place. In the Gogebic district the existence of impervious basements in the form of pitching troughs seems to be the essential structural feature of the ore deposits. Localization of the ores within and adjacent to fissures in the iron-bearing formation is also apparent. On the other hand, in the Mesabi district the conspicuous feature is the localization of the ores by fractures in the iron-bearing formation, the impervious basement being so gently flexed as to make it difficult to ascertain whether or not it forms pitching troughs that control the localization of the ore body.

SHAPE AND SIZE OF THE ORE BODIES.

Because of the wide variety of conditions outlined under the preceding heading, the shapes of the deposits of this region are so various that they may collectively be designated by the term "amœboid," though there are several groups of more uniform shape, as described below. They may be roughly tabular in a horizontal plane, as in the Mesabi district, or roughly tabular in steeply inclined planes, or in steeply pitching linear shoots, as in the Menominee district, or they may assume almost any combination of these shapes. The mine cross sections (Pls. X, XXVII; figs. 14, 29, 36, 46, 47, 48) will give the best notion of the shapes of the ore bodies.

The horizontal dimensions known at the surface range up to a mile. Indeed, in the Hibbing area of the Mesabi district the deposits are more or less connected for a distance of 10 miles, and the horizontal area would range up to 2 square miles. The maximum depth of iron mining in the Lake Superior region at the present time is 2,200 feet, in the Gogebic district.

It is therefore apparent that the size, shape, and structural relations of the Lake Superior ores are of widest variety. In the flat-lying formations of the Mesabi district the ore bodies have wide lateral extent as compared with depth, have extremely irregular outlines partly controlled by jointing, abut irregularly on the bottom and sides against unaltered portions of the iron-bearing formation, and when the glacial overburden is removed are accessible to surface operations with steam shovels. Steeply dipping formations, comprising most of the formations of the districts other than the Mesabi, have greater vertical dimensions as compared with horizontal dimensions, usually abut not only against unaltered parts of the iron-bearing formation but against well-defined impervious walls consisting of slate, quartzite, dolomite, or bosses or dikes of greenstone, and must be worked by underground mining.

TOPOGRAPHIC RELATIONS OF THE ORE BODIES.

The ore deposits are associated with hills or ranges, a fact that explains the common use of the term "range" in connection with the ore-producing districts. There are, however, exceptions to this relation in the Cuyuna district of Minnesota and perhaps elsewhere, as shown in the detailed descriptions. The ore deposits occur in places on the top of the hill, as in the Vermilion district; commonly in the middle slopes, as is well illustrated by the Mesabi district, and on the low ground adjacent to the hills, as in parts of the Gogebic, Marquette, and Menominee districts. In general the middle slopes seem to be favored, but there are so many exceptions to this that there is no warrant for limiting prospecting to such localities. As the formation of the ore bodies is a function of the rapid circulation of waters from above, it is believed that the common association of the ore deposits with hills may be due to the fact that these are places where the circulating waters have considerable head. It would not follow that ore deposits should for this reason be confined entirely to the vicinity of hills, for circulation, perhaps less deep, seems to be effective also in relatively flat areas, as in the Cuyuna district of Minnesota. The effectiveness of the head at different elevations and with different structural relations is not well known. It is to be remembered, also, that the ore deposits have not been concentrated entirely in relation to the present topography, but that when these deposits were formed the topography was more or less different, and that, therefore, ore deposits now found independent of topographic elevations may still have originated under control of an elevation which has since been removed. Notwithstanding these various limitations, to be considered in the interpretation of the relation of ore deposits to topography, the present prevalence of by far the greater number of ore deposits on the middle slopes of the ranges is extremely suggestive, for these are the places where the flow of meteoric waters directly from the surface should be at a maximum.

OUTCROPS OF THE ORE BODIES.

By far the greater number of the Lake Superior ore deposits are softer than at least one of their walls. They therefore occupy depressions which are largely covered with glacial drift and generally they do not outcrop. A few of the ores, such, for instance, as the hard ores of the Vermilion and Marquette districts, are nearly or quite as hard as the wall rock, have resisted erosion, and here and there project above the mantle of drift. Considering the number of ore bodies in the Lake Superior region and their variety of structural relations, it is surprising that so few have been found to outcrop. The lean siliceous and magnetic parts of the iron-bearing formations have withstood erosion to such an extent that they outcrop rather commonly. These, together with magnetic variations, have served as guides to the location of the iron-bearing formations and have led to the discovery of ores in the covered areas by underground work.

In the iron-ore deposits that have their greatest dimensions on the erosion surface the ratio of area of iron ore to area of iron-bearing formation is greater than the ratio of tonnage of iron ore to tonnage of iron-bearing formation. In the Mesabi district the former runs up to nearly 8 per cent for the producing part of the district; in most of the other ranges it is far smaller, usually less than 1 per cent.

CHEMICAL COMPOSITION OF THE ORES.

The average composition of the iron ore mined in the Lake Superior region during the years 1906 and 1909, as shown in the table below, has been calculated from the cargo analyses published by the Lake Superior Iron Ore Association, of Cleveland, together with analyses of ores of different mine grades furnished by individual mining companies. The averages are obtained by combining all grades in proportion to their tonnage, and the table represents more nearly the average composition of all the ore mined in the Lake Superior region in any one year than anything before attempted. Analyses of iron ore used in other parts of this report are also taken from the Lake Superior Iron Ore Association's tables unless otherwise stated.

Analyses of iron ore may represent the composition of a dried ore (dried at 212° F. or 100° C.), or they may show the composition of the ore in its natural moist condition as it comes from the ground. The latter are designated natural analyses and include the moisture or uncombined water as one of the constituents of the ore. The natural iron content is the basis on which the value of ore is figured commercially. It may be computed from the iron content of the dried ore and the moisture, as follows: Percentage of natural iron = percentage of iron in dried ore × (100 − percentage of moisture). The following average analyses represent the dried ore:

Average composition of total yearly production of Lake Superior iron ore for the years 1906 and 1909.

	1906.	1909.
Moisture (loss on drying at 212° F.)	....	11.28
Analysis of ore dried at 212° F.:		
Iron	59.80	58.45
Phosphorus	.0810	.091
Silica	6.83	7.67
Alumina	1.60	2.23
Manganese	} 2.70	.71
Lime		.54
Magnesia		.55
Sulphur		.060
Loss by ignition	3.92	4.12

The range in percentages shown by the analyses from which the foregoing averages are derived is as follows:

Range in percentage for each constituent of ores mined in 1906 and 1909, as shown by average cargo analyses.

	1906.	1909.
Moisture (loss on drying at 212° F.)	....	0.50 to 17.40
Range in composition of ore dried at 212° F.:		
Iron	38.15 to 66.07	35.74 to 65.34
Phosphorus	.008 to .850	.008 to 1.28
Silica	3.21 to 40.97	2.50 to 40.77
Manganese	....	.00 to 7.20
Alumina	.20 to 3.59	.16 to 5.67
Lime	....	.00 to 4.96
Magnesia	....	.00 to 3.98
Sulphur	....	.003 to 1.87
Loss by ignition	0.00 to 10.0	.40 to 11.40

The sulphur in the Lake Superior ores ranges from a trace to 1.87 per cent and in some of the ores of the Florence, Iron River, and Crystal Falls districts it is present in sufficient quantity to affect the value of the ore. Titanium is not present in the Lake Superior sedimentary ores in amounts sufficient to be harmful. The titanium content of the ores varies from 0.1 to 0.2 per cent, TiO_2, but in some of the hard magnetite ores of the Marquette district it is found to run as high as 1.6 per cent. Titanium is higher in the paint rocks and interbedded slates than in the ores themselves.

The proportions and ranges of the constituents for the individual districts are given under the discussions of the districts. Figure 71 shows the chemical compositions of all grades of ore mined in the region in 1906, in terms of ferric oxide, silica, and minor constituents. This average is lower in iron than those of previous years. (See pp. 493–494.)

The grade of ore shipped and its general uniformity for given districts and periods are primarily controlled by the nature of the ores available, yet the commercial conditions to some extent

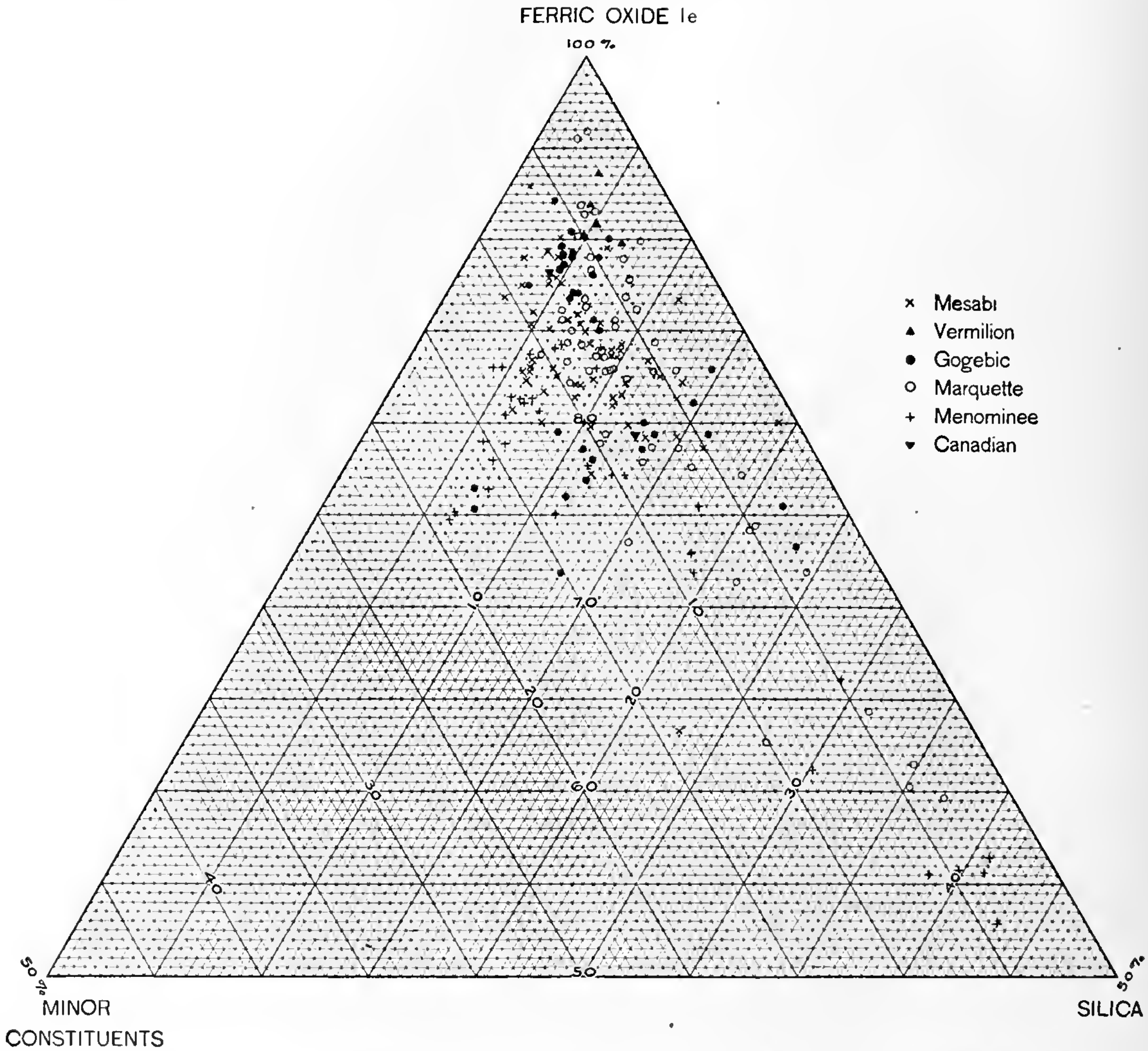


FIGURE 71.—Triangular diagram showing chemical composition, in terms of ferric oxide, silica, and minor constituents, of all grades of iron ore mined in the Lake Superior region in 1906. The ores of each district are indicated by distinctive symbols. For description of this method of platting, see p. 182.

determine the grade shipped. For instance, if high, medium, and low grade ores are available, a period of financial depression may make it possible to ship only the highest grade ores, whereas business prosperity may make it possible to mix considerable quantities of lower grade ores with those of higher grade, thereby lowering the average grade. This control by commercial conditions is further illustrated by the fact that the acid Bessemer steel process for years determined that an unusually high proportion of low-phosphorus ores were to be shipped.[a] The

[a] A Bessemer ore is one which will with a proper flux and coke make a pig iron in which the phosphorus does not exceed 0.1 per cent. It is approximately true that a Bessemer ore is one in which the content of phosphorus divided by the content of iron gives a quotient not exceeding 0.00075. This ratio may be changed, however, by the phosphorus content of the coke and limestone used with the ore in the furnace, as it is necessary to figure on the phosphorus in the flux and fuel as well as that in the ore itself.

recent rapid development of the open-hearth process has allowed shipment of ores higher in phosphorus. The development of the basic open-hearth process depends ultimately on the availability of large reserves of non-Bessemer ore, but in turn the development of the open hearth reacts upon and determines the grade of ore shipped from any district or for any period.

MINERALOGY OF THE ORES.

The iron-ore minerals in general are as follows:

Magnetite: Magnetic oxide (Fe_3O_4), including titaniferous magnetite. Theoretical iron content of the pure mineral, 72.4 per cent; generally containing some hematite.

Hematite: Anhydrous sesquioxide (Fe_2O_3), including specular hematite, red fossil ore, oolitic ore, etc. Theoretical iron content of the pure mineral, 70 per cent.

Brown ore: Hydrous sesquioxide ($Fe_2O_3.nH_2O$), including turgite, limonite, goethite, or a mixture of these minerals, known locally as brown hematite, bog ore, gossan ore, etc. Theoretical iron content of iron minerals, 59.8 to 66.2 per cent, depending on degree of hydration.

Carbonate: Siderite, iron carbonate ($FeCO_3$), known locally as spathic ore, black band ore, etc. Theoretical iron content of the pure mineral, 48.2 per cent.

The Lake Superior iron ores are (1) soft, brown, red, slaty, hydrated hematites; (2) soft limonite; (3) hard massive and specular hematites; (4) magnetites; and (5) various gradations between the other classes. The proportions for the entire region of these different classes shipped in 1906, as calculated from average cargo analyses, are as follows:

Total production of iron ore in Lake Superior region, by grades, for 1906.

Class of ore.	Tons.	Per cent of total.
Soft brown, red, slaty, hydrated hematite } Soft limonite ores }	35,652,174	93
Hard massive and specular hematite	2,741,323	7
Magnetite (less than 1 per cent; included with hard ores).		
	38,393,497	100

The approximate mineral composition of the average ore of the entire region for the years 1906 and 1909, calculated from the average analyses, is as follows:

Approximate mineral composition of average iron ore of Lake Superior region for 1906 and 1909.

	1906.	1909.
Hematite[a] (more or less hydrated), with some magnetite ($3Fe_2O_3.H_2O$)	88.60	86.45
Quartz	4.53	4.89
Kaolin	6.87 (Kaolin to Apatite)	5.25
Chlorite (and other ferromagnesian silicates)		1.01
Dolomite		.81
Apatite (all phosphorus figured as apatite)		.48
Miscellaneous	....	1.11
	100.00	100.00

[a] The iron minerals may be expressed in terms of hematite and limonite as follows: 1906, hematite 66.60, limonite 22.00; 1909, hematite 66.75, limonite 19.70. These minerals do not, in fact, exist in these proportions, there being a number of hydrates between hematite and limonite.

The mineral compositions above given are necessarily only approximate, as ferric and ferrous iron are not separated in the chemical analysis, and water, carbon dioxide, and possibly a small amount of organic matter are all included under loss on ignition. The mineral compositions were calculated from the average analyses, as follows: All phosphorus was figured as apatite; the remaining lime was combined with the proper amount of magnesia and CO_2 to form dolomite; the remaining magnesia was combined with the proper amounts of alumina, silica, and water to form chlorite; the alumina not used for chlorite was taken with sufficient silica and water to form kaolin; the remaining water, combined with the iron figured as ferric oxide, was figured as hydrated hematite.

The proportions of the different minerals for the individual districts calculated in the same way are given in the discussion of these districts.

In the above table are mentioned the abundant minerals associated with the iron, such as quartz, kaolin, and chlorite. Many of the minerals termed miscellaneous in the table are present in small amounts at a few places. Some of these minerals are apatite, adularia, wavellite, calcite, dolomite, siderite, pyrite, marcasite, chalcopyrite, tourmaline, masonite, ottrelite, chlorite, mica, garnet, rhodochrosite, manganite, pyrolusite, barite, gypsum, martite, aphrosiderite, analcite, goethite, and turgite.

Though many of the Lake Superior ores are slightly magnetic, there are only two mines in the region which ship ores classed as magnetite ores, the Republic and Champion, and even these ores are largely specular hematite with considerable quantities of magnetite. There are in the region, however, great quantities of lean nontitaniferous magnetic iron-bearing rocks, as at the east end of the Mesabi range and in the Gunflint district, where the Duluth gabbro cuts and overlies the iron-bearing formation; at both the east and west ends of the Gogebic range, where Keweenawan intrusive rocks cut the iron-bearing formation, and in parts of the Marquette district.

The magnetite ores consist of coarse-grained magnetite-quartz rock carrying a considerable variety of metamorphic silicates, including amphiboles, pyroxenes, garnets, chlorites, olivines, cordierite, riebeckite, dumortierite, etc. (See pp. 545 et seq.) Locally pyrite, pyrrhotite, and iron carbonate are present. The minerals show greater variety and more complex chemical constitution than those of other phases of the iron-bearing formation. Where altered at the surface the magnetite may be locally coated with limonite and the silicates may have gone over to chlorite, epidote, and calcite. The yellowish-green colors so developed are extremely characteristic of the surface of the exposures.

PHYSICAL CHARACTERISTICS OF THE ORES.

GENERAL CHARACTER.

The ores range from the massive and specular hematite and magnetite through ores which are partly granular and earthy and partly in small hard chunks to ores which are almost entirely soft and earthy (Pls. XXXVIII and XXXIX). There is no very sharp distinction between the hard ores and the soft ores. The latter make up the great bulk of the annual shipments; of the ore shipped in 1906 fully 93 per cent would be classed locally as soft ores. The principal hard ores come from the Vermilion district and from the upper horizons of the Negaunee formation in the Marquette district. Most of the soft ores contain small hard chunks, usually bounded by parallelepiped phases due to being broken up in the bed by minute joints. Screening tests showing the textures of the typical ores for each of the districts are given in the chapters on the individual districts. A summary of these screening tests for all the Lake Superior ores is shown graphically in figure 72. The data of the screening tests on the different ores were kindly furnished by the Oliver Iron Mining Company.

There is a striking contrast in the coarse texture of the magnetite ores and the fine cherty textures of the other phases of the iron-bearing formation. The quartz grains in the jaspers of the eastern part of the Marquette district average from 0.01 to 0.03 millimeter, whereas in the western and southwestern portions of the same district in the amphibole-magnetite phases of the iron-bearing formation the quartz grains average about 0.1 to 0.4 millimeter and run as high as 1 millimeter. The quartz grains of the amphibole-magnetite rocks may thus have a million times the volume of those of the jaspers. The quartz grains near the gabbro in the eastern part of the Mesabi district reach a diameter of 3 or 4 millimeters, but in the central and western portions of the district they are in general not greater than 0.1 millimeter. In a given amphibole-magnetite rock the grains are fairly uniform in size and have a tendency toward polygonal shape (see Pl. XLVII, *A*, p. 548), whereas in the other parts of the formation they are most irregular in size and shape (see Pl. XLIV, p. 534) and show the characteristic scalloped boundaries of cherts.

The mineral density of the ores ranges from 3.5 to 5.0 and averages about 4.30; the pore space ranges from less than 1 per cent to 60 per cent and averages about 35 per cent; and the free moisture held in this pore space ranges from 0 to 16 per cent and averages about 10.42 per cent.

PLATES XXXVIII—XXXIX.

PLATE XXXVIII.

CHARACTERISTIC SPECIMENS OF IRON ORES.

A. Soft hematite from Mesabi district, Minnesota.
B. Hard hematite from Ely, Minnesota.
C. Hard hematite from Gogebic district, Michigan.

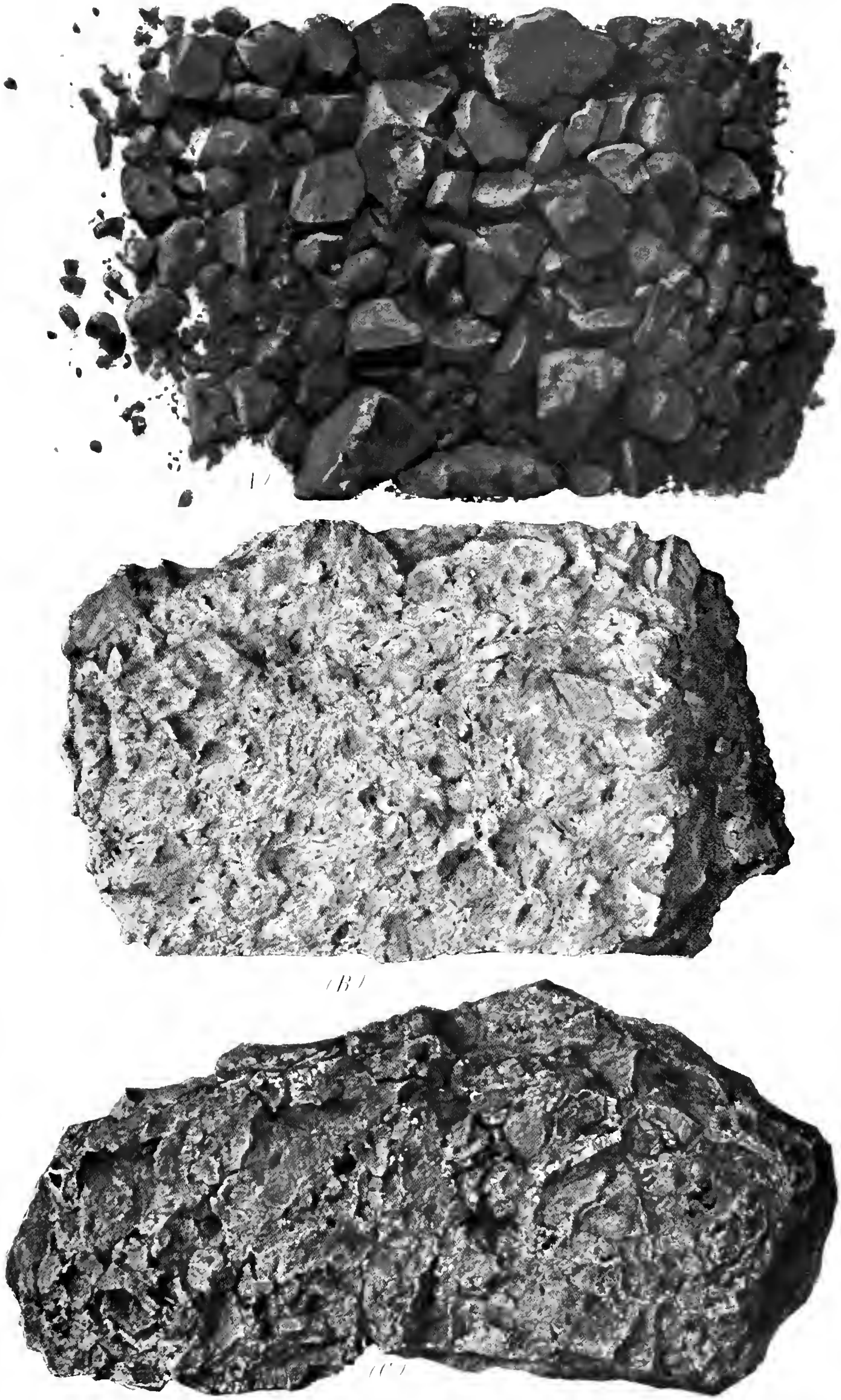
Ores of these kinds form 93 per cent of the Lake Superior shipments.

PLATE XXXIX.

CHARACTERISTIC SPECIMENS OF IRON ORES.

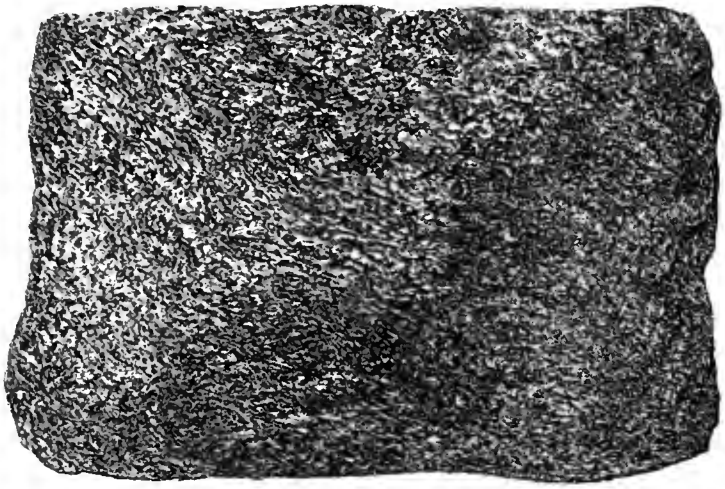
A. Hard hematite from Marquette district, Michigan.
B. Specular hematite from Marquette district, Michigan.
C. Magnetite from western Marquette district, Michigan.

These ores form 7 per cent of the Lake Superior shipments.

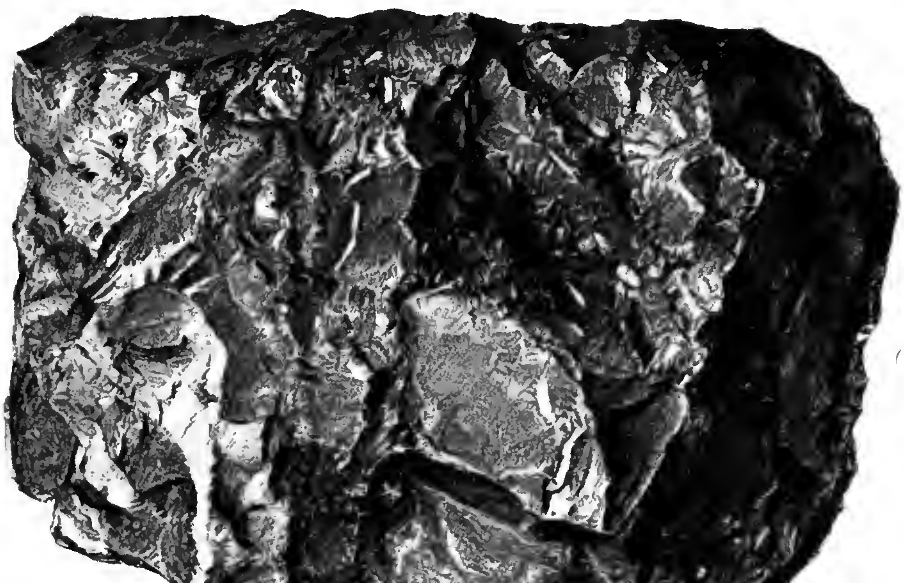


CHARACTERISTIC SPECIMENS OF IRON ORES

(A)



(B)



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CHARACTERISTIC SPECIMENS OF IRON ORES

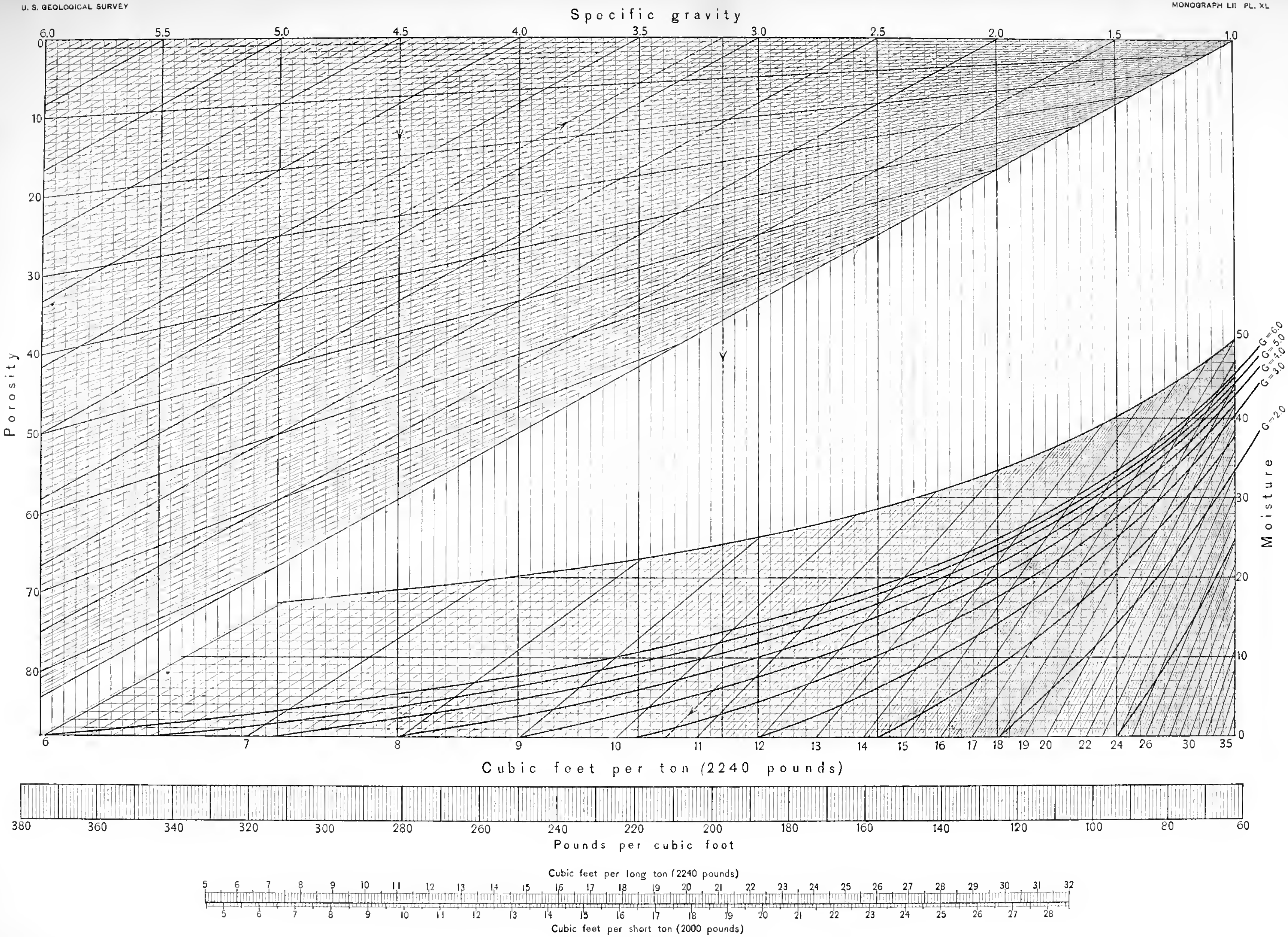


DIAGRAM SHOWING RELATION OF DENSITY, POROSITY, AND MOISTURE TO CUBIC FEET PER TON.

See page 482.

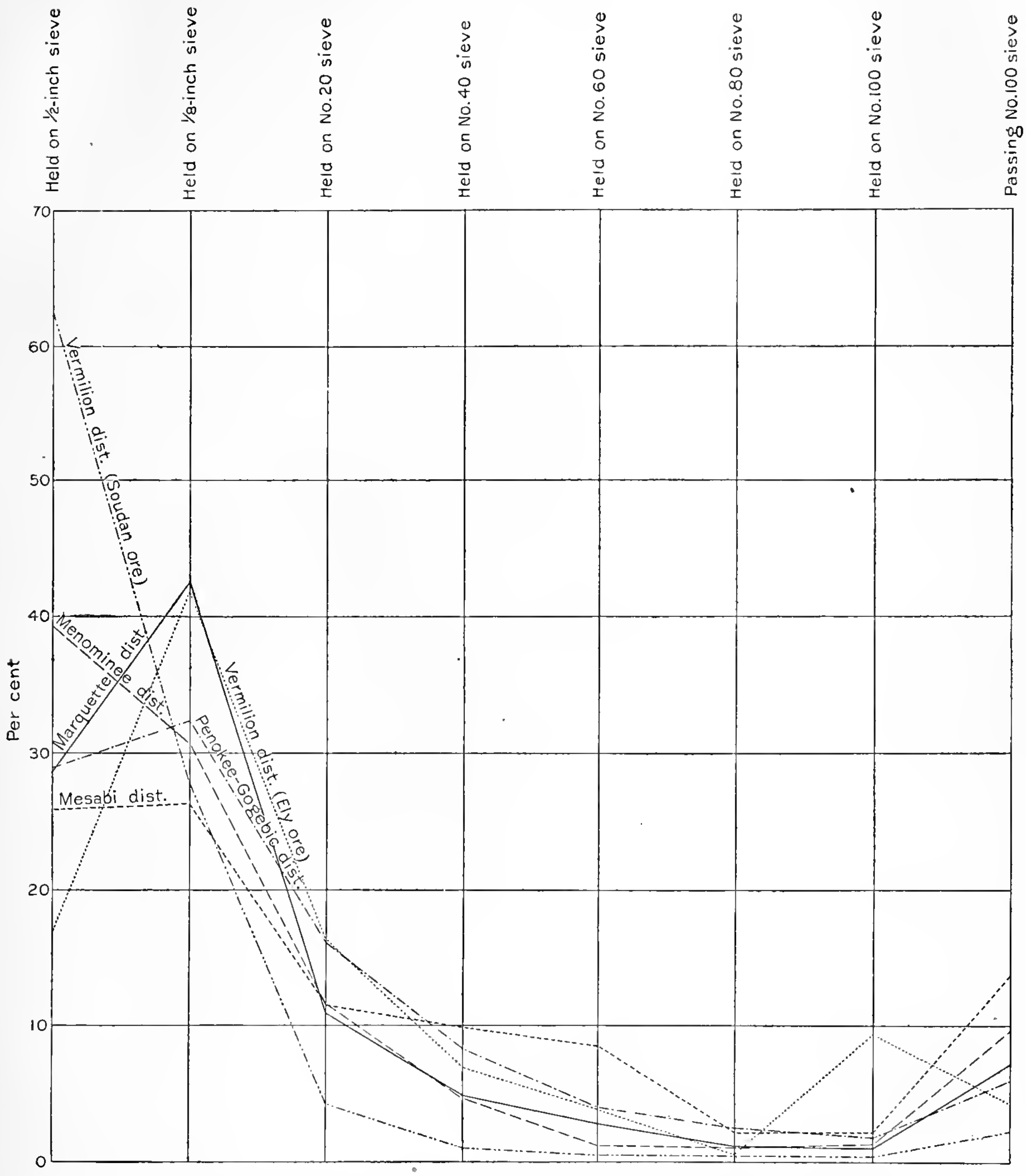


FIGURE 72.—Textures of Lake Superior iron ores as shown by screening tests. Biweekly samples, representing 43 grades of ore and an aggregate of 22,376,723 long tons, were taken by the Oliver Iron Mining Company during 1909, and tests were made on the average year's sample. The results of mine tests are averaged for each district in proportion to the tonnage mined to give the figures shown on the diagram.

CUBIC CONTENTS OF ORE.

RANGE AND DETERMINATION.

The cubic content per ton ranges from 7 cubic feet for the hard ores to 17 cubic feet for the soft ores. It depends on the density, the pore space, and the moisture and may be calculated directly according to the method following.

The cubic content of an ore is a direct function of (*a*) true specific gravity of the material—that is, the specific gravity unaffected by porosity or moisture; (*b*) porosity of the material, in terms of percentage of volume occupied by pore space or voids; (*c*) percentage of moisture in the material—that is, the percentage loss in weight on drying at 110° C.

To facilitate the determination of the cubic content of ores the diagram or graphic equation shown in Plate XL was devised, expressing the relation between these three factors and the number of cubic feet per ton. Actual determinations in the ground are unsatisfactory in that they do not show the individual effects of the three factors mentioned, especially moisture content, which may vary widely at different times and places. By use of the diagram the three factors are considered separately and their individual, relative, and net effects may be observed. The use of the diagram is not confined to iron ores but is also applicable to other ore or mineral substance in the ground.

USE OF THE DIAGRAM.

The operation of the diagram may perhaps be made clear most easily by applying a concrete problem as an illustration. Given an ore with a specific gravity of 4.5, porosity 30 per cent, and moisture 7 per cent. Select a point on the upper edge of the diagram indicating the given specific gravity (4.5); from this point move downward, as indicated by the dotted line, to the line representing the given porosity. (There are two sets of inclined lines crossing the upper part of the diagram; the less steeply inclined set, numbered at the left side of the diagram, indicates degree of porosity.) From this point move upward to the right along the more steeply inclined lines to the edge of the diagram. This point (3.15) indicates the specific gravity as corrected for porosity. From this point move directly downward to the lower edge of the diagram, where the number of cubic feet per ton is indicated. This shows 11.4 cubic feet per ton of dry material. The factor of moisture has not yet been considered. When moisture is present the material is heavier and consequently the volume per ton smaller. To introduce this factor of moisture, move directly upward from the last point (11.4) to the horizontal line indicating the given percentage of moisture (7), and from this point down the inclined line to the lower edge of the diagram, where the number of cubic feet per long ton is found to be 10.6.

At the lower edge of the plate is a transformation table showing the relation between cubic feet per long ton (2,240 pounds) and cubic feet per short ton (2,000 pounds). For example, 10.2 cubic feet per long ton is equivalent to 9.1 cubic feet per short ton.

CONSTRUCTION OF THE DIAGRAM.

The following discussion of the derivation of the diagram is given with the idea that one desiring to make use of it would first wish to be assured that it rests on a rational mathematical basis.

The top and bottom lines of the diagram proper, labeled respectively "Specific gravity" and "Cubic feet per ton" and connected by parallel vertical lines, constitute a transformation table by means of which the number of cubic feet per ton of a material of a given density may be at once determined (or vice versa) by moving vertically between the upper and lower edges of the diagram. Immediately below the edge of the diagram proper is a scale of pounds per cubic foot, which may be used by moving vertically downward from any point on the "specific gravity" or "cubic feet per ton" scales.

Effect of porosity.—The effect of porosity is to decrease the density of a substance, hence rock specific gravity is less than mineral specific gravity in proportion to the degree of porosity of the material considered. To introduce the factor of porosity in the diagram, the upper line was extended to the right to the point indicating a specific gravity of zero (not shown on the diagram). The line at the left edge of the diagram was drawn perpendicular to the upper edge and divided into 100 equal divisions, representing percentages of pore space. Each of the points of the vertical "porosity" line was then connected with the point indicating a specific gravity of zero. Hence on moving vertically downward from any point on the "specific gravity" line, a succession of equally spaced lines are crossed indicating percentages of pore space. To enable the diagram to show automatically the change in specific gravity resulting from a given porosity of a substance of known mineral specific gravity, a set of parallel lines was drawn, properly connecting points on the "porosity" and "specific gravity" lines. These lines were drawn parallel to the line connecting 100 per cent porosity with zero specific gravity and agree with the following formula:

$$G_r = G_m (1 - P)$$

where G_r = rock specific gravity, G_m = mineral specific gravity, and P = porosity. The diagram then automatically shows the relation between mineral specific gravity, porosity, and cubic feet per ton. To illustrate, a certain ore with a mineral specific gravity of 5.0 has 40 per cent of pore space. Beginning at the point 5.0 on the upper edge of the diagram, move downward to the line indicating a porosity of 40 per cent; from this point move along the parallel inclined lines upward to the right, to the edge of the diagram, where the specific gravity as reduced by pore space (rock specific gravity) is found to be 3.0; immediately below this point, on the lower edge of the diagram, it is seen that the ore runs 11.95 cubic feet per ton and 187.25 pounds per cubic foot.

Effect of moisture.—The diagram so far takes no account of moisture and hence is applicable only to perfectly dry material. Moisture when present in an ore or similar substance occupies the pore space. When the pore space is filled with moisture the material is said to be saturated. As the moisture occupies the natural openings in the ore, its presence affects the weight of the ore and not its volume, hence its effect is to increase the density and decrease the number of cubic feet per ton. Moisture is expressed in percentage of total weight.

Let D= density as affected by porosity; then, as a cubic foot of water weighs 62.5 pounds,

$$\text{Cubic feet per ton} = \frac{2{,}240}{D \times 62.5}$$

When moisture (M) is present the above equation becomes—

$$\text{Cubic feet per ton} = \frac{2{,}240\ (1-M)}{D \times 62.5}$$

The lower part of the diagram is crossed by a set of parallel horizontal lines indicating percentages of moisture, as shown at the right-hand edge of the diagram. Following the above equation, a set of inclined lines were drawn, properly connecting points on the "moisture" and "cubic feet per ton" lines. Given the number of cubic feet occupied by a ton of any porous material when dry, the effect of any percentage of moisture is indicated automatically by the diagram. For example, a certain ore when dry occupies 12 cubic feet per ton; it is desired to know the effect of 10 per cent of moisture. From the point 12 on the lower edge of the diagram move vertically upward to the horizontal line indicating 10 per cent moisture; from this point move downward along the inclined line to the edge of the diagram, where it is found that the moist material occupies 10.8 cubic feet per ton.

Moisture of saturation.—Up to this point it has been shown that, given the mineral specific gravity, porosity, and moisture content of an ore or similar substance, the diagram automatically indicates the number of cubic feet per ton. In many classes of ore the factor of moisture is the most variable of the three named above. The mineral specific gravity and porosity of an ore determine the amount of moisture which it can hold. This maximum, or moisture of saturation, may be calculated as follows:

G_m = mineral specific gravity.
D = density of dry porous material.
P = porosity.
M = moisture of saturation.
$D = G_m(1-P)$.

from which $P = 1 - \frac{D}{G_m}$ and $M = \frac{P}{G_m(1-P)+P}$

Substituting the value above given for P—

$$M = \frac{1 - \frac{D}{G_m}}{D + 1 - \frac{D}{G_m}}$$

By substituting values for D and G_m in the above equation the curves for moisture of saturation were constructed across the lower part of the diagram. These curves enable one to determine at once the moisture of saturation of any material, given the mineral specific gravity and porosity. Each curve corresponds to a certain mineral specific gravity, and the moisture of saturation is found by moving vertically from the point indicating the number of cubic feet per ton of the dry material to the proper curve for moisture of saturation. For example, an ore with a mineral specific gravity of 4.0 and a porosity of 36.0 per cent occupies 14 cubic feet per ton if dry; its moisture of saturation is found by moving upward from the point 14 to the curve $G = 4.0$, and reading the indicated moisture—12.2 per cent; that is, 12.2 per cent of moisture would fill the pore space of this ore.

Excess of moisture handled in mining.—It frequently happens in mining that ore as hoisted to the surface contains a larger percentage of moisture than it did before it was mined; in fact, it may contain a percentage of moisture greater than the moisture of saturation of the unmined ore. This may be caused by the handling of broken ore on undrained mine floors. The ore after being broken down has a much larger percentage of voids than before and hence a greater ability to absorb and retain moisture. The diagram is useful in this connection in showing, from determinations of specific gravity and original porosity of hand specimens, the moisture of saturation of the ore in place. This figure compared with the percentage of moisture of ore as it leaves the mine tells at once whether or not an unnecessary amount of water is being hoisted with the ore, owing to improper drainage.

EXPLORATION FOR IRON ORE.

The location of explorations within the areas of the iron-bearing formations is determined by outcrops, by magnetic lines, by mining, and by general geologic structure. It has been possible to confine most of the exploration to the area of the iron-bearing formations, but in certain districts, notably the Cuyuna, Florence, Crystal Falls, and Iron River districts, the distribution and limits of the iron-bearing formation are so uncertain that much exploratory work has had to be done even to locate the formation. All the facts bearing on the distribution of the iron-bearing formation discussed in this monograph are taken into account in choosing areas for exploration. Some of the larger mining companies employ their own geologists to make special reports on the geology of given areas as a preliminary to underground exploration, and nearly all the explorers make liberal use of all the geologic information available in localizing their work.

As the few ore deposits exposed at the surface were found years ago, explorations are now largely conducted by drilling and sinking test pits and shafts. The large size of the iron-ore deposits makes it possible to find and outline them by drilling to an extent not possible in smaller ore deposits, with the result that the greater number of ore bodies, especially in recent years, are thoroughly explored by drilling before mining begins. It has usually been assumed that if drilling does not locate an ore body it is useless to sink a shaft for this purpose. Mining operations have necessarily disclosed much ore which had not previously been found by drilling, especially in certain districts like the Menominee or the Gogebic, where the structural conditions are such as to make the location of ore by drilling extremely difficult. In the region as a whole mining operations have almost everywhere disclosed greater reserves of ore than the drilling had indicated.

The great dependence placed on drill work has resulted in enormous expenditure for this purpose. Accurate estimates of the amount of drilling done so far in the region can not be made, but a rough estimate compiled from tentative estimates of engineers of the several districts is as follows:

Drilling done for iron ore in the Lake Superior region.

District.	Number of drill holes.	Average depth of drill holes (feet).[a]
Mesabi	15,000	175
Vermilion	1,000	600
Cuyuna	1,500	250
Marquette	5,000	500
Other Michigan ranges and Wisconsin ranges	4,000	300
	26,500	

[a] Estimates probably low.

This totals 7,200,000 feet, or about 1,363 miles of drilling. At an average cost of $3 a foot, which is a low estimate, the total expenditure has been roughly $21,600,000.

It is estimated that at the present time there are 400 drills in operation in the region. In the earlier days of exploration test pits were relied upon to a large extent, especially in areas where the surface drift is thin and the water level below the rock surface. This method of exploration, however, is unsatisfactory because of the great depth of the drift at many places, the difficulty of handling water, and the difficulty after finding the ledge of penetrating it by this method. In later years the use of test pits has been largely superseded by drilling.

Both diamond and churn drills are in use. Through surface and soft-ore formations the churn drill is used. Much of the Mesabi district may be so explored. The cost of churn drilling has ranged from $1 to $3.50 and averaged about $2.50 a foot, varying from district to district according to accessibility and cost of transportation and other factors. The cost of diamond drilling has ranged from $2.25 to $8 a foot and averages at present about $3.75, but varies from district to district. Test pits are cheap, averaging perhaps $1.25 a foot.

The necessity for the most careful study of the structural geology in drilling is illustrated by the frequent failure of drills to locate ore deposits even after what seemed to be careful drilling and the subsequent discovery of the deposits either by further drilling or by mining operations. Indeed, as one comes to realize the variety and complexity of underground structural conditions, he is likely to become more and more disinclined to submit a negative report on any property, no matter how extensively it has been drilled. This difficulty is illustrated by the ore shoots in the Gogebic and Menominee districts, many of which have been missed by drilling and picked up in mining operations. Many of the ore shoots in the Vulcan member of the upper Huronian slate of Michigan pitch beneath the surface, following the axes of drag folds, and it is easy for drills to pass one side or the other, or, if the drill hole is inclined, to go above or below them. On examination of drilling plats of exploration areas it is easy to see where linear shoots of ore might pass through at places not penetrated by the drilling. In fact, drilling in some of these localities is almost as uncertain as shooting a bird on the wing. There are many ways of missing the ore. As knowledge of structural conditions increases, however, adverse chances diminish, with the result that in certain areas after the local structural problems are solved, it is possible to drill with a high degree of success.

A higher average of success in drilling would unquestionably result if greater care were taken in the interpretation of drill records. The drill runner is often allowed to report the character of the drillings and the samples are not kept, with the result that many valuable inferences that might be drawn from the lithology, the dip and strike of bedding and cleavage, and other features are lost. Not infrequently also failure to plat drill records in such a manner that they may be considered in three dimensions may cause promising chances for ore to be overlooked.

There has been a considerable tendency to generalize the principles of ore occurrence and in exploration to carry such principles from one district to another. As a matter of fact, although some of the basic principles are general for the region, the local variations of structure require the most careful study of each area to prevent mistakes in interpretation. When explorers of the Gogebic district, where the ores lie in regular, impervious, pitching basins, went to the

Mesabi district, where the rocks are of the same age, they naturally attempted to use the same methods in exploration. But here the flatter dip of the formation, the shallowness of basins, the effect of overlying slates in ponding waters, and the unusually large influence of joints in localizing the concentration of ore made the finding of ore largely a new problem, which was solved at much expense and trouble. Recognizing the danger of carrying the method of exploration of one district into another, certain explorers have gone to the other extreme and have attempted to disregard all guides derived from the study of the structural geology, with results even more unsatisfactory than if they had used principles developed for other districts.

Much the greater part of the exploration of the region has been conducted without taking the fullest advantage of all geologic knowledge available, but there has been a rapidly increasing tendency to follow geologic structure and therefore an increasing demand for geologic information, as shown by the cordial support that the mining men have given to the efforts of the United States and State surveys in this region and by their considerable expenditures for private geologic surveys. Certain of the drilling companies doing contract work now have geologists on their staff to aid in the interpretation of records, notwithstanding the fact that such interpretation is primarily in the hands of their clients. The problems of underground exploration are followed keenly, intelligently, and energetically by a large number of skilled men in the employ of mining companies, with the result that advances are being made with a rapidity which is sometimes almost bewildering. Six months may see the development of new facts requiring changes in the interpretation of the drilling of a district. The statements as to structural conditions presented in another chapter of this book may require some modification by the time the book is given to the public, because of the amount of rapidly accumulating information in the interval between the writing and the printing.

MAGNETISM OF THE LAKE SUPERIOR IRON ORES AND IRON-BEARING FORMATIONS.

All ores of iron are found to be magnetic when tested by sufficiently delicate means. Ordinarily magnetite is the only iron mineral which causes conspicuous disturbance of the magnetic needle. Practically all the Lake Superior iron-bearing formations contain at least minute quantities of magnetite, and hence all exert an influence on the magnetic needle, but in widely varying degree. The iron-bearing formation of the Vermilion district and other Keewatin areas is strongly magnetic. The same is true of the formation in the east end of the Mesabi district, the Gunflint district, the Cuyuna district, and the east and west ends of the Gogebic district, and of most of the Negaunee formation of the Marquette district. Less magnetic parts of the iron-bearing formations are those producing principally hematite and limonite, as the central and western parts of the Mesabi, the central part of the Gogebic, and parts of the Menominee and Crystal Falls districts. The iron-bearing member of the Iron River district of Michigan affects the magnetic needle only locally and slightly.

Every known iron-bearing formation in the Lake Superior region, with the exception of that in part of the extreme west end of the Mesabi district, has been outlined partly as a result of magnetic surveys. In some of the districts, as, for instance, the Iron River district, the magnetic variation is slight, but careful observations will detect it. In addition several magnetic belts are known in which exploration has not yet shown the character of the iron-bearing formation. On the general map (Pl. I, in pocket) magnetic belts are not indicated over all of the iron-bearing formations. They are shown only in places where the formation is not naturally exposed or uncovered by exploration.

Strong magnetic disturbance does not necessarily mean ore, and, vice versa, ore does not necessarily cause strong magnetic disturbance. Lean amphibolitic schists may be highly magnetic, while rich hydrated soft ore has but little effect on the needle. Although magnetic disturbance is usually caused by an iron-bearing formation, it is also caused by certain basic igneous rocks, like the ellipsoidal basalts of the Keewatin or gabbro intrusives. There is little difficulty in ascertaining the cause of the attractions, however, for somewhere along most of the magnetic belts in the Lake Superior region there are outcrops which indicate the nature of the rock causing the disturbance. If the rock is entirely covered, it may still be possible to determine whether the disturbance means iron-bearing formation or some other rocks. The iron-bearing formations are sedimentary deposits with certain linear characteristics of distribution, giving even lines or "belts" of magnetic attraction, whereas the basic igneous rocks are likely to cause a much more irregular magnetic field.

Because of the conditions above outlined, it is seldom practicable in the Lake Superior region to draw from magnetic observations inferences with regard to the shapes of the iron-ore deposits themselves as distinguished from the rest of the iron-bearing formation—such inferences as have been drawn by magnetic surveys of deposits in eastern Canada, Sweden, and elsewhere. In those regions the ores consist of magnetite associated with relatively non-magnetic wall rocks, and the magnetic disturbances are produced by the iron ore itself, not by iron ore and wall rock; hence it is possible to draw satisfactory inferences as to the shape and attitude of the iron-ore deposits. In the Lake Superior region the magnetic attractions are useful in locating iron-bearing formations and thus ultimately the iron ore by underground exploration, but do not directly point out the iron-ore deposits themselves. The highly developed Swedish methods of determining both the intensity and the direction of the magnetic pull are therefore unnecessarily detailed and slow for use in the Lake Superior region, and when attempts have been made to locate ore deposits by them the results have been disappointing

Although the iron ores may not be discriminated by means of the magnetic disturbances, it is possible under some conditions to draw useful inferences from them as to the dip or folding of a buried iron-bearing formation. A sharp, narrow belt of magnetic attraction leading up to a definite maximum usually means a highly tilted formation presenting a narrow erosion edge at the rock surface, as in the Gogebic or Vermilion district. A wide, more irregular, and less well defined belt of attraction is ordinarily associated with a flatter dip, exposing a greater area of iron-bearing formation to the erosion surface. The producing part of the iron-bearing Biwabik formation of the Mesabi district illustrates this. Unequal magnetic gradient on two sides of a maximum may indicate the direction of dip of the iron-bearing beds. The outward dip of the iron-bearing formation about the Archean ovals of the Crystal Falls district is so indicated. Several roughly parallel, more or less discontinuous magnetic belts, here and there converging and joining, may indicate repeated pitching folds, as in the Cuyuna district.

General laws of interpretation of magnetic attraction require much local modification. It is usually necessary to ascertain for each locality the magnetic character of the iron-bearing formation, to correlate this with known facts from outcrops or underground workings, and from the knowledge thus obtained to interpret the results of the magnetic formations in covered parts of the area where the magnetic readings alone are available. H. L. Smyth,[a] in connection with much magnetic field work in the Lake Superior region, has developed mathematical relations between magnetic fields and various attitudes of the rock beds which may serve as a useful guide in detailed surveys.

The instruments which have been used in Lake Superior magnetic surveys are the dip needle and the dial compass. The dip needle determines the vertical component of the magnetic pull, as well as the direction of the horizontal pull; the dial compass determines only the direction of the horizontal pull. Methods of using and interpreting these instruments are discussed in detail by Smyth. The dial compass is essential in most of the work because it affords means of keeping accurate directions necessary for location and of reading the horizontal component of the magnetic variation. It may be used only on sunny days, and thus magnetic work in the Lake Superior region is likely to be slow and expensive. The dip needle may be used at any time, but in a disturbed field it affords no means of keeping horizontal directions, and hence location. This is an essential defect in a country in which the roads and other works of man afford little aid in keeping location.

In theory the use of the magnetic needle is simple, but much practice is required to insure uniformly accurate observations. The unskilled observer finds many pitfalls in the mechanism

[a] Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 336-373.

of the instrument, in the manner of holding it, in the effects of temperature, in electrification from rubbing the glass, etc. There is much opportunity for the exercise of good judgment in the determination of the intervals at which readings shall be taken, the direction and number of runs, etc. These should be varied for different areas, depending on the structure found or suspected. Finally, the interpretation of the results calls for consideration and careful balancing of a great variety of factors, capacity for which is acquired only by wide experience and painstaking observation.

MANGANIFEROUS IRON ORES.

All the Lake Superior iron ores contain minute quantities of manganese, and certain ores carry as high as 20 to 25 per cent. In the Cuyuna district of Minnesota a drill hole in the iron-bearing member averages 13 per cent for the upper 35 feet and about 2 per cent below. Another hole, in sec. 28, T. 47 N., R. 29 W., has an average of 11.33 per cent for the upper 30 feet. Similar results have been obtained from drilling in the Baraboo district.

The larger part of the manganiferous ores shipped so far have come from the Gogebic district. Manganiferous ores are often not discriminated from the iron ores in figures of shipment, and this makes it difficult to estimate the tonnage of manganese iron ore and the average percentage of manganese in so-called manganiferous iron ores. E. C. Eckel[a] estimates that during 1906 the Lake Superior region produced about 1,000,000 long tons of low-manganese iron ore with an average manganese content of about 4 per cent and ranging as shipped from 1 to 8 per cent. According to Burchard,[b] the total production of manganiferous iron ore in the Lake Superior region from 1885 to 1909, inclusive, has been 8,968,449 long tons, or about 77 per cent of the total production for the United States during that period.

The percentage of manganese in the manganiferous ores of the Lake Superior region is so low that the ore may not be classed either as a manganese or a highly manganiferous iron ore like those of Arkansas and Colorado. It produces a basic pig. None of the ore shipped from the Lake Superior region has been high enough in manganese to be available for ferromanganese or spiegeleisen, which require at least 15 per cent of manganese.

Mineralogically the manganese is mainly in the form of pyrolusite (MnO_2). In the Cuyuna district this has been found at the surface to be mixed with rhodochrosite ($MnCO_3$). The psilomelane so commonly associated with pyrolusite in the Appalachian manganese ores has not been especially looked for in the Lake Superior region but is probably present.

The conspicuous association of manganese with the upper parts of the iron-ore deposits seems to prevail in the Lake Superior region, as in deposits of manganiferous iron ore in other parts of the United States.

IRON-ORE RESERVES.

DATA AVAILABLE FOR ESTIMATES.

Up to 1910, 335 mines have been in operation in the Lake Superior region, and many thousands of test pits and churn and diamond drill holes have been sunk. The mines and explorations, together with natural exposures, afford data for a fair estimate of ore reserves in the producing areas. There are considerable areas not yet explored.

AVAILABILITY OF ORES.

Evidently the question of the present and future availability of the iron ores is one of costs—in mining, in transportation, and in the furnace. The costs are determined—

(1) By the character of the ore itself, its percentage of iron and deleterious constituents, and the nature of its principal gangue material.

(2) By the cost of mining, whether, for instance, by open pit or underground method.

(3) By whether or not the ore must be concentrated, as, for instance, the sandy taconites of the western Mesabi.

[a] Mineral Resources U. S. for 1906, U. S. Geol. Survey, 1907, p. 106.

[b] Burchard, E. F., The production of manganese ore in 1909: Extract from Mineral Resources U. S. for 1909, U. S. Geol. Survey, 1911, p. 10.

(4) By the cost of transportation to the furnace. Between Vermilion and Marquette ores there is a difference of about 75 cents a ton in the cost of transportation to the lower lakes. Viewed in another way, the cost of transportation is the amount necessary to bring together the coal, limestone, and iron and to transport the finished product to consuming centers. This introduces another set of costs for ores smelted at the upper lakes.

(5) By the cost of reduction in the furnace, depending on the character of the ore and on the success in modifying and applying furnace practice to local conditions. For instance, the use of by-products from coke in certain furnaces in the Lake Superior region makes approximately the difference between profit and loss for the combination of conditions there existing.

(6) By the nature of the ownership. A large corporation holding a variety of ores and equipped to assemble the raw material under the existing conditions can handle ore which would not be available to a smaller company not equipped to control the situation in a large way.

In recent years the average percentage of iron in the ore shipped has varied between 60 and 54 per cent for the ore in the natural state (see pp. 477, 493), the grade on the whole lowering. These grades may be regarded as approximately the lowest average grades available under the conditions prevailing in those years. Low-grade, high-silica ores, running as low as 40 per cent in iron, favorably located for cheap mining and transportation, have been used to a small extent for mixtures, as, for instance, ores in the Palmer area of the Marquette district and in the Menominee district. In most of the region at the present time ore running 50 per cent (natural) in metallic iron is considered of about as low grade as is at present available, and estimates are made accordingly. Locally ores of lower grade are included as available ores, either because of favorable conditions of mining and transportation, because of differences in the policy of the companies making the estimates, or because they may be concentrated by washing, as in the western Mesabi.

The table of production (see pp. 49–69) shows what has been the relative availability of ores of the different districts, all factors considered.

RESERVES OF ORE AT PRESENT AVAILABLE.

ESTIMATES.

The authors have made no independent detailed estimates of Lake Superior iron-ore reserves for this monograph. They have, however, had access to the detailed estimates of the principal mining companies and to the records of the Minnesota Tax Commission and are from their field study familiar with most of the large deposits or groups of deposits. The estimates here given represent their judgment as to the approximate tonnage of ore now available, based on the above information. The variations in the independent estimates of mining companies and the difference of opinion as to how low a grade of ore in any given place is to be included in the available ores give latitude for considerable variations in estimates. The authors can claim no finality for the figures published. They are what seem to them reasonable approximations.

Estimates of the available pre-Cambrian iron ore of the Lake Superior region.

	Long tons.
Marquette district	100,000,000
Gogebic district	60,000,000
Menominee and Crystal Falls districts	75,000,000
Mesabi district	1,600,000,000
Vermilion district	30,000,000
Cuyuna district	40,000,000
	1,905,000,000

The reserve reported includes about 130,000,000 tons of washable ores from the western Mesabi, averaging 46 per cent of iron (dry) of non-Bessemer character. Of the remainder of Mesabi ores, approximately 40 per cent are Bessemer.

There is a further low-grade reserve in the Clinton ores of Wisconsin which may be of considerable magnitude. (See pp. 566–567.)

LIFE OF ORE RESERVES AT PRESENT AVAILABLE.

Figure 73, prepared by H. M. Roberts, shows the total production of ore from the Lake Superior region for 30 years before 1907 and the rate of increase of production. To the close of 1910 20.5 per cent of the known reserves had been consumed. If the above estimates of

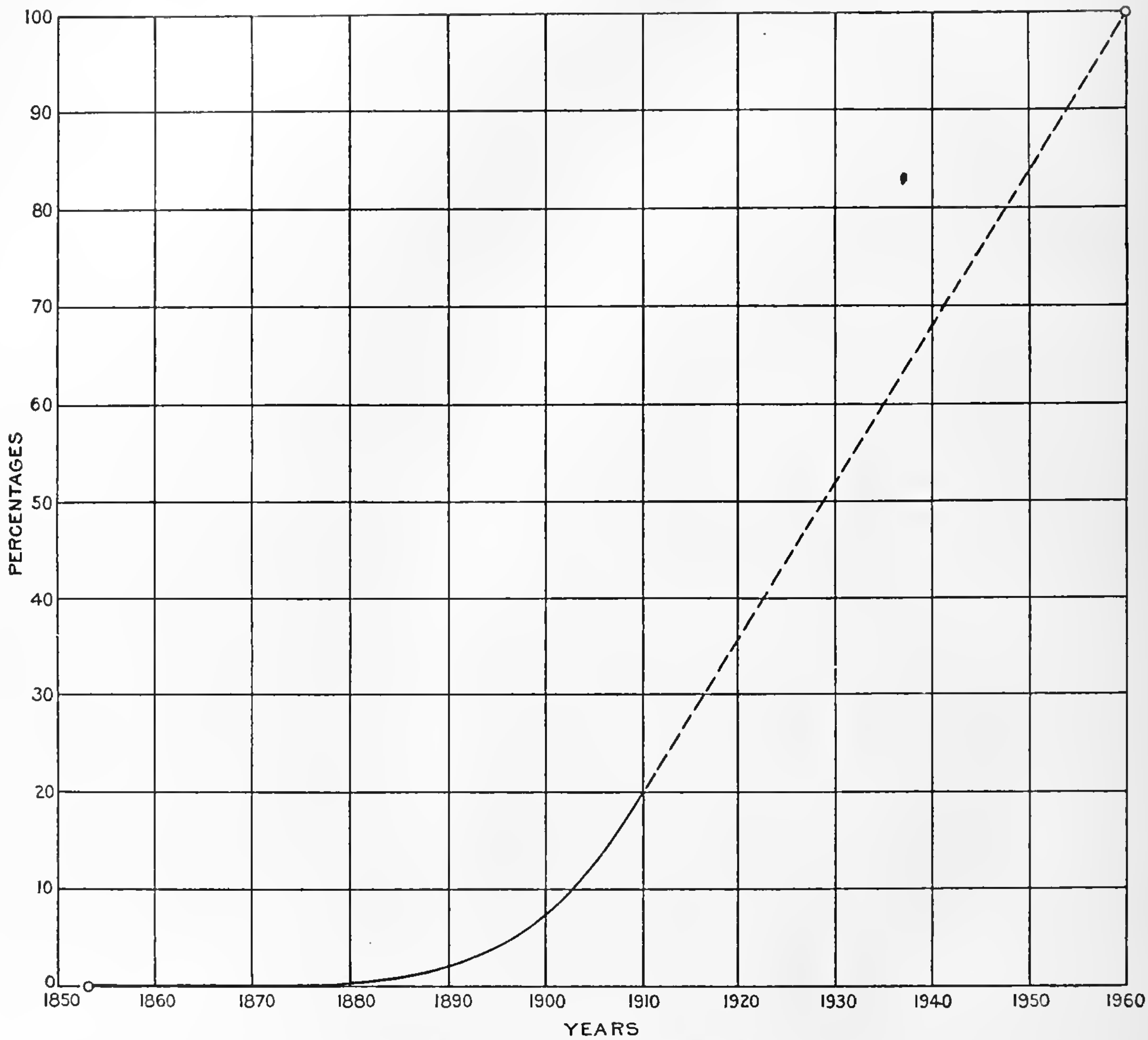


FIGURE 73.—Diagram showing relation between estimated ore reserves of the Lake Superior region and rate of production. The estimated reserve, 1,905,000,000 tons, plus the total amount of ore mined to the end of 1910, is represented as 100 per cent on the vertical line. For each year there is shown the percentage of this total which had been removed to the end of that year. For example, 15.9 per cent of the known ore was removed to the close of 1907. For the last five years, 1905 to 1910, the curve is practically a straight line. If this line is projected at a uniform slope, it indicates complete exhaustion of the known reserves in 1960. Reasons are given in the text, however, for the belief that the date of exhaustion will be later.

reserves at present available are even approximately correct and the rate of production remains the same as that in 1910, the life of the ore deposits as now estimated will be 45 years—that is, to 1956. If the rate of production increases in the future this time will obviously be shorter. As some increase in the rate of production seems likely in spite of the probable temporary recessions due to business depressions, if only high-grade ores are mined the exhaustion of the existing deposits, or, if not these, of the amount of high-grade ore equivalent to that now in sight, will probably occur earlier than this date. But even this conclusion must be modified by the fact that in proportion as the inadequate supply of high-grade ores becomes depleted there will be an increased use of lower-grade ores with the high-grade material, whose life will be thereby prolonged. This factor is regarded as so important as to render it probable that the use of the high-grade ores will be distributed through a much longer period than 45 years, just as there will be first-growth white pine remaining uncut long after the date when all the white pine would be gone at the present rate of use. Also new discoveries of ore of present commercial grade are made yearly. Prior to 1911 the discoveries have kept well ahead of the shipments. The region is now so well known that there is little likelihood of discovering another Mesabi range. Though it is not impossible that in the next few years the reserves may be sufficiently increased by discovery to keep pace with the shipments, this is rather unlikely. Still less likely is it that the increase of reserves will keep pace with an acceleration of production. If, for instance, the increase of production for a year amounts to 2,000,000 tons, and it is estimated that the present reserves will last 20 years at the lower rate, it will be necessary in that year of increase to discover 40,000,000 tons of ore in order that the life of the reserves may not be lessened.

RESERVES AVAILABLE FOR THE FUTURE.

ESTIMATES.

Reserves available for the future must be considered as having a present small and intangible value, for the reason that the estimates of ores at present available include all ores which can be immediately mined or which will be taken out in the normal course of development of present mines. When we remember that iron is one of the most widely disseminated metals of the earth's crust (by actual analysis constituting 4 per cent of all the rocks of the earth), it is apparent that only the most arbitrary limits can be placed on future reserves. In the following estimates of future reserves are included rocks containing a percentage of iron lower than the percentage in the reserves at present available but sufficiently higher than that in the common rocks of the earth's crust to give them future priority in use as iron ores over the average rocks of the earth's crust. It will probably be many hundreds of years before any but an insignificant portion of these reserves available for the future are utilized. The additional discovery of high-grade ores—as, for instance, those of the great field in Brazil—the enormous quantities of low-grade ores now available from Alabama and Cuba, the extension of the known high-grade reserves of Lake Superior, and the increased use of scrap iron and steel will postpone the use of the bulk of the low-grade Lake Superior reserves available for the future. On the other hand, the diminution in supply of the reserves at present available will lead gradually, and probably in the not far distant future, to the drawing on minor amounts of these future reserves for mixtures.

It is to be remembered that the available ores are associated with iron-bearing formations, which differ from the ore mainly in having more silica and which show all gradations to the ore. The character of these formations, so far as iron is concerned, is best shown by the following table of analyses from drill sections compiled by the Oliver Iron Mining Company:

Character of iron-bearing formations in Lake Superior region (not including available ore).

Diamond-drill Averages.

Range.	Number of holes.	Total number of feet.	Number of analyses.	Average percentage of iron.
Gogebic	15	5,890	490	36.65
Baraboo	30	4,814	1,517	36.40
Marquette	32	11,025	1,726	35.12
Menominee	30	5,287	1,681	37.93
Mesabi	24	5,400	1,094	38.00
Other Sources.				
Marquette	Trenches	975	94	41.53
Menominee	Levels		905	38.40

These analyses include both the lean and the partly concentrated parts of the iron-bearing formations, but do not include the available ore. If the partly concentrated parts of the formation are left out of consideration, the average would be 25 per cent of iron.

In the following table column 4 contains a rough estimate of the tonnage of all iron-bearing formations outside of "available" ore to a depth of 1,250 feet for the steeply dipping formations and to a depth of 400 feet for the Mesabi district, where the thickness ranges from a knife-edge to 900 feet. Column 5 contains a rough estimate of the tonnage of the part of the iron-bearing formations which will run above 35 per cent in iron.

Total tonnage of iron-bearing formations to given depths and tonnage estimated to run 35 per cent or more in iron.

District.	(1) Area.	(2) Depth.	(3) Volume.	(4) Quantity of iron formation.	(5) Quantity containing 35 per cent or more of iron.
	Sq. mi.	*Feet.*	*Cu. mi.*	*Tons.*	*Tons.*
Michigan:					
Crystal Falls	7.8	1,250	1.85	24,100,000,000	1,500,000,000
Marquette	28.5	1,250	6.75	87,800,000,000	16,000,000,000
Menominee	5.6	1,250	1.30	16,900,000,000	3,500,000,000
Gogebic	5.8	1,250	1.40	18,200,000,000	1,250,000,000
Swanzy	1.0	1,000	.20	2,600,000,000	260,000,000
Minnesota:					
Mesabi	127.0	400	9.60	125,000,000,000	30,000,000,000
Vermilion	15.6	1,250	3.70	48,100,000,000	1,025,000,000
Wisconsin:					
Florence	.7	1,250	.16	2,150,000,000	215,000,000
Penokee	5.8	1,250	1.40	18,200,000,000	1,250,000,000
Baraboo	11.0	350	.70	9,100,000,000	910,000,000
Ontario:					
Animikie	10.0	100	.19	2,500,000,000	250,000,000
Michipicoten	6.6	1,250	1.57	20,400,000,000	2,040,000,000
North shore of Lake Superior	30.0	1,250	7.10	92,400,000,000	9,240,000,000
Other ores	....	....	....	....	200,000,000
	255.40	....	35.92	467,450,000,000	67,640,000,000

We may conclude, therefore, that while the ores at present available would probably be exhausted within about 50 years if they alone were drawn from, the increasing use of lower-grade ores, already begun, will lengthen this period many times.

COMPARISON OF LAKE SUPERIOR RESERVES WITH OTHER RESERVES OF THE UNITED STATES.

For comparison a table showing ores available at present and in the future in different parts of the United States is given below. The figures, with the exception of those for Lake Superior, are those of the National Conservation Commission.[a]

Iron-ore reserves of the United States available at present and in the future.

Commercial district.	Ore at present available.	Ore available in the future.
	Long tons.	*Long tons.*
1. Northeastern	*298,000,000	1,095,000,000
2. Southeastern	538,440,000	1,276,500,000
3. Lake Superior	1,905,000,000	67,640,000,000
4. Mississippi Valley	315,000,000	570,000,000
5. Rocky Mountain	57,760,000	120,665,000
6. Pacific slope	68,950,000	23,905,000
	3,183,150,000	70,726,070,000

1. Vermont, Massachusetts, Connecticut, New York, New Jersey, Pennsylvania, Maryland, Ohio.
2. Virginia, West Virginia, eastern Kentucky, North Carolina, South Carolina, Georgia, Alabama, eastern Tennessee.
3. Michigan, Minnesota, Wisconsin.
4. Northwest Alabama, western Tennessee, western Kentucky, Iowa, Missouri, Arkansas, eastern Texas.
5. Montana, Idaho, Wyoming, Colorado, Utah, Nevada, New Mexico, western Texas, Arizona.
6. Washington, Oregon, California.

It appears from this table that the Lake Superior region contains approximately 60 per cent of the reserves at present available and 96 per cent of the future reserves, as figured in tons. If measured in units of iron, the Lake Superior reserves form a still larger proportion of the total.

[a] Bull. U. S. Geol. Survey No. 394, 1909, p. 103.

LOWERING OF GRADE NOW DISCERNIBLE.

Lower and lower grades of ore are being included in successive estimates of available ores. A comparison of the iron-ore tonnage of the United States with the production of pig iron for the last 20 years shows a distinct increase in the number of tons of iron required to make a ton of pig iron, and thus a lowering of the grade of iron ore mined. Figure 74, prepared by H. M. Roberts, compares the pig iron and tons of ore used and shows an average annual drop in grade of the ores for the last 20 years of 0.35 per cent in iron. Each temporary increase of

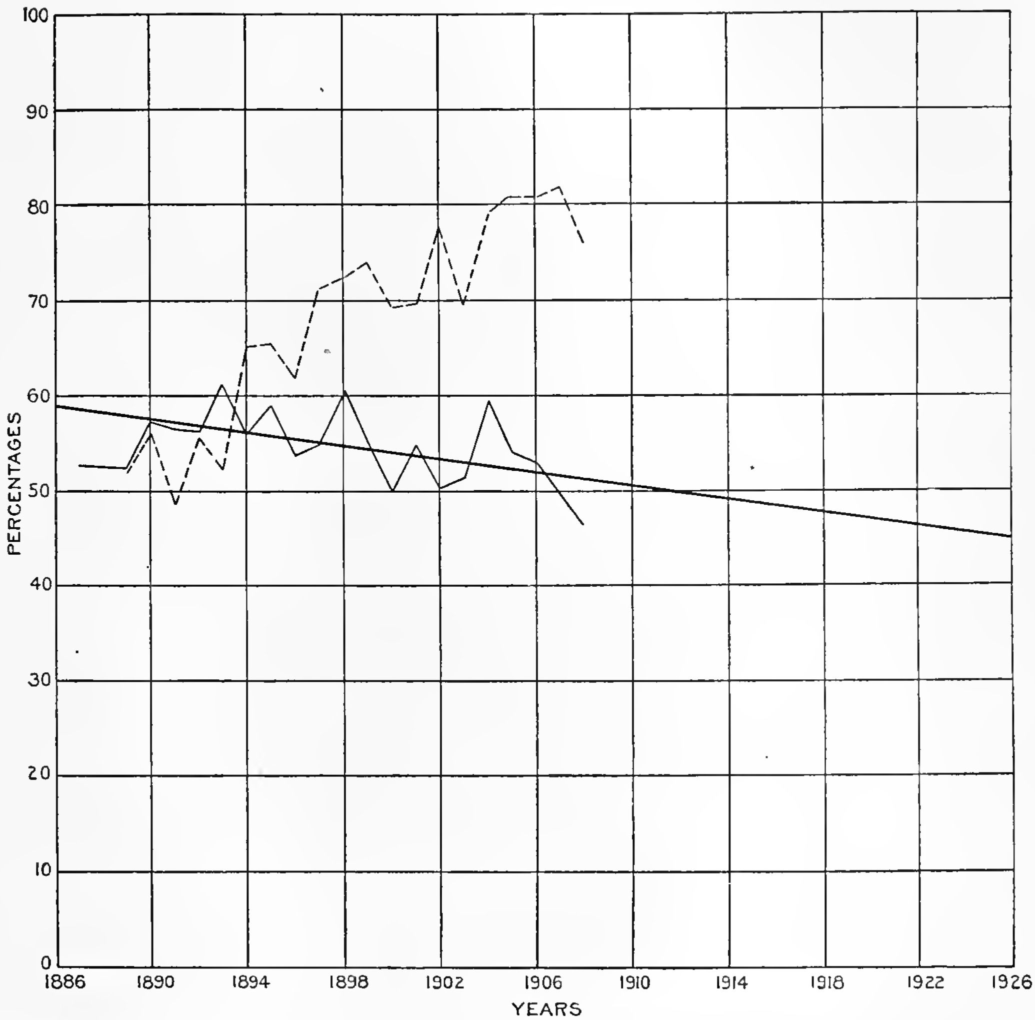


FIGURE 74.—Diagram representing decline in grade of Lake Superior iron ore since 1889. The light black line represents the approximate average percentage of metallic iron in the total production for the United States for each year. The heavy black line is the average slope computed by method of least squares, from the variations of the light continuous line. It represents the average decline of grade since 1889, which amounts to about 0.35 per cent per year. The broken line shows the percentage of the entire production of the United States which comes from the Lake Superior region. As this proportion has steadily increased, it is apparent that the drop in grade of the iron ores, figured for the entire United States, is shared by the Lake Superior ores.

production has been followed by a lowering in grade, and decrease of production has meant raising of the grade in about the proportion that might be calculated from the general drop in grade with increase in production for the last 20 years. It is not likely that the grade will lower as rapidly in the future as in the past, for as successively lower grades of ore are utilized the amounts available are larger.

As the Lake Superior region produces nearly 80 per cent of the iron ore of the United States, the conclusion as to lowering of grade drawn from the diagram may be taken to apply conspicuously to this region.

The present marked tendency toward the use of lower-grade ores does not necessarily mean that the higher-grade supplies are exhausted, but simply that they are being conserved for the future. In working a series of deposits ranging from the highest to a low grade, in strong financial hands, it is regarded as the best business policy not to rob the deposits of their highest grade, as was formerly done, but so to mix the high and low grades as to give the maximum tonnage of an ore just rich enough to be commercially available. The prospective short life of the highest-grade ores, probably not more than 50 years, is undoubtedly influencing the present conservative action. The conservation of the higher-grade supplies is favored by the marked concentration of control of the industry in a few hands. When the ore was held by many owners the range of grade available to each owner was necessarily limited; when it is in few hands the range is greater and correspondingly greater care can be taken in the proper mixing of grades in order to yield a maximum amount of the lowest grade which the market will stand. In the discussion of mining methods (p. 498) some reference is made to the care taken in getting out the proper grades from any individual deposit. The same general methods are applied by the United States Steel Corporation in apportioning the desired ores among the different deposits available.

EFFECT OF INCREASED USE OF LOW-GRADE ORES.

If it is established that the high-grade ores have a limited life and that the direction of the development of the ore industry is now toward the use of lower-grade ores and is likely to be more so in the future, and that this tendency will lengthen greatly the life of the ore deposits, there are certain consequences which may be expected.

1. The distribution of the production of iron ore is likely to be modified and the relative importance of iron-mining centers will vary somewhat. As the grade falls, new "low-grade" districts will come into existence and some old districts which have had a somewhat precarious existence in competition with higher-grade districts will be enabled to meet them on less unequal terms. This will be the effect not only locally within the Lake Superior region, but also in the relations between the Lake Superior and other regions. Western iron ores not now mined will come into the market. Appalachian ores, which can even now, in spite of their low grade, compete with Lake Superior ores because of favorable conditions of transportation and proximity to smelting materials and consuming centers, may in the future attain an even stronger position, for the difference in composition of the ores marketed is sure to become less, in view of the fact that the change toward low grade in the Lake Superior region is likely to be much more rapid than it is on the large low-grade supplies of the Southeast. The same general arguments will apply to the large Cuban reserves.

This increased use of lower-grade southern Appalachian ores is further favored by the distribution of the population of the United States and the prevailing freight rates. In a personal communication Judge E. H. Gary, chairman of the board of directors of the United States Steel Corporation, says:

> Under the existing freight rates for the cruder forms of steel products, if the freights from Birmingham be taken to a series of points extending approximately east and west, so selected that the rate from Birmingham to each point is the same as the rate from Chicago to that point or the rate from Pittsburg to that point, and a line be drawn connecting these points, more than 30 per cent of the population of the United States lives in the territory south of the line so formed, and the rail freight rates from Birmingham to all points in this territory are lower than the freight rates from either Pittsburg or Chicago to these points.
>
> If a line be located approximately north and south by selecting the points reached at equal freight rates from Chicago and Pittsburg, about 32 per cent of the population of the United States lives in the territory west of this Pittsburg-Chicago line and north of the Birmingham line, and about 38 per cent of the population of the United States lives east of the Pittsburg-Chicago line and north of the Birmingham line.

The preeminence of the Lake Superior region is due to the richness of its ores, which offsets relatively adverse conditions of distance and transportation. The lowering of the grade of ore will undoubtedly for a time favor other regions more than the Lake Superior region, but it would be rash to assume that the preeminence of the Lake Superior region will be lost. The lower-grade supplies of the Lake Superior region will not be called into use until long after those from other districts, and this will make it possible to maintain for a long time a higher grade of output in the Lake Superior region than in other districts.

2. As a result of the increasing use of low-grade ores, the distribution of blast furnaces and steel plants may be changed. At present the higher transportation charges on ores to lower lake ports as compared with upper lake ports are just about counterbalanced by increased cost of fuel and flux for smelting at upper lake points as compared with lower lake points. As the grade of ore is lowered this equilibrium will be disturbed.

3. As a result of decrease in reserves of low-phosphorus ores, the change from the acid Bessemer process to the open-hearth process of steel making will continue. The amount of high-grade Bessemer ore now in sight is scanty. Attention should be called, however, to the fact that the low-grade ores which may be drawn upon in the future are not necessarily high in phosphorus. In fact, the ratio of phosphorus to iron remains substantially the same whether the ore is lean or rich, the difference between grades of ore being mainly in the percentage of silica present. Lowering of grade may call into use new methods of smelting iron.

4. The lowering of the grade of the ore may favor combination of capital in the mining industry if such combination will make possible additional economies and the use of a wider range of ores.

COMPARISON WITH PRINCIPAL FOREIGN ORES.

The large deposits of low-grade limonite in Cuba have already been mentioned. These will doubtless be largely developed for use of the iron industry along the east coast of the United States. The local ore supplies of England and Germany are of low grade. Both countries import high-grade ores for mixture, partly hematites from Bilbao, Spain, and partly magnetites from northern Sweden and Lapland. The high-grade Bilbao deposits are nearly exhausted. Sweden limits the exports of its magnetite ores. Bessemer hematites of the highest grade are known in enormous quantities within 300 miles of the coast in Minas Geraes, Brazil. Steps are now being taken to develop these deposits. They are likely to be an important factor in the future in the British and German markets, and it is not improbable that they may be used on the east coast of the United States, especially for mixture with the Cuban ores.

TRANSPORTATION.

The transportation of the Lake Superior ores is one of the most important factors determining their availablity. They have been able to stand high transportation charges because of their high grade.

MINE TO BOAT.

The following table shows the principal ore-carrying railways, distances, rates, and the total tonnage hauled to December, 1908:

Ore-carrying railroads of the Lake Superior region.

Railroads.	Ranges supplying traffic.	Principal range shipping points.	Lake termini at which ore docks are located.	Average haul.	Approximate average cost per ton from mine to dock.	Total iron ores hauled to December, 1908.
				Miles.		*Tons.*
Duluth and Iron Range	Vermilion	Tower, Ely	Two Harbors, Minn.	70-90	$0.90-$1.00	75,153,936
	Mesabi	Eveleth, Sparta, Biwabik.		65	.80	
Duluth, Missabe and Northern	Mesabi	Virginia, Hibbing, Coleraine.	Duluth, Minn.	80	.80	79,118,051
Great Northern	Mesabi	Virginia, Hibbing, Nashwauk.	Superior, Wis.	120	.80	[a] 40,268,854
Chicago and Northwestern	Gogebic	Hurley, Ironwood, Bessemer, Wakefield.	Ashland, Wis.	40	.40	[b] 131,219,397
	Marquette	Michigamme, Negaunee.	Escanaba, Mich.	70		
	Swanzy	Princeton		45		
	Menominee	Iron Mountain, Norway.		45		
	Crystal Falls	Crystal Falls, Amasa		80		
	Iron River	Iron River		83		
	Florence	Florence		63		
Duluth, South Shore and Atlantic.	Marquette	Ishpeming, Negaunee	Marquette, Mich.	12-15	.25	28,493,359
		Michigamme		35		
Lake Superior and Ishpeming	Marquette	Negaunee, Ishpeming	Marquette, Mich.	12-15	.25	17,426,583
	Swanzy	Gwinn		36		
Wisconsin Central	Gogebic	Bessemer, Hurley, Ironwood.	Ashland, Wis.	50	.40	16,592,713
Chicago, Milwaukee and St. Paul.	Menominee	Crystal Falls, Iron Mountain.	Escanaba, Mich.	40-60	.40	

[a] Since January 1, 1897. [b] Since 1880. Includes ores other than iron ores between June 1, 1888, and July, 1903.

Eighty-five per cent of the tonnage has been hauled 50 miles or more and 15 per cent has been hauled less than 50 miles. The average cost for hauling the ore to the lake has been 60.42 cents a ton.

Four of the railways hauling the ore are controlled directly by the companies owning or mining the ore. The United States Steel Corporation owns the Duluth, Missabe and Northern and the Duluth and Iron Range railroads; J. J. Hill controls the Great Northern Railway; and the Cleveland-Cliffs Company the Lake Superior and Ishpeming Railway.

DOCKS.

The docks and their capacities are as follows:

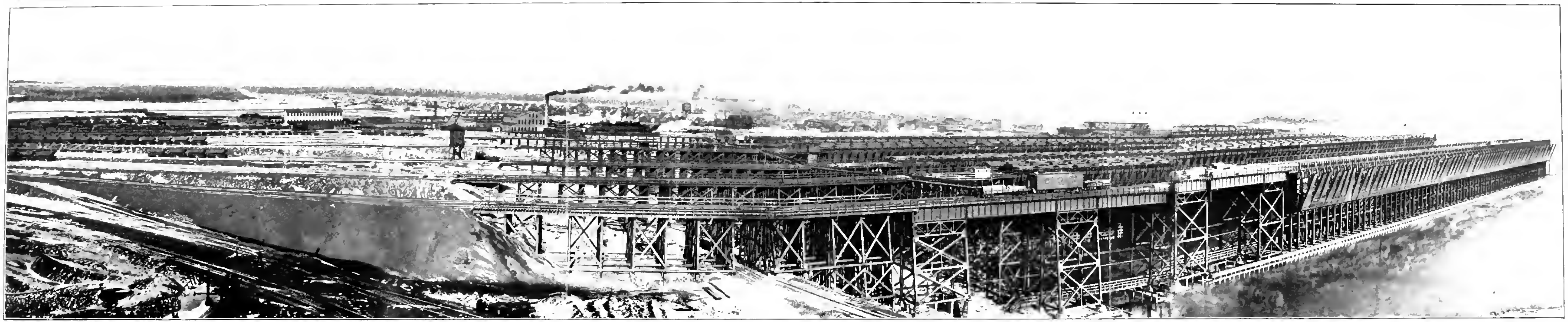
Record of ore docks on the Great Lakes.

[Revised to May 1, 1909. Table furnished by Oliver Iron Mining Co.]

Railroad.	Location.	Dock No.	Number of pockets.	Storage capacity.	Height from water to center hinge hole.	Height from water to deck of dock.	Width of dock from outside to outside of partition posts.	Length of spouts.	Length of dock.	Angle of pockets	Capacity per pocket to bottom of stringers.
				Tons.	*Ft. in.*	*Ft. in.*	*Ft. in.*	*Ft. in.*	*Feet.*	° ′	*Cubic feet.*
Chicago and Northwestern	Escanaba, Mich	1	184	21,143	28 10	48 6	37	21	1,104	39 30	1,918
Do	do	3	226	28,792	31 2	52 8	37	27	1,356	45	1,969
Do	do	4	250	34,925	36 6	59 2	37	30	1,500	45	2,191
Do	do	5	202	29,310	28 6	53 3	37	21 8	1,212	40	2,832
Do	do	6	320	69,760	40	70	50 2	30	1,920	45	4,114
Do	Ashland, Wis	1	234	42,120	40	70	50 2	30	1,404	45	3,915
Do	do	2	234	42,120	40	70	50 2	30	1,404	45	3,915
			1,650	268,170	....	....	....	....	....	....	....
Duluth and Iron Range	Two Harbors, Minn	1	202	40,400	35 5	59 6	49	27	[a] 1,388	38 42	3,006
Do	do	2	208	41,600	33 5	57 6	49	27	1,280	38 42	3,006
Do	do	3	170	34,000	40	66	49	27	1,054	43 32	3,006
Do	do	4	168	36,960	37	62	49	29	1,042	38 42	3,270
Do	do	5	168	35,450	39	66 9	49	30	1,050	43 32	3,126
Do	do	[b] 6	148	43,246	40	73	53	32 4	920	45	4,272
			1,064	231,656	....	....	....	....	....	....	....
Duluth, Missabe and Northern.	Duluth, Minn	2	384	69,120	32	57 6	49	27 9	2,336	45	2,363
Do	do	3	384	80,640	40 7	67 ½	59	27 9	2,304	45	2,782
Do	do	4	384	119,274	41 9½	72 6	57	30 1½	2,304	45	3,867
			1,152	269,034	....	....	....	....	....	....	....
Great Northern	Superior, Wis	1	374	100,980	40	73	62 8	32 4	2,244	45	4,972
Do	do	2	350	94,500	40	73	62 8	32 4	2,100	45	4,972
Do	do	3	326	88,020	40	73	62 8	32 4	1,956	45	4,972
			1,050	283,500	....	....	....	....	....	....	....
Duluth, South Shore and Atlantic.	Marquette, Mich	4	200	28,000	27 9	47 3	36 8	21 1	1,200	39 45	1,839
Do	do	5	200	50,000	40	70 10	51	32 4	1,236	45	3,848
			400	78,000	....	....	....	....	....	....	....
Lake Superior and Ishpeming	do	1	200	36,000	30 9	54	50	27 7	1,232	38 40	2,713
Wisconsin Central	Ashland, Wis	1	314	48,356	40	66 2	36	27	1,908	50 45	2,435
Chicago, Milwaukee and St. Paul.	Escanaba, Mich	1	240	50,400	40 2¾	66 6	52	120 27 120 29	1,500	45	2,900
Do	do	2	240	63,500	40 11½	69 2	54	30 4½	1,500	45	3,150
			480	113,900	....	....	....	....	....	....	....
Algoma Central and Hudson Bay.	Michipicoten, Ontario	1	12	....	34	43 4	25	22 6	311¾	44	....
Canadian Northern	Key Harbor, Ontario	[c] 1	20	2,000	....	61 9	28	30	240	....	....

[a] 312 feet single pockets; 1,076 feet double pockets.
[b] Steel superstructure on concrete.
[c] Pockets filled by belt conveyor from stock pile trestle 30 feet high.

The cost of unloading from train to dock and from dock to boat aggregates 4 cents a ton. Most of the structures up to the present time have been made of wood and are so inflammable as to require almost prohibitory insurance rates, are easily choked in cold weather by the freezing of the water in the ore, and are easily tied up by strikes. The destruction or tying up of a dock is a most serious setback to the iron-ore industry and one which can be less easily



ORE DOCKS AT TWO HARBORS, MINN.

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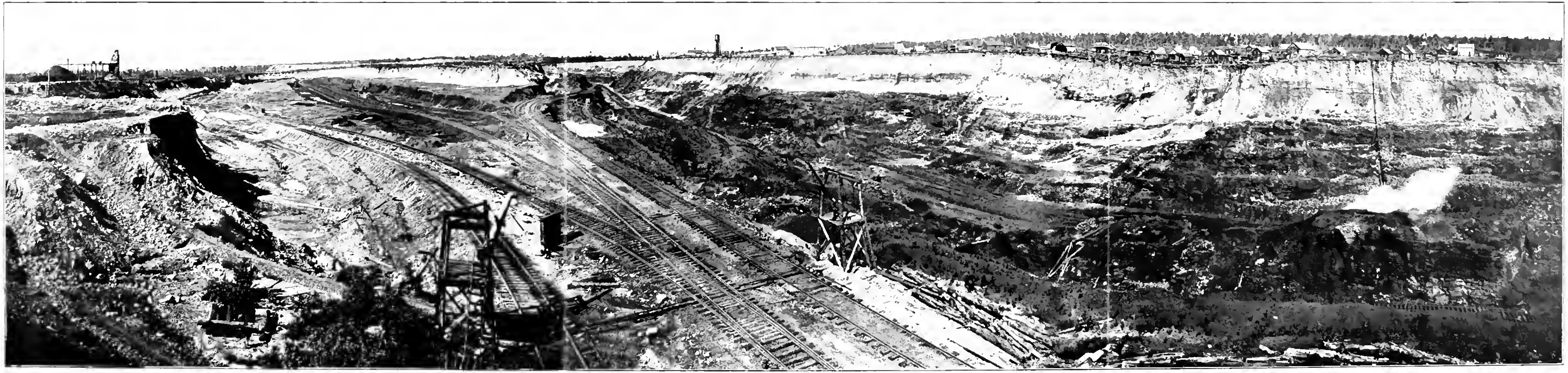

EXCAVATIONS AT STEVENSON, MINN.

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avoided and less quickly remedied than any other of the misfortunes affecting the industry. Steel is used in new docks at Two Harbors, Minn. (Pl. XLI, *A*), and this may be the beginning of a revolution in dock building. The docks have undergone little structural modification since they were first used in the Lake Superior region. There is still room for mechanical improvement to make the movement of ore more certain and continuous between the train and the boat.

BOATS.

The ore is carried on the Great Lakes by a fleet of vessels numbering 660 in 1907. Of the total tonnage which has gone down the Great Lakes much the largest percentage has gone to Cleveland and a small percentage to Chicago. The proportion going to Chicago is constantly increasing. The following table shows tonnage and rates from upper Lake ports in 1907:

Quantity of ore shipped from upper Lake ports in 1907, with rates per ton.

ERRATUM.

The rate stated on page 497, in the last sentence under the heading "Dock to furnace," is incorrect. In 1910 the rate per ton from Lake Erie docks to the Youngstown district was 64 cents, to Pittsburgh $1.04, and to Philadelphia $1.53.

DOCK TO FURNACE.

Still another transportation charge to be added to the ore is that of unloading at the Lake docks and short rail transportation to lower Lake furnaces. From Conneaut and Ashtabula to the furnaces the distance is 50 miles and the charge 50 cents a ton.

TOTAL COST OF TRANSPORTATION.

The average cost of transporting Lake Superior ores to the furnaces during 1907 was $2.14 a ton. When it is remembered that approximately three-fourths of the transportation is done by companies controlling the ore and that this transportation charge contains a considerable profit for the mining companies, the real cost of carrying ore to the furnaces is seen to be considerably lower.

Although the cost of transportation for the ore has been high, on the other hand the furnaces have been located fairly close to the distributing centers for finished materials, so that transportation of the finished material has been correspondingly less. As the center of population has moved westward, the smelting in the vicinity of Chicago has become proportionally more important and the cost of transportation of the ore proportionally less.

METHODS OF MINING.

It is the purpose here merely to mention some of the most elementary features of the mining methods used in the Lake Superior region. The ores in general are taken from the ground by open-pit and underground methods or some combination of them. By far the larger number of mines are underground mines. Most of the open-pit mines (see Pls. XI, p. 180; XLI, *B*) are in the Mesabi district, where, in 1908, 63.7 per cent of the ore was so produced. The production of the Mesabi open-pit mines is so large that, notwithstanding their small number as compared with the total number of mines in the region, they produced, in 1908, 42 per cent of the

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Quantity of ore shipped from upper Lake ports in 1907, with rates per ton.

Port.	Shipped in 1907.	Percentage of total.	Rate per ton to lower lakes.	Rate times percentage carried.
	Tons.			
Escanaba	5,761,988	13.95	$0.60	837
Marquette	3,013,826	7.30	.70	511
Ashland	3,437,672	8.43	.75	633
Two Harbors	8,188,906	19.79	.75	1,485
Superior	7,440,386	18.00	.75	1,350
Duluth	13,445,977	32.00	.75	2,400
	41,288,755	99.47	....	7,216
				72.16

The average cost per ton of transporting all the ore shipped in 1907 from the upper to the lower Lake ports was 72.16 cents.

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It is the purpose here merely to mention some of the most elementary features of the mining methods used in the Lake Superior region. The ores in general are taken from the ground by open-pit and underground methods or some combination of them. By far the larger number of mines are underground mines. Most of the open-pit mines (see Pls. XI, p. 180; XLI, *B*) are in the Mesabi district, where, in 1908, 63.7 per cent of the ore was so produced. The production of the Mesabi open-pit mines is so large that, notwithstanding their small number as compared with the total number of mines in the region, they produced, in 1908, 42 per cent of the entire Lake Superior shipments. Stripping operations in the Mesabi district, taking into account the removal of ore, are far more extensive than the work conducted at the Panama Canal, the total material removed during 1909 in the Mesabi district being 49,750,000 cubic yards as compared with 35,100,000 cubic yards at the Panama Canal.[a]

The underground methods have in common the general use of gravity in milling the ore to lower levels from which it may be trammed to the shaft and then hoisted to the surface. The ores are taken out by square-set rooms running up from sublevels, or by top and side slicing downward from the upper parts of the deposits, or by milling through untimbered chutes to levels below after the surface material has been taken from the top. The cost of this work has ranged from 40 cents to $1.60 a ton, or even higher. An average figure would be perhaps $1 a ton.

The essential feature of open-pit mining is the removal of the surface material and the transfer of the ore directly to railway cars without the intermediate use of the tram or shaft, and without the loss due to leaving pillars. The thickness of drift removed ranges up to 100 feet or more. The general method of work is much more scientific than would at first appear, for it is not a matter of shoveling ore at random onto cars. The character and physical conditions of the deposits are determined by drilling, and the steam-shovel cuts and tracks are distributed so as to reach the desired grades of ore by handling the least possible amount of waste. The possible grades which the mine may produce are ascertained, and when a certain grade is desired by the market the greatest care is taken to extract this grade from the ore body without leaving undesirable ores which must be later moved at a loss. It would be obviously undesirable to take out a high-grade ore and leave a low-grade ore adjacent which could not be sold because of its low grade when by mixing a high and low grade it would be possible to get a medium grade which could be sold. Extreme care is taken to match the different grades in such a manner as to leave them accessible at proper times. The problem is primarily an engineering problem and is worked out by engineers from most careful measurements and calculations. When a request for a certain grade of ore comes to an open-pit mine, orders are sent out to load so many cars from a certain cut and so many cars from another cut, or to make a steam-shovel cut in a certain position; and it is known in advance that the analysis of the ore thus ordered will run very close to that required. The grading of the ore is becoming closer every year. In the utilization of expert engineering help the open-pit mines are fully as far advanced as any other form of mining.

In connection with grading the ore accurate analytical chemical work on a very large scale is necessary. The work of sampling and analyzing the ores, both at the mines and at the works, has been developed to a remarkable degree of accuracy. An illustration of this is shown by the following pairs of analyses, representing the total average of 21,030,909 tons of ore shipped by the Oliver Iron Mining Company from the Lake Superior region in 1909. The average from mine analyses was iron 59.19, phosphorus 0.068, moisture 12.22, silica 6.38; and the average of the same ore as analyzed at the smelting plants was iron 59.04, phosphorus 0.068, moisture 12.33, silica 6.66. This is an exceedingly close check on perhaps the largest piece of quantitative chemical work recorded.

The cost of open-pit work depends primarily on the amount of overburden to be removed and the ratio of this to the size of the ore body. The average cost of loading on the car may be only 4 or 5 cents a ton. The average cost of stripping, however, to uncover a ton of ore may run from 20 to 30 cents. It is obvious that the figure would be small where the drift is thin or where the amount uncovered is large in proportion to the thickness of the cover, so that the cost of surface removal may be charged against a large number of tons. In general the cost of steam-shovel mining has probably averaged less than 30 cents a ton.

With this great difference in cost in favor of the open-pit method of mining, the question may naturally be asked why any of the Lake Superior ores are mined by underground methods. For many of the deposits the answer is obvious. Their larger dimensions are vertical rather

[a] Min. and Sci. Press, vol. 101, 1910, p. 769.

than horizontal, requiring hoisting apparatus to get them to the surface. But even in the Mesabi district 37 per cent of the ores are mined by underground methods and for such mines the reason is perhaps not so obvious. It may be that the drift is too thick; that the topography does not afford a sufficiently gentle slope for the approach of the track; that adjacent land for a proper approach is owned by others; that the deposit may have a considerable amount of low-grade material on top which must be moved before the material of better grade can be obtained. It may be that the company has insufficient financial resources to make the large initial expenditure necessary for the open-pit method before ore is mined or sold, or it may be that the deposit is not sufficiently large in proportion to the expense of preparing it for the open-cut method to warrant piling up this great advance charge against the ore deposit.

It may be noted that the percentage of ore uncovered by open-pit methods is being rapidly increased and that conditions which a few years ago were regarded as insuperable obstacles to open-pit handling are now easily managed. It may be pointed out further that this change in methods has accompanied the combination of mining capital, strong concerns being able to do what the weaker concerns could not attempt.

RATES OF ROYALTY AND VALUE OF ORE IN THE GROUND.

The ores of the Lake Superior region are leased at royalties ranging from 10 cents to $1.35 a ton. The average for the region is somewhere between 30 and 50 cents a ton. The higher figures appear in the later leases. The Mesabi range has the highest general average of royalties. Here the Oliver Iron Mining Company pays the J. J. Hill ore interests a royalty of 85 cents a ton on a minimum of 750,000 tons for 1907; this minimum to be increased by 750,000 tons annually until it reaches 8,250,000 tons a year, after which it remains constant, the royalty to increase 3.4 cents a ton per year for ore carrying over 59 per cent in iron.

The royalty rate practically measures the value of the ore in the ground to the fee owner. The fee owner demands on an average as high a price as the leaseholder can afford to pay for the ore. On this basis the value of the ore in the ground is between 10 cents and $1 a ton. The value is high in proportion as grade is high and costs of mining and transportation are low. The Minnesota State Tax Commission has adopted an excellent classification of ore reserves, based on compulsory returns from the mining companies, and has valued the ores for purposes of taxation at 8 to 33 cents a ton, this valuation being 40 per cent of what is regarded as the real value. The tax-commission figures would therefore indicate that the value of the ore in the ground is from 20 to 75 cents a ton in Minnesota.

The present cash value of a ton of ore is obviously less than the value which will ultimately be realized from royalty after a period of years. If it be assumed, for instance, that the ore must lie in the ground 15 years before the royalty is received, its present cash value would be roughly 42 per cent of its ultimate royalty value.

ORIGIN OF THE ORES OF THE LAKE SUPERIOR PRE-CAMBRIAN SEDIMENTARY IRON-BEARING FORMATIONS.

OUTLINE OF DISCUSSION.

Under the above heading are included all the productive pre-Cambrian ore deposits of the Lake Superior region. It is proposed to show in the following discussion—

That these iron ores are altered parts of chemically deposited sedimentary formations, originally consisting mainly of cherty iron carbonate and greenalite.

That a few of the iron-ore deposits represent originally rich layers of iron formation, in which secondary concentration has made only minor changes.

That in by far the greater number of deposits, including all the larger deposits, the secondary concentration has been the essential means of enriching iron-formation layers to iron ores.

That the conditions of sedimentation of the iron formation may be roughly outlined.

That the weathering and erosion of bed-rock surfaces of average composition would be inadequate as a source of the materials of the iron-bearing sediments, and that the materials for these formations have been derived largely from basic igneous rocks.

That some parts of the sedimentation accompanied or immediately followed the several introductions of pre-Cambrian basic igneous rocks into the outer zone of the earth and another part came under ordinary weathering conditions later than the extrusions of the parent basic igneous rocks.

That the chemistry of deposition of the iron-bearing formations under such conditions may be approximated and that original phases of the sedimentary iron-bearing formations may be synthesized in the laboratory.

That the subsequent oxidation of the iron-bearing formations, the transfer of iron salts, and the leaching of silica by agents carried in the meteoric waters have secondarily concentrated the ores and developed all but an insignificant portion of the ore deposits now mined.

That this second concentration has been localized by a considerable variety of structural and topographic conditions.

That in some places before and in other places after concentration the iron-bearing formations have been extensively modified by mechanical deformation or by igneous intrusions, with contact effects such as to prevent the further concentration of ore deposits.

That the sequence of events developing the present features of the ore deposits may be outlined for each district and for the region as a whole.

That the development of the ores in general represents a partial metamorphic cycle.

THE IRON ORES ARE CHIEFLY ALTERED PARTS OF SEDIMENTARY ROCKS.

The iron-bearing formations are bedded and locally cross-bedded. The Huronian iron-bearing formations are conformable to other sedimentary formations—quartzite, conglomerate, slate, and limestone—and are not different from those of the Keewatin, which are associated with but little fragmental sediment. They contain recognizable sedimentary material, such as iron carbonate, greenalite, shale, sand, and conglomerate. We may anticipate our discussion of the secondary alterations of the ores by stating that the original constituents of the iron-bearing formations were dominantly cherty iron carbonate and iron silicate (greenalite), with minor amounts of hematite and magnetite and with varying amounts of the constituents of the mechanical sediments—mud, sand, and gravel. In tracing the development of the iron-bearing formations we must therefore inquire principally into the derivation of the cherty iron carbonate and greenalite. These two substances are nonclastic, though locally some clastic material appears in them; as will be shown later, they are chemical sediments.

The sedimentary nature of the iron-bearing formations scarcely needs more elaborate proof. It is so obvious in the field that it has been doubted by only three geologic observers. Whitney, Wadsworth, Winchell, and Hille have held these formations to be of surface igneous origin (see pp. 569–570), but as these views are not now regarded seriously by most men who have studied the subject, and as they have been abandoned by Wadsworth, it will be unnecessary here to marshal evidence against them.

CONDITIONS OF SEDIMENTATION.

IRON-BEARING FORMATIONS MAINLY CHEMICAL SEDIMENTS.

The iron-bearing formations are regarded mainly as chemical sediments (1) because they consisted originally of iron carbonate and ferrous silicate and possibly some iron oxide, similar to substances known elsewhere to be deposited as chemical sediments; (2) because they may be synthesized in the laboratory by the simple chemical reagents which were probably present where the iron-bearing rocks were formed; and (3) because they usually lack fragmental particles. To a minor extent they are fragmental sediments derived from the erosion of earlier iron-bearing and other formations.

ORDER OF DEPOSITION OF THE IRON-BEARING SEDIMENTS.

The greater mass of the Keewatin iron-bearing rocks, as exhibited in the Vermilion district, lies above the Keewatin basalts and porphyries and is infolded with them. Another part is interbedded with the basaltic flows. This general association is believed to hold as a rule for the Keewatin of the pre-Cambrian shield of North America. The Keewatin iron-bearing formations are in beds of limited and irregular extent and thickness. It is concluded that the deposition of a few feet of iron-bearing sediments directly in shallow depressions bottomed by basalt was followed by the superposition of another lava flow, and this in turn by more iron-bearing sediments, and so on. Later, when the outflow of lava practically ceased, the main mass of the iron-bearing formation was deposited. Locally a little fragmental material went down immediately upon the basalt basements before iron deposition began.

The deposition of the middle Huronian, containing the iron-bearing Negaunee formation of Michigan, began with a coarse conglomerate and sandstone (Ajibik quartzite), changing somewhat gradually into a mud (Siamo slate), and this in turn into a chemically deposited iron-bearing formation (Negaunee). In the Cascade or Palmer portion of the Marquette range fragmental quartz sand and ripple marks are conspicuous in the iron-bearing formation. South of the Marquette district the fragmental beds underlying the Negaunee formation are thin or lacking. In certain districts the iron formation is replaced over large areas by basic volcanic rocks (Clarksburg and Hemlock formations and perhaps others unknown). In general, then, during middle Huronian time local sedimentation of sand and clay was followed by more widespread deposition of chemical iron-bearing sediments lacking fragmental material and by simultaneous igneous flows.

The iron-bearing formations of the upper Huronian are the most widespread of the pre-Cambrian. Quartz-sand deposition (Pokegama quartzite, Palms formation, and Goodrich quartzite) was followed suddenly by the widespread deposition of chemical iron-bearing sediments (Biwabik, Ironwood, Bijiki, Vulcan, etc.), with very insignificant amounts of clastic material, and this in turn gave way somewhat gradually to the deposition of mud of probable delta origin (see pp. 612–614) in masses so thick that the thin iron-bearing formations and quartzites previously deposited may be regarded as forming the lower selvage of a mud formation. Thin slate layers and a few quartzite layers are interbedded with the upper Huronian iron-bearing formations, especially in their upper portions, and the formations locally show a tendency to be replaced along the strike by slate, as in the Mesabi, Gogebic, and Menominee districts. In the Menominee district slate divides the iron-bearing formation, and in addition there are considerable quantities of fragmental quartz sand, iron oxide, and ferruginous slate near the base of the iron-bearing formation.

In the Crystal Falls, Florence, Iron River, and Cuyuna districts the ore is in siderite lenses in the upper Huronian slate, and the basal fragmental quartzite has been only locally recognized. These occurrences are apparently farther from the base of the formation than those in the Mesabi, Gogebic, Felch Mountain, and Menominee districts, where quartz sand, iron-bearing formation, and slate were successively deposited as distinct formations.

On the south side of Lake Superior, in the western Marquette, eastern Gogebic, and northwestern Menominee districts the deposition of the upper Huronian iron-bearing formations was interrupted by the contemporaneous extrusion of great masses of submarine ellipsoidal basalts. These extrusions may have been more extensive than now appears, because evidence of them may be buried or may have been removed by erosion.

ARE THE IRON-BEARING FORMATIONS TERRESTRIAL OR SUBAQUEOUS SEDIMENTS?

It is believed that the iron-bearing formations are subaqueous for the following reasons:

1. They were originally ferrous compounds in major part. Terrestrial sedimentation usually produces ferric oxides—hematite or limonite and laterite, except in bogs—and reasons are advanced elsewhere to show that only a part of the Lake Superior iron-bearing formations may be so developed.

2. The middle and upper Huronian iron-bearing formations are parts of sedimentary groups containing quartzites and slates of probable subaqueous origin. The slates are essentially delta deposits.

3. All the iron-bearing formations are associated with basalts having conspicuous ellipsoidal structures, which can be best explained as developed by flowing out under water. They contrast in this regard with the basic lavas of the Keweenawan series.

4. Between the underlying basalts, which are probably subaqueous extrusions, and the iron-bearing formations in the Keewatin series neither weathering nor erosion has taken place except very locally. The two are conformable.

BOG AND LAGOON ORIGIN OF PART OF THE IRON-BEARING ROCKS.

The iron-bearing members of the Crystal Falls, Iron River, and Cuyuna districts are associated with slates of probable delta origin, which near the iron-bearing rocks are so uniformly black and graphitic and generally pyritiferous that black slate is usually regarded as a favorable indication in prospecting for ore. Much black slate in the upper Huronian is not associated with the iron-bearing formations, but ore is almost never found without the black slate. The iron-bearing rocks in such associations with black slate are originally carbonate. Smaller amounts of graphitic slates are found also in connection with the Keewatin iron-bearing formations. The thicker iron-bearing formations of the Mesabi, Gogebic, Marquette, and Menominee districts are associated with black slates to a less degree.

It is suggested elsewhere that some of the slates most abundantly associated with the iron-bearing formations may represent delta deposits, and that the carbon content of the iron formations is probably to be explained as organic. So far as direct evidence is concerned, the organic origin of the graphite and sulphides in the black slates, notwithstanding its probability, should not be regarded as proved, although there is no reason to doubt such an origin. Similar associations elsewhere, as in the Carboniferous, have been shown to be truly of organic origin. On the other hand, in the Lake Superior black slates, as in all other Lake Superior pre-Cambrian formations, no organic forms have been found.

These facts raise the question whether the carbon of the slates may not have been effective in the original deposition of the iron-bearing formations, as bog or lagoon deposits, in the manner of Carboniferous and Cretaceous carbonates—that is, by the progressive burial of ferric oxide with organic material, resulting in the reduction of the oxide and the formation of iron carbonate. The way in which reducing organic substances aids in dissolving and transporting iron salts is discussed on pages 519–520.

This is probably the origin of the discontinuous carbonate lenses in the carbonaceous slates of probable delta origin in the upper Huronian, but difficulties appear when we attempt to explain in the same way the main, thick, continuous masses of iron-bearing formation of the Keewatin, middle Huronian, and upper Huronian.

HYPOTHESIS OF BOG AND LAGOON ORIGIN NOT APPLICABLE TO THE MAIN MASSES OF THE IRON-BEARING SEDIMENTS.

The main masses of the iron-bearing sediments are not closely associated with carbonaceous slates; they are not characteristically discontinuous or lens-shaped, but are extensive and thick; they rest with sharp contacts on quartzite, conglomerate, or basalt. The Lake Superior iron-bearing formations also carry more chert than deposits of known bog origin of the carbonate type.

The bog theory of origin involves the assumption that the Lake Superior region may have been, during each of the iron-depositing periods, covered by great bogs or lagoons in which vegetable matter could grow at or near the surface of the water over great areas, as in lagoons in advance of barriers thrown up by the sea encroaching over a gently sloping surface, or under delta conditions. As a process necessarily confined to a shallow zone near the surface, its continuous operation would involve continuous and uniform subsidence at a rate commensurate with the deposition of the iron salts in order to produce the thicknesses now known. Although this theory is probably applicable to some of the thin lenses of small extent associated with carbonaceous slates, it is not clear how this process could produce a thousand feet of iron-bearing sediments showing uniformity of lithology and bedding and having so little extraneous material through hundreds of square miles.

HYPOTHESIS OF GLAUCONITIC ORIGIN NOT APPLICABLE.

The greenalite of the iron-bearing formations of the Mesabi and other districts is so similar to glauconite as to suggest similarity in conditions of origin—that is, as fillings of cavities in or replacements of Foraminifera in deep-sea deposits. Dredgings have brought up glauconite from deep and quiet waters but not from places of rapid sedimentation. No glauconite is known with so little foreign material as the greenalite beds of the iron-bearing formations. The thickness of the deep-sea glauconite beds is not known. In geologic sections the thickest known deposit is 35 feet. The deposition of 1,000 feet of greenalite beds in the same manner as glauconite is known to be deposited would require a development of Foraminifera in the pre-Cambrian not known in any other geologic period.

IRON-BEARING SEDIMENTS NOT LATERITE DEPOSITS.

In many parts of the world, especially in tropical climates, there are bedded iron ores of the laterite type, presumed to develop from the katamorphism of basalt or other basic igneous rock in place. They are characteristically associated with bauxite, clay (lithomarge or bole), usually resting on it. Gradational types between lateritic iron ore and igneous rock have been described. The Lake Superior iron beds associated with basalts can not in any considerable part be referred to decomposition of the basalt in place after the manner of laterite deposits; the almost complete absence of clay associated with the iron ores and the presence of abundant chert preclude this explanation. Although lateritic decomposition of basalt surfaces may have been an ultimate partial source of the iron ore, transportation and sorting have eliminated the clay, which would be present if the iron beds resulted from lateritic decomposition. The principal impurity in the Lake Superior iron is silica. This could not have developed from decomposition of the basalt in place.

In reading accounts of the origin of iron beds associated with basalts in different parts of the world,[a] one notes a tendency to ascribe a lateritic origin to the iron beds, even in places where the iron lacks the associated clay to be expected from such a mode of origin. It would seem necessary at least to introduce the factors of sorting and transportation to explain these ores. Clay is as stable as iron oxide under surface conditions, and so far as quantitative evidence goes, it remains with the residual iron oxide in a more or less uniform proportion throughout a cycle of decomposition.

Finally the evidences of water sedimentation and physical separation of most of the iron formations and basalts are not in accord with the hypothesis of lateritic origin.

IRON-BEARING SEDIMENTS NOT CHARACTERISTIC TRANSPORTED DEPOSITS OF ORDINARY EROSION CYCLES.

The oxidized carbonate lenses associated with the graphitic slates (see p. 501) may be regarded as one of the incidental results of a normal erosion cycle. The fragmental bases of the Vulcan formation in the Menominee district, of the Bijiki schist in the Marquette district, and of the Cretaceous rocks in the Mesabi district contain a great deal of detrital ferruginous chert and iron ore derived from the breaking up of iron-bearing rocks that lie unconformably below, but all these phases of the iron-bearing rocks are of minor importance as compared with the thick masses of iron-bearing formation derived from the alteration of iron carbonate and greenalite rocks.

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[a] Cole, G. A. J., The red zone in the basaltic series of the county of Antrim: Geol. Mag., decade 5, vol. 5, No. 530, 1908, pp. 341-344.

1. It has long been recognized that there are difficulties in the way of explaining the thick and uniform masses of chemical sediments constituting the thicker iron-bearing formations, accompanied by so little mechanical sediment, on the assumption that the iron-bearing formations have been derived from the weathering of average land areas. If the peculiar character of chemical sediments depends on depth of water and distance from the shore, then the great thickness of the formations involves uniform subsidence over a great area to keep the conditions uniform.

2. The iron-bearing formations may or may not be associated with ordinary clastic sediments. In the Keewatin they usually are not. The middle Huronian consists, from the base up, of quartzite, slate, and iron-bearing formation. The upper Huronian where best exposed consists of quartzite, iron-bearing formation, and slate. The association of the Keewatin iron-bearing formations with extrusive basalts and not with other sediments shows that the iron ores of the Keewatin, at least, are not the result of deposition in any ordinary cycle of erosion and deposition, and this strongly suggests that the variety of succession in the sedimentary iron-bearing formations of the Huronian is also not due to ordinary cycles of erosion and deposition, and that the deposition of the iron-bearing formations probably was not uniformly related to sea transgression or recession or any other one phase of a topographic cycle.

The fact that in many places the sediments above and below the Huronian iron-bearing formations are different is the only feature which suggests that the deposition of iron-bearing sediment is a part of a cycle of erosion and deposition, though it is conceivable that volcanism itself would cause this change, either by effecting changes of levels of land and water or by introducing new rocks for erosion to work upon.

Until investigation has disclosed all the different combinations of factors which may produce a particular order of sedimentation, it is unsafe to be too positive in concluding that the varied relations of the iron-bearing formations to the order of sedimentation indicate their deposition under exceptional conditions. The conditions producing alternations of iron-bearing sediment with other sediments in varying succession may not be necessarily different from those favoring the deposition of limestone with a variety of associations—for instance, the Paleozoic limestones, which in some places overlie sand and in others mud and are in turn followed by sand or mud. But the lack of uniformity in the relations of the iron-bearing formations above noted is taken to indicate a probability that conjunction of their deposition with a certain phase of a topographic cycle is not an essential condition to their development.

3. Were the iron-bearing formations derived from the weathering of the older rocks against which they lie, it would be difficult to explain the complete absence of weathered material between certain bands of Keewatin iron-bearing formations and the associated basalts, or of erosion irregularities in the underlying surface.

4. The surface streams are only locally carrying iron in quantity at the present time. All available analyses of river waters show a lack of iron, with the exception of minute quantities in Ottawa and St. Lawrence rivers. Many of the springs carry iron, but this is conspicuously deposited at the point of escape and does not join the run-off. These facts are correlated with known observations of the manner of weathering of rocks. The ferrous iron becomes oxidized and, next to alumina, is the most stable of all substances under surface conditions. In fact, so little iron is lost by weathering that Merrill, Watson, and others have used both iron and alumina as a basis against which to measure the loss of other constituents.

5. If it is regarded as possible that the iron-bearing formations are derived from the weathering of ordinary land surfaces, why should the iron-bearing formations not be reproduced on the same scale in the Paleozoic rocks, which were deposited on pre-Cambrian rocks similar to those beneath the iron-bearing formations? The deposition of the Paleozoic rocks was preceded by perhaps the longest period of weathering of which there is record in the Lake Superior country. In many parts of the United States Paleozoic and later sediments contain thin beds of sedimentary iron-bearing formation, but these beds are at their maximum insignificant in thickness as compared with those of the Lake Superior region.

6. A comparison of the composition of the iron-bearing series with the possible sources from which they might be derived by ordinary weathering further shows that the iron is present in higher percentage in the iron-bearing formations than in the rocks from which they may have been so derived.

The jaspers of the Keewatin series of the Vermilion district average between 28 and 38 per cent in iron, but the associated basalts average 9.56 per cent. The jaspers have little other sedimentary material with them to be figured in this comparison. Therefore the jaspers probably derived their iron from some other source than the weathering of the adjacent basalts, or the complementary fragmental detritus was washed away.

The middle Huronian, containing the iron-bearing Negaunee formation, has an average iron content of 11.72 per cent, as indicated by the available figures of composition of the three formations of the middle Huronian and their relative thickness. Because of the unconformity at the top there is a question as to what factor should be added for materials that have been eroded, but there is no evidence that any large amount of material has been taken away, and as part of the material which has been removed belonged to the iron-bearing formation, this factor can not be assumed to cause much change in the figures given.

The composition of the rocks of the ancient land area from which the middle Huronian may have been derived by weathering is not definitely known, but it may be supposed to be not far from the average given by Clarke[a] for igneous and crystalline rocks, in which the iron content is 4.46 per cent. Were the shore made up of basic rocks such as the Kitchi schist or Mona schist the iron content would be about 9 per cent. It is thus apparent that, whether we regard average igneous rocks or basic rocks as representing the original land from which the middle Huronian may have been derived by weathering, the sediments contain a considerable excess of iron not accounted for.

The iron content of the upper Huronian of the Mesabi and Gogebic districts ranges from 6 to 9 per cent, depending on the thickness of slate which is chosen for the calculation. The smallest percentage is higher than that of the average igneous rock that may be supposed to represent the land area from which these sediments were derived. The highest is about equal to the percentage of iron in the greenstones.

In general, then, if it is assumed that all of the iron of the ancient land areas was transferred and contributed to the iron-bearing formations that were being deposited in neighboring submerged areas (which, as above shown, it was not), this would not be enough to account for the iron in the iron-bearing rocks when the associated sediments are taken into account and allowance made for complementary sediments deposited elsewhere.

The major part of the iron of the iron-bearing formations was originally deposited as a chemical sediment from solution. In view of the fact that in weathering only a small proportion of the iron present is observed to be carried off in solution, the rest remaining as insoluble ferric oxide, it becomes even more apparent that the iron-bearing formations were not derived by chemical solution and deposition of the materials of average land areas. A similar conclusion is to be drawn from the silica content in the iron-bearing formations.

Silica of course is derived abundantly from the weathering of rocks in cold solutions and is precipitated principally in the form of chert in limestones. The part mechanically carried is deposited as quartz sand, differing in texture from the chert. The latter mode of derivation is practically excluded for the iron-bearing formations of the Lake Superior region because they contain only small amounts of fragmental quartz at a few localities and horizons. If we attempt to ascribe the cherts of the iron-bearing formations to weathering, we may look only to the silica carried in solution. To have produced the thick iron-bearing formations containing an average of about 70 per cent by volume of chert, the solution of silica must have proceeded on an enormous scale, probably too large to be explained by ordinary weathering. That some chert was so derived, just as some iron and some fragmental quartz were so derived, is altogether likely, and it would be difficult to prove the contrary. The percentage of chert in the iron-bearing groups described on page 461 ranges upward from 63 per cent in weight,

[a] Clarke, F. W., The data of geochemistry: Bull. U. S. Geol. Survey No. 330, 1908, p. 26.

while Clarke's average of igneous and crystalline rocks, which might represent the composition of an average surface under weathering, is a little less than 62 per cent in silica and the basic greenstones contain less than 50 per cent in silica. Hence, even if all the silica had been leached (together with the iron) from these rocks (which never happens), it would not yield a percentage of silica as large as that known in the iron-bearing groups. Organic agencies might localize precipitation of silica in certain areas, but not enough to account for existing proportions over the entire region.

The calcium-magnesium content furnishes still another argument. In the average crystalline or igneous rocks or in the basic igneous rocks or in sediments derived from the igneous rocks, calcium preponderates over magnesium, but in the iron-bearing formations the average proportion of magnesium to calcium is over 5 to 1.

It appears in general that the composition of the pre-Cambrian sedimentary groups containing the iron-bearing formations differs from that of the average crystalline rocks which formed the shores at those periods in having a higher content of iron and silica and in having a different calcium-magnesium ratio. It might be that the extensions of these iron-bearing sedimentary groups outside of the Lake Superior region would be of such different composition as to bring the average more nearly down to what would be expected from derivatives of the crystalline rocks. Yet it is believed that the excess of certain constituents in the Lake Superior sedimentary groups that carry the iron-bearing formations over those which seem to have been probably available from ordinary weathering is not counterbalanced by corresponding deficiencies elsewhere, for the reason that the sections on which these figures are based are taken through a wide area in the Lake Superior region, and for the further reason that this peculiar composition is repeated over this wide area in the rocks of three successive geologic epochs. If the occurrence of iron-bearing formations in the Lake Superior region is simply a matter of areal segregation and concentration of the normal products of weathering, it is very remarkable that this areal concentration should always have resulted in bringing these peculiar iron-bearing phases in the same region. We conclude, therefore, that the excess of iron and silica and the reversal of the calcium-magnesium ratio in the sedimentary groups carrying the iron-bearing formations, as compared with the average crystalline rocks from which they might have been derived by erosion, is probably to be regarded as evidence that some unusual source of material was available.

7. It appears, then, from the foregoing paragraphs that there are objections to regarding the iron-bearing formations entirely as sediments produced by weathering of the rocks that were most abundant in the adjacent lands. It is not meant to imply that ordinary erosion and katamorphic processes which are known to segregate iron-bearing sediments were set aside in this region. Indeed, as already indicated, there is definite evidence that some of the iron-bearing sediments were so produced. But it seems that these processes are not adequate to explain the facts. In character and size the iron-bearing formations are unique as chemical sediments and differ from other chemical sediments derived by normal weathering processes. Some unusual and additional factor seems to be required to explain them. Such a factor is discussed under the following headings.

ASSOCIATION OF IRON-BEARING SEDIMENTS WITH CONTEMPORANEOUS ERUPTIVE ROCKS.

All the Lake Superior iron-bearing formations are more or less closely related in time and place to basalt flows, usually rich in iron at present and giving evidence of having exuded iron salts at the time of their consolidation. The iron-bearing formations of the Keewatin series have such relations to the associated ellipsoidal basalts as to point to their deposition in the short periods separating the successive flows of basalt or immediately following the principal extrusions. Detailed evidence of this has been noted in a number of places and especially in the Vermilion district. (See pp. 126–127.) The Negaunee formation of the middle Huronian is associated with abundant contemporaneous igneous activity, producing ellipsoidal basalts of submarine origin and other extrusive rocks similar to those in the Keewatin series in many places in the Marquette district, especially at the west end (the volcanic Clarksburg formation), and in the Crystal Falls and adjacent districts (the Hemlock formation). The iron-bearing formations of the upper Huronian (Animikie group) are associated with igneous activity similar to that of the preceding periods in the Marquette district (the Clarksburg formation), in the Gogebic district (the volcanic rocks of the east and west ends of the district), and in the Menominee, Florence, and Iron River districts. The iron-bearing formation of the Animikie group on the north shore of Lake Superior is not associated with basic greenstones of known contemporaneous development, but as shown on pages 213–214 there is little doubt of its direct continuity with the rocks of the Cuyuna district and the upper Huronian of the south shore, which are associated with basic volcanic rocks.

Especially remarkable are the evidences of the close association of iron-bearing sediments and basaltic flows in the upper Huronian of Michigan. Here ellipsoidal basalt, basalt tuffs, and ashes are so intermingled with the iron-bearing formation and stained by secondary alteration that there is difficulty in discriminating them. Recent work has shown the existence of more of the igneous rocks than had before been suspected. Drill holes in the Iron River and Amasa areas of Michigan pass through igneous beds from 2 to 50 feet thick in the midst of the iron-bearing formation. In these places the eye can scarcely detect the break between the grayish and greenish carbonate slates of the iron-bearing sediments and the fine-grained greenish basalts and tuffs. Under the microscope the surface of contact is seen to be an extremely irregular one, the carbonate apparently irregularly replacing part of the greenstone. This replacement has not been accompanied by any oxidation. It is found in drill holes hundreds of feet beneath the surface, apparently in an association determined at the time of the deposition of the iron-bearing formation. In the Keewatin of the Vermilion district of Minnesota similar close association may be observed between the jaspers and the basalts. (See Pl. XLVIII, p. 564.)

The significance of the apparent gradation of carbonate of iron and silica and their alteration products into the greenstone is not yet fully apparent. It can scarcely be doubted that this relation was developed at the time of the deposition of the iron-bearing formation, probably soon after the extrusion of the igneous rocks. It is suspected that these phases represent a transition between reactions associated with the hot igneous masses and the normal precipitation of a sedimentary formation. Attempt has been made in the laboratory to reproduce these remarkably close relations by some combination of igneous and sedimentary processes, but thus far without successful results.

Probably of significance in connection with the derivation of the iron-bearing formations is the fact that in many places acidic intrusive and extrusive rocks of the porphyry type closely follow extrusive basalts and are locally even more closely associated with the iron-bearing formations than the basalts themselves. This relation is well illustrated in the Vermilion district, where, in a series of interbedded basalt flows, jaspers, and amygdaloidal porphyries, the igneous rock immediately next to the jaspers is commonly porphyry as well as basalt. (See fig. 13, p. 123.) Similar conditions appear in the Woman River district of Ontario [a] and elsewhere. It is suspected that this relation is more general than is yet known. (See p. 513.)

The amount of igneous material extruded is not measured by the areas of upper Huronian volcanic rocks now exposed, for extensive extrusive rocks were undoubtedly present in parts of the formation that have been removed by erosion and exist in parts not yet uncovered. It is suggested in the chapter on the Keweenawan (Chapter XV) that the present shore of the Lake Superior basin was the locus of the extrusion of the Keweenawan igneous rocks. If the basin began to form in Animikie time, as is thought possible (see pp. 622–623), a similar suggestion, for similar reasons, might be made for the Animikie group, in which case the north shore Animikie may really not be so distant from igneous rocks as now appears. The iron-bearing formation of the Animikie group of the north shore is thus associated in time with igneous extrusions, but may be somewhat distant in place.

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[a] Allen, R. C., Iron formation of Woman River area: Eighteenth Ann. Rept. Ontario Bur. Mines, pt. 1, 1909, pp. 254–262.

The deposition of the lower Huronian was not accompanied by basic flows, and it does not contain a well-developed iron-bearing formation. The Paleozoic of the Lake Superior region lacks basic igneous rocks and also lacks iron-bearing formations like those of the pre-Cambrian.

ASSOCIATION OF IRON-BEARING SEDIMENTS AND ERUPTIVE ROCKS OUTSIDE OF THE LAKE SUPERIOR REGION.

The derivation of the iron-bearing formations from the associated igneous rocks is suggested by the close association of these rocks not only in the Lake Superior country but in other parts of the world.

Practically all the numerous iron-bearing sediments extending through the Height of Land country of Canada, as far east as the Quebec boundary, are interbedded with basalt flows. Most of these belts, in the writers' judgment, belong in the Keewatin.

On the east coast of Hudson Bay there are younger Algonkian rocks containing an iron-bearing formation, interbedded with fragmental sediments and ellipsoidal basalts. As Low [a] had called attention to the similarity of these iron-bearing sediments to those of the upper Huronian or Animikie of the Lake Superior region, the junior author visited them in 1909 and found a very close similarity, even to the possession of carbonate and greenalite phases. Freedom from vegetation and precipitous shores afford fine exposures for study. Fragmental sediments of the type now being formed along the shores are interbedded with extrusions of ellipsoidal basalt which give evidence by their textures and associations of having been extruded along tidal flats, and by their high content of jasper and magnetite of having been rich in iron salts at the time of their extrusion. Immediately following the basalt comes the iron-bearing formation, closely associated with volcanic muds. It requires no preconceived hypothesis to lead the observer to the view that the extrusion of the igneous rocks was the variant in the normal conditions of sedimentation necessary to produce the iron-bearing formations. The story is so clear that it is possible to outline the probable conditions of sedimentation in some detail.[b]

Geikie [c] remarks concerning lower Carboniferous basalts of the Fife coast:

> These lavas are thin sheets, often not more than 15 or 20 feet in thickness, and they, as well as the associated tuffs, are intercalated among shallow-water deposits, such as cyprid shales and limestones, coal seams with fire clays, thin sandstones, and ironstones. Some of the basalts have caught up portions of the mud on the sea bottom, but in others the muddy, sandy, or ashy sediment of the next deposit has fallen into the interspaces between the pillows.

He also says [d] concerning the basaltic lavas of County Tyrone, Ireland:

> These greenish lavas are occasionally interleaved with gray flinty mudstones, cherts, and red jaspers, which are more particularly developed immediately above. In lithological character, and in their relation to the diabases, these siliceous bands bear the closest resemblance to those of Arenig age in Scotland, but no recognizable Radiolaria have yet been detected in them.

Describing the Carboniferous volcanoes of the Isle of Man, Geikie [e] says:

> Pauses in the succession of eruptions are marked by the intercalation of seams of limestone or groups of limestone, shale, and black impure chert. Such interstratifications are sometimes curiously local and interrupted. They may be observed to die out rapidly, thereby allowing the tuff above and below them to unite into one continuous mass. They seem to have been accumulated in hollows of the tuff during somewhat prolonged intervals of volcanic quiescence, and to have been suddenly brought to an end by a renewal of the eruptions. There are some four or five such intercalated groups of calcareous strata in the thick series of tuffs, and we may regard them as marking the chief pauses in the continuity or energy of the volcanic explosions.

Again, Geikie [f] states that in the Carboniferous volcanoes of Devonshire—

> Bands of black chert and cherty shale are interpolated among the tuffs, which also contain here and there nodular lumps of similar black impure earthy chert—an interesting association like that alluded to as occurring in the Carboniferous volcanic series of the Isle of Man, and like the occurrence of the radiolarian cherts with the Lower Silurian volcanic series.

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[a] Low, A. P., Report on an exploration of the east coast of Hudson Bay from Cape Wolstenholme to the south end of James Bay: Ann. Rept. Geol. Survey Canada, vol. 13, new ser., pt. D, 1903, pp. 45–46.

[b] Leith, C. K., An Algonkian basin in Hudson Bay—a comparison with the Lake Superior basin: Econ. Geology, vol. 5, 1910, pp. 227–246.

[c] Abstracts Proc. Geol. Soc. London, session 1907–8, London, 1908, p. 42.

[d] Geikie, Archibald, Ancient volcanoes of Great Britain, vol. 1, London, 1897, pp. 240–241.

[e] Idem, vol. 2, 1897, p. 24.

[f] Idem, vol. 2, 1897, p. 36.

The following section in Tertiary volcanoes of the Antrim Plateau of Ireland is described by the same author:[a]

Upper basalt, compact and often columnar sheets.
Brown laminated tuff and volcanic clays.
Laminated brown impure earthy lignite, 2 feet 3 inches.
Brown and red variegated clays, tuffs, and sandy layers, with irregular seams of coarse conglomerate composed of rounded and subangular fragments of rhyolite and basalt, 3 feet 4 inches.
Brown, red, and yellowish laminated tuffs, mudstones, and bole, with occasional layers of fine conglomerate (rhyolitic and basaltic), pisolitic iron-ore band, and plant beds, 8 feet 10 inches.
Lower basalt, amygdaloidal.

* * * * * * * * *

The pale and colored clays that occur in this marked sedimentary intercalation have doubtless been produced by the decomposition of the volcanic rocks and the washing of their fine detritus by water. Possibly this decay may have been in part the result of solfataric action. * * *

* * * The original area over which the iron ore and its accompanying tuffs and clays were laid down can hardly have been less than 1,000 square miles. This extensive tract was evidently the site of a lake during the volcanic period, formed by a subsidence of the floor of the lower basalts. The salts of iron contained in solution in the water, whether derived from the decay of the surrounding lavas or from the discharges of chalybeate springs, were precipitated as peroxide in pisolitic form, as similar ores are now being formed on lake bottoms in Sweden. For a long interval quiet sedimentation went on in this lake, the only sign of volcanic energy during that time being the dust and stones that were thrown out and fell over the water basin or were washed into it by rains from the cones of the lava slopes around.

Concerning the Tertiary volcanoes of the plateau of Small Isles, Geikie[b] writes:

It is a noteworthy fact that the sedimentary intercalations among the Canna basalts generally end upward in carbonaceous shales or coaly layers. The strong currents and overflows of water, which rolled and spread out the coarse materials of the conglomerates, gave way to quieter conditions that allowed silt and mud to gather over the water bottom, while leaves and other fragments of vegetation, blown or washed into these quiet reaches, were the last of the suspended materials to sink to the bottom.

The Arenig eruptions in the Silurian of North Wales contain interesting sediments, described by Geikie[c] as follows:

Many of the tuffs that are interstratified with black slates (? *Lingula* flags) at the foot of the long northern slope of Cader Idris consist mainly of black-slate fragments like the slate underneath, with a variable proportion of gray volcanic dust. * * *

One of the most interesting deposits of these interludes of quiescence is that of the pisolitic ironstone and its accompanying strata on the north front of Cader Idris. A coarse pumiceous conglomerate with large slaglike blocks of andesite and other rocks, seen near Llyn-y-Gadr, passes upward into a fine bluish grit and shale, among which lies the bed of pisolitic (or rather oolitic) ironstone which is so widely diffused over North Wales. The finely oolitic structure of this band is obviously original, but the substance was probably deposited as carbonate of lime under quiet conditions of precipitation. The presence of numerous small *Lingulæ* in the rock shows that molluscan life flourished on the spot at the time. The iron exists in the ore mainly as magnetite, the original calcite or aragonite having been first replaced by carbonate of iron, which was subsequently broken up so as to leave a residue of minute cubes of magnetite.

Radiolarian cherts are characteristically associated with sandstones and basalts, partly ellipsoidal, at Point Bonita,[d] Angel Island,[e] and at many other points in the Coast Ranges of California. In describing the eruptive rocks of Point Bonita, Ransome says:[f]

Spheroidal basalt, apparently similar to that described, has been noted by the writer at Tiburon, Marin County; at Port Harford, San Luis Obispo County; and on the summit of the north peak of Mount Diablo. It is noteworthy that in these widely separated occurrences the rock is always associated with the red jaspers, and with what is apparently the San Francisco sandstone.

These cherts were called "phthanites" by Becker[g] and regarded as due to secondary silicification. Lawson[h] and Ransome,[i] on the other hand, regard them as original siliceous deposits

[a] Geikie, Archibald, Ancient volcanoes of Great Britain, vol. 2, 1897, pp. 204–205.
[b] Idem, vol. 2, 1897, p. 223.
[c] Idem, vol. 1, 1897, pp. 180–181.
[d] Ransome, F. L., The eruptive rocks of Point Bonita: Bull. Dept. Geology, Univ. California, vol. 1, 1893, pp. 71–114.
[e] Ransome, F. L., The geology of Angel Island: Bull. Dept. Geology Univ. California, vol. 1, 1894, pp. 193–240.
[f] Ransome, F. L., The eruptive rocks of Point Bonita: Bull. Dept. Geology Univ. California, vol. 1, 1893, pp. 109–110.
[g] Becker, G. F., Geology of the quicksilver deposits of the Pacific coast: Mon. U. S. Geol. Survey, vol. 13, 1888, pp. 105–108.
[h] Lawson, A. C., Sketch of the geology of the San Francisco peninsula: Fifteenth Ann. Rept. U. S. Geol. Survey, 1895, pp. 420–426.
[i] Ransome, F. L., The geology of Angel Island: Bull. Dept. Geology Univ. California, vol. 1, 1894, p. 200.

which are changed into red jaspers and glaucophanic jaspers here and there at igneous contacts. These cherts locally pass into iron ore and are characteristically associated with manganese beds.[a] The cherts are characterized by minute oval spots found in part to represent radiolarian remains, but in part of unknown origin. Lawson[b] discusses their origin as follows:

It thus seems to the writer that the bulk of the silica can not be proved to be the extremely altered débris of Radiolaria. The direct petrographical suggestion is that they are chemical precipitates. If now we accept this hypothesis, it becomes apparent that there are three possible sources for the silica so precipitated, viz, (1) siliceous springs in the bottom of the ocean, similar to those well known in volcanic regions; (2) radiolarian and other siliceous remains, which may have become entirely dissolved in sea water; and (3) volcanic ejectamenta, which may have become similarly dissolved. The last is the least probable, because we are not actually familiar with such a reaction as the solution of volcanic glass by sea water. Our ignorance is, however, no proof that such solution may not take place under special conditions. * * *

The hypothesis of the derivation of the silica from siliceous springs and its precipitation in the bed of the ocean in local accumulations, in which radiolarian remains became embedded as they dropped to the bottom, seems, therefore, the most adequate to explain the facts, and there is nothing adverse to it so far as the writer is aware. The abundance of the Radiolaria may be due to the favorable conditions involved in the excessive amount of silica locally present in the sea, or simply to the favorable conditions for preservation afforded by this kind of rock. If the springs were strong, the currents engendered might in some places have been sufficient to deflect sediment-laden counter-currents, and this may serve to explain the general absence of clastic material in the chert.

The Pilot Knob deposits of Missouri are interbedded with porphyry flows, tuffs, and ashes, suggesting close genetic relation between igneous rocks and sediments.

Illustrations could be multiplied, but enough have been cited to show that basalts, especially the ellipsoidal phases, are characteristically interbedded with more or less graphitic slates, clays, cherts, jaspers, volcanic tuffs, iron ores, and in places sandstone. Practically all the features of the association of basalt with sediments described for the above-mentioned districts are to be seen in the Lake Superior region. The explanations of these associations in other regions therefore become significant in the study of the origin of the Lake Superior ores.

In general there seems to be little doubt that some genetic relationship exists among surface basalts, carbonaceous slates, cherts, and jaspers, to which attention has been called by several writers working from different standpoints.[c] They agree that most of the carbonaceous materials are organic, that the deposition is largely subaqueous, and that some of the associated iron is deposited partly through the agency of weathering assisted by organic means. Lawson suggests that the cherts and jaspers may be the result of inorganic chemical deposition by hot solutions. In the Lake Superior region the iron-bearing formations are much thicker and they have certain phases, notably the greenalite or ferrous silicate phase, which are not common elsewhere, all these features seeming to favor the hypothesis that the iron formations are in part related to the more or less direct contribution of the iron-bearing materials by hot concentrated solutions from the igneous rocks.

SIGNIFICANCE OF ELLIPSOIDAL STRUCTURE OF ERUPTIVE ROCKS IN RELATION TO ORIGIN OF THE ORES.

The basalts associated with the iron-bearing formations have so commonly the peculiar ellipsoidal or pillow structure that one is led to assume that conditions favorable to the development of the ellipsoidal structure may be also favorable to the deposition of the iron ore in this district. Clements[d] has described the structure in some detail for the Crystal Falls district, and from comparison with occurrences elsewhere concludes it to have been probably a submarine extrusive, similar to the aa lavas of Hawaii described by Dutton.[e] Daly[f] reaches the same

[a] Lawson, A. C., op. cit., pp. 423–424.

[b] Idem, pp. 425–426.

[c] We have received too late for discussion a paper on British pillow lavas and the rocks associated with them, by Henry Dewey and J. S. Fleet (Geol. Mag., vol. 8, Dec. 5, 1911, pp. 202–209, 241–248), emphasizing the genetic association of cherts and ellipsoidal basalts. Albitization of the feldspars of the basalts is regarded as evidence of pneumatolytic emanations, containing soda and silica in solution and possibly other substances. The cherts are deposited by those emanations. This independent conclusion is remarkably in accord with the inferences drawn in this monograph.

[d] Clements, J. M., The Crystal Falls iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 112–124.

[e] Dutton, C. E., Hawaiian volcanoes: Fourth Ann. Rept. U. S. Geol. Survey, 1884, pp. 95–96.

[f] Daly, R. A., Variolitic pillow lava from Newfoundland: Am. Geologist, vol. 32, 1903, p. 77.

conclusion for the variolitic pillow lavas of Newfoundland. Later, from a personal study of Hawaiian volcanoes, Daly[a] regards the ellipsoidal and aa lavas as different, though he is not disposed to question the subaqueous origin of ellipsoidal lavas. Geikie[b] repeatedly cites the probable subaqueous origin of the ellipsoidal structure, based on his observations in Great Britain and Ireland. Clement Reid[c] has recently concluded that the pillow lavas near Port Isaac in Cornwall are of submarine origin, and in the discussion of Reid's paper Geikie[d] remarked that all the examples of pillow lavas with which he was acquainted were undoubtedly true lavas and belonged to submarine eruptions. Some of them, however, must have been poured out in shallow water, as is particularly observable in the case of the lower Carboniferous basalts of the Fife coast. (See quotation on p. 508.)

Fenner[e] concludes that ellipsoidal and other structures in the traps of the Newark group are evidence of flowage of the traps into lakes. He says:

> When we came to examine the lava itself we saw that it carried in its own mass plain evidences of the structural changes which were produced by the presence of the lakes and of the water-bearing strata beneath. Whereas beyond the borders of the lakes the lava was of a close, firm texture and showed a condition of quiet and tranquillity during the process of cooling and hardening, over the area of lake bottom there was evidence of violent agitation having affected it during the initial flows, and rapid cooling and the production of much glassy material during succeeding flows, followed still later by the crystallizing effects wrought by heated waters and the production of secondary minerals.

By others the ellipsoidal structure has been regarded as the result of rapid cooling or rapid flow developing large blocks that have rolled one over another, a process which may have been subaerial or subaqueous, or both. This is the explanation offered by Cole and Gregory.[f] Ransome[g] concludes for the ellipsoidal structure in the basalt of Point Bonita, California, that one sluggish outwelling of lava was piled upon another to form the whole mass of the flow, the blocks or ellipsoids being incidental to the cooling and movement. He makes no reference to submarine or subaqueous origin. Russell[h] observes that the ellipsoidal structure found locally in the Snake River basalts is developed by the flowage of the basalts into lake basins, but concludes[i] that whether the lava develops the ropy or pillow or block structure is determined by—

> the ratio between rate of cooling and the rate of motion. But this ratio is not the same for different lavas. When a lava sheet cools without motion, neither a characteristic pahoehoe nor an aa surface is produced. Many of the older sheets of Snake River lava illustrate this; they are simply plane surfaces, composed of either vesicular or compact granular basalt.
>
> The explanation of the origin of aa adopted above was not accepted by Dana,[j] who suggests that the breaking of a lava crust may be due to moisture derived from the rocks over which lava flows and leading to quicker cooling in certain areas than in others. Such an occurrence, however, even if proved to exert an influence, seemingly introduces a variation into a more general process without supplanting the controlling conditions.

Dr. Tempest Anderson and Dr. Flett[k] describe such structure developing subaerially at Mount Pelee, and Anderson[l] describes it also developing subaerially in Iceland.

The evidence seems to be that the ellipsoidal structure is both subaqueous and subaerial in its development, that it is produced by the rolling of blocks developed during the flow of the lava as a result of cooling, and that its development is therefore determined by the speed of flow and the rate of cooling, which in turn may be affected by entrance into water. Where associated with sediments, the structure seems to be with little doubt subaqueous in origin, as concluded by Geikie. In the Lake Superior region the interbedding of ellipsoidal basalts with sediments of subaqueous origin, according well with the associations of basalt flows and sedimentary rocks that are observed elsewhere, seems to be adequate evidence that the

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[a] Verbal communication.

[b] Geikie, Archibald, Ancient volcanoes of Great Britain, London, 1897.

[c] Reid, Clement, and Dewey, Henry, The origin of the pillow lava near Port Isaac in Cornwall: Abstracts Proc. Geol. Soc. London, session 1907-8, London, 1908, p. 42.

[d] Idem.

[e] Fenner, C. N., Features of trap extrusions in New Jersey: Jour. Geology, vol. 16, 1908, p. 326.

[f] Cole, G. A. J., and Gregory, J. W., On the variolitic rocks of Mont Genèvre: Quart. Jour. Geol. Soc., vol. 46, 1890, p. 316.

[g] Ransome, F. L., The eruptive rocks of Point Bonita, California: Bull. Dept. Geology, Univ. California, vol 1, 1893, p. 112.

[h] Russell, I. C., Geology and water resources of the Snake River plains of Idaho: Bull. U. S. Geol. Survey, No. 199, 1902, pp. 82 et seq.

[i] Idem, p. 98.

[j] Dana, J. D., Characteristics of volcanoes, New York, 1890, pp. 242-244.

[k] Cited in Abstracts Proc. Geol. Soc. London, session 1907-8, London, 1908, p. 42.

[l] Idem, p. 44.

ellipsoidal structure of the Lake Superior basalts is largely of subaqueous origin. It should not be assumed, however, that all the ellipsoidal basalts of the Lake Superior region are necessarily subaqueous. The region is a large one, the conditions are varied, the ellipsoidal structures are locally associated with structures ordinarily regarded as of subaerial origin, ellipsoidal structure is known elsewhere to develop subaerially, hence it is rather likely that a part of the structures in the Lake Superior region are of subaerial origin. There is little prospect that evidence will be forthcoming to determine exactly the quantitative importance of the subaerial deposit as compared with the subaqueous deposit; indeed, there seems to be little need of such determination when it is recognized that both are present. Qualitatively the evidence favors the subaqueous origin of the major part of the ellipsoidal basalts.

ERUPTIVE ROCKS ASSOCIATED WITH IRON-BEARING SEDIMENTS OF LAKE SUPERIOR REGION CARRY ABUNDANT IRON.

Abundant sulphides and associated magnetite are disseminated in quartz veins and irregular quartz masses through the ellipsoidal greenstones of the Lake Superior region and of much of the pre-Cambrian shield of Canada. The abundance of these sulphides through all parts of these greenstones has been noted by many observers. They are exceptionally conspicuous in the Canadian part of the region, where erosion has cut down into the fresh rocks and exposed sulphide veins that have not had time to be deeply oxidized at the surface since the glacial epoch. That certain of the sulphides and the associated magnetites of the basic igneous rocks crystallized soon after the crystallization of the igneous rocks, and are not later secondary replacements of such rocks, is shown by evidence of several kinds, as follows:

1. They are minutely disseminated through the greenstone and grade into pegmatitic veins.

2. The sulphides and the greenstones of this type are colimital, and the sulphides are not found so abundantly in any other rocks, a fact which would be difficult to explain were the sulphides the result of later introduction by percolating meteoric waters or by later extrusions.

3. The matrix of the ellipsoidal basalt flows is in places so highly charged with magnetite as to disturb the magnetic needle greatly, and the amount of magnetite is much less at the ellipsoids. Illustrations of this are found in the Hemlock formation in the vicinity of the Armenia and Mansfield mines, in the Crystal Falls district of Michigan, and in the Keewatin basalts associated with jaspers southwest of Ely, in the Vermilion district of Minnesota. The matrix being the last part of these masses to crystallize, the magnetite is obviously introduced late in the extrusion of the mass. Sulphide of iron is present in the same relations.

4. Many of the amygdules in the basalts are wholly or partly filled with magnetite or jasper, or both. Near the Gibson mine, south of Amasa, in the Crystal Falls district of Michigan, red jasper fillings in amygdaloids are very conspicuous. The amygdule fillings in general are characteristic of hot solutions such as would accompany the extrusion of the mass and not of cold meteoric solutions. (See Pl. XXXVI, *A*.)

5. Plate XLVIII (p. 564) shows a Keewatin basalt with gradation phase through siliceous basalt into banded siliceous iron-bearing formation. In the area from which these specimens were taken, as well as in other parts of the Keewatin, it is practically impossible to draw a line between unaltered basalt and the iron-bearing formation. This gradation seems to be one developed on the original solidification of the mass. The freshness of the basalt, the lack of katamorphism along the contact with the quartz, and the extremely vague surfaces and general lack of vein structures are not characteristic of later introductions of the quartz after weathering.

6. Some parts of the magnetic iron-bearing formations are so related to the associated basalts as to suggest that the iron represents pegmatitic vein material which developed directly from the igneous rock. Such instances are cited for the Atikokan and Vermilion districts.

Evidence is everywhere to be found that these various iron salts associated with the surface extrusive rocks represent remnants of outpourings of concentrated iron solutions after the main mass of the basalt had crystallized. Deep-seated equivalents of the basaltic extrusive rocks are believed to be the gabbros which carry large masses of titaniferous magnetite representing iron salts that did not have an opportunity to escape at the surface.

The fact that in some places the iron-bearing formation seems to be related to late acidic phases of extrusions, as has been noted on page 507, suggests the extrusion of the iron and the acidic phases as extreme differentiation products from the magma. The association of extremes of this type is not uncommon.

GENETIC RELATIONS OF UPPER HURONIAN SLATE TO ASSOCIATED ERUPTIVE ROCKS.

The iron-bearing formations of the upper Huronian are so closely associated with slate that evidence bearing on the origin of the slate throws light on the origin of the associated iron-bearing formations. In figure 76 (p. 612), prepared by S. H. Davis, the mineralogical composition of the upper Huronian slate, calculated from chemical composition, is compared graphically with that of a variety of other clays and soils. It appears from this comparison that the slate as a whole gives evidence by its composition of being less leached of its bases than average slates or residual clays and that it has been derived from basic rocks. It may be due partly to weathering of the greenstones, to direct contribution of volcanic ash and muds, and possibly even to direct reaction with sea water. (See pp. 610–614.)

MAIN MASS OF IRON-BEARING SEDIMENTS PROBABLY DERIVED FROM ASSOCIATED ERUPTIVE ROCKS.

The close association of iron-bearing sediments with contemporaneous basic eruptive rocks in the Lake Superior region and in other parts of the world, the richness of these eruptive rocks in iron salts, and the probable derivation of the upper Huronian slates associated with the iron-bearing formations from the eruptions make it a plausible hypothesis that these iron-rich eruptive rocks were the principal source of the iron in the iron-bearing sediments. As to the manner in which the iron was transferred from the eruptive rocks to the place of sedimentation, there are several possible hypotheses. (1) It may have been transferred in hot solutions migrating from the eruptive material during its solidification, carrying iron salts from the interior of the magma which had never been crystallized; (2) so far as the lavas were subaerially extruded, iron may have been transferred by the action of meteoric waters working upon the crystallized iron minerals in the magma, either hot or cold; (3) the iron may have been transferred by direct reaction of the hot magma with sea water, in which the iron-bearing sediments were deposited.

DIRECT CONTRIBUTION OF IRON SALTS IN HOT SOLUTIONS FROM THE MAGMA.

That the igneous rocks contributed some of their iron solutions directly to the water in which the iron-bearing sediments were being deposited is suggested by the fact that basic extrusive rocks have a widely developed ellipsoidal structure, which has been ascribed by many observers to submarine extrusion. (See pp. 510–512.) If these lavas are submarine, then any iron salts extruded must have been contributed directly to the ocean. It will be shown in the following pages that if the salts were so contributed simple and probable chemical reactions would develop the original greenalite or iron silicate phases of the iron-bearing formations. Such phases largely lack the carbonaceous slates so closely associated with the carbonates. It was found in the laboratory that the precipitation of the greenalite phase of the iron-bearing formations required heat in the presence of carbon dioxide and the probable presence of salt water, in both contrasting with the precipitation of iron carbonate, which goes on in cold solution, favored by the presence of reducing organic agencies. Direct contribution would favor the deposition of the iron salts in a ferrous condition in the absence of reducing carbonaceous material and would avoid the oxidation and precipitation which they would undergo if partly carried subaerially.

Further, the fact that iron-bearing formation seems to be lacking in association with certain similar greenstones in the Lake Superior region and Canada may be evidence that the iron-bearing formations derive their materials by direct magmatic contributions. Such contributions are known to be local and variable in composition, and this may explain the localized distribution of the iron-bearing formations. If derived entirely by weathering of basic igneous rocks, iron-bearing formations should be more abundant in association with igneous rocks outside of the Lake Superior region.

The percentages of both iron and silica in the iron-bearing formations seem to be too high for direct derivation from crystallized basalt by weathering. They seem to accord better with the hypothesis that the iron and silica, especially the silica, were precipitated from concentrated solutions coming directly from the magma. The local presence of acidic igneous rocks between the lavas and the basalts and the fact that the acidic rocks are slightly later than the basalts suggest that the development of the iron-bearing formation came at a time when acidic phases of the extrusion were coming out. The iron salts and the acidic phases then might represent the extreme differentiation products of a primary magma of which the basalt was the first extrusion.

Favoring the hypothesis of direct contribution of the iron salts from the lava to the sea water into which it was poured is the lack in many places of any fragmental material between the iron-bearing formation and the contemporaneous lava on which it rests, the mutual conformity at these places, and the absence of any erosion channels in the greenstones. In the Vermilion district of Minnesota bands of iron-bearing formation have been traced for considerable distances resting directly upon the amygdaloidal upper surface of a lava flow, showing no evidence of intervening erosion and having a contact like a knife edge.

The subaqueous extrusion of igneous rocks would mean the sudden destruction of any organic material in the near-by sea, to judge from results observed near present-day extrusions. It has been shown that after an eruption the sea floor has been covered to a depth of several feet off Hawaii by dead fish and other organic material. It is entirely possible that this may explain the origin of some of the carbonaceous materials so closely associated with the iron-bearing formations, especially in the Keewatin, where seams of rich graphitic slate are locally associated with the iron-bearing formation and the basalt. It is possible also that this material might be a source for the carbon dioxide necessary for the formation of the iron carbonates. Quantitatively it is probably inadequate to explain either the amount of carbon dioxide necessary for the formation of the iron carbonates or the amounts of carbon to be seen in the associated slates. It is mentioned merely as a possible source of a part of these substances. Its importance can not be quantitatively demonstrated.

So far as the parent igneous rocks were extruded subaerially, the escaping iron solutions would be mingled with meteoric waters, perhaps deriving additional iron salts from the breaking up of crystallized minerals described under the next heading.

CONTRIBUTION OF IRON SALTS FROM CRYSTALLIZED IGNEOUS ROCKS IN METEORIC WATERS.

Some of the basaltic extrusive rocks have textures indicative of subaerial crystallization. Atmospheric agencies, therefore, have been applied during the transfer of the iron solutions to the ocean. Weathering agents would effectively attack sulphides at or above the surface of the water, especially when aided by organic material and residual heat. Under ordinary weathering these sulphides oxidize and form soluble iron sulphate, which becomes available for the sedimentation of the iron-bearing formations. The same reaction liberates free sulphuric acid, which may attack the iron in the adjacent rocks. Still further, it has been found that acidic gaseous emanations from igneous rocks attack readily the adjacent rocks, leaching from them their iron, partly depositing it in place as hydrated oxide and partly carrying it away in solution as a sulphate. A highly instructive quantitative study of the Hawaiian basalts by Maxwell [a] shows the effectiveness of acidic solutions of this kind in decomposing the rocks and segregating the iron. The marked softening and disintegration of the rocks may furnish a source for the unusually large amount of basic mud associated with

[a] Maxwell, Walter, Lavas and soils of the Hawaiian Islands: Rept. Exper. Sta. Hawaiian Sugar Planters' Assoc., Div. Agr. and Chem., Special Bull. A, Honolulu, 1905, pp. 8-22.

the iron-bearing formation. It is entirely conceivable that some of the thin bands of the iron-bearing formation interbedded with basic flows, with little other sedimentary material, may be essentially residual iron oxide or laterite deposits developed in this way. This seems especially likely where the iron-bearing formation is high in alumina, as, for instance, in some of the hornblendic Keewatin belts or in the iron ranges near Lake Nipigon, where E. S. Moore[a] has found dumortierite. However, the generally low percentage of alumina in the iron-bearing formations seems to show that for the most part they may not be regarded as metamorphosed residual products of rock alteration.

Vegetation is known to develop on basic extrusive lavas with great rapidity, as indicated by the cultivation of the slopes of Vesuvius and Hawaiian volcanoes in an incredibly short time after eruptions, and hence organic agencies may have aided in the transfer. The chemistry of the transfer of iron salts through these agencies is discussed elsewhere (pp. 519–520). Favoring the view that weathering is a factor in the process is the fact that parts of the original rocks of the iron-bearing formation are made up of iron carbonate associated with black carbonaceous slates, such as may have developed in delta deposits. (See p. 502.) There is no more reason to doubt the organic origin of the carbon in these slates than that of the carbon in the carbonaceous slates, iron-bearing formation, and basalts in County Antrim, Ireland, and elsewhere, except that definite organic forms are lacking.

The iron-bearing formations grade locally into phases rich in calcium and magnesium carbonates, as at Gunflint Lake and in the east end of the Gogebic district. It is usually assumed that calcium and magnesium carbonates are ordinary products of weathering and sedimentary deposition.

It may be asked why weathering did not also deposit iron abundantly in the Paleozoic sea when it advanced later on these same rocks. To some slight extent iron was so deposited at the Clinton horizon. The answer is believed to lie partly in the essential contemporaneity of the basic extrusive rocks with the associated iron-bearing formations, indicating that the process of derivation of the iron salts and deposition went on soon after the extrusion of the igneous rocks, very rapidly at first owing to juvenile contributions and to leaching during the residual heat, but slowly later when the rocks were colder and the easily accessible sulphides had been reached. Still later, when the Paleozoic sea came over the area, while it derived some iron from these rocks, it was unable to do the work on the same scale as was accomplished immediately after their extrusion. Since glacial time alteration of pyrites in the pre-Cambrian shield has penetrated only a fraction of an inch or at most a few inches below the striated glacial surfaces, indicating a relatively slow alteration of these substances under ordinary weathering—probably too slow to account for the heavy and rapid chemical deposition of iron-bearing formation without admixture of fragmental material.

Powdered Keewatin rocks containing abundant iron sulphide have been treated with oxygenated waters and kept agitated for a period of six weeks. A slight amount of sulphuric acid was also introduced to accelerate the alteration. At the end of this time barely enough iron had gone into solution to be detected by the most refined methods.

The slate that is so abundantly present with the upper Huronian iron-bearing formations gives evidence in its composition of derivation from the greenstone. (See p. 612.) It is in part doubtless derived by weathering of the type here described. In part also the slate represents volcanic dust and mud directly deposited from the volcanic extrusions, and in part it may result from reaction between the hot lavas and sea waters described below.

CONTRIBUTION OF IRON SALTS BY REACTION OF HOT IGNEOUS ROCKS WITH SEA WATER.

When basaltic magmas are extruded into the ocean there is reaction with the salt water. The behavior of basic lavas when extruded into salt water has not been carefully observed. There seems to be a tendency in Hawaii and Iceland for rapid powdering and disintegration at these contacts. What the chemical results are is not apparent. When pottery is sprayed

[a] Geology of Onaman iron range area: Ann. Rept. Ontario Bur. Mines, vol. 18, pt. 1, 1909, pp. 212-215.

with salt water while hot, a glaze of sodium silicate (water glass) is formed, which is more or less soluble. In connection with the present study fresh basalts were heated in a muffle furnace to a temperature of 1,200° C., a temperature sufficient to fuse the exterior, and then plunged into salt water of the composition of sea water, the result being a violent reaction, producing principally sodium silicate (see p. 525) but also bringing a small amount of iron into solution. From the available evidence it seems likely that such a process may account for part of the sodium silicate which, by reaction with ferrous salts, produces the greenalite with excess of silica. (See pp. 521–523.) The experiment does not seem to suggest an adequate source for the iron in this reaction. There was also during this reaction a tendency toward disintegration. This may indicate a partial source for some of the muds so closely associated with the iron-bearing formations.

CONCLUSION AS TO DERIVATION OF MATERIALS FOR THE IRON-BEARING FORMATIONS.

Ordinary processes of weathering, transportation, and deposition of iron salts from terranes of average composition were as effective in the pre-Cambrian of the Lake Superior region as in other times and places, but these processes account for only thin and relatively unimportant phases of the iron-bearing rocks; for instance, the lenses of iron carbonates associated with graphitic slates of the upper Huronian, probably deposited in lagoons and bogs of a delta. For the derivation of the unique thick and extensive iron-bearing formations of the Lake Superior region it is necessary to appeal to some further agency. This is believed to be furnished by the large masses of contemporaneous basic igneous rocks. The association of sedimentary iron-bearing formations and basic igneous rocks is known in many localities outside of the Lake Superior region. The iron salts have been transferred from the igneous rocks to the sedimentary iron-bearing formations partly by weathering when the igneous rocks were hot or cold, but the evidence suggests also that they were transferred partly by direct contribution of magmatic waters from the igneous rocks and perhaps in small part by direct reaction of the sea waters upon the hot lavas.

VARIATIONS OF IRON-BEARING FORMATIONS WITH DIFFERENT ERUPTIVE ROCKS AND DIFFERENT CONDITIONS OF DEPOSITION.

The basalts contributing the iron being both subaerial and subaqueous in their extrusion, it is to be expected that the contribution of iron to the body of water in which the iron-bearing formations were being deposited was both direct and indirect. Evidence is not available which will clearly discriminate iron-bearing formations contributed to the ocean in these two ways. In general the parts of the iron-bearing formations originally consisting of carbonate seem to be related to the indirect contribution from the igneous rocks through the agencies of weathering, and the parts of the iron-bearing formations originally consisting of greenalite or iron silicate seem to have been contributed in the main directly to the waters without intervening atmospheric or organic agencies. The locally close association of these two types of the original iron-bearing rocks indicates the close association of direct and indirect methods of contribution of iron-bearing materials. The fact that the upper Huronian iron-bearing formation in the Mesabi district was largely greenalite, while the upper Huronian iron-bearing formation of the Gogebic district was largely carbonate, might therefore signify simply that in one district the salts had been derived primarily from subaerial weathering and in the other from subaqueous contribution, but in each district partly in both ways and in both districts essentially from the same rocks. It is noted elsewhere that in many places where the greenalite and carbonate occur together the greenalite occupies the lower horizon. This might be explained not only by conditions of subaerial contribution succeeding subaqueous contribution, but, as explained elsewhere, by the more rapid settling of the greenalite when precipitated simultaneously with the carbonate.

The iron-bearing lavas extruded at three widely separated periods could scarcely be expected to produce iron-bearing formations of exactly the same character, even were the conditions of deposition the same, for in so far as the ores were directly contributed by magmatic solutions, they were subject to extreme variations in composition.

The conditions of deposition of iron salts were also different during these three periods of volcanism. The Keewatin lavas were extruded in larger quantities than at any later time and the associated iron-bearing formations constituted only discontinuous beds between the hot extrusives, but in the middle and upper Huronian the extrusions were much less abundant and sedimentation proceeded on a larger scale and less directly under the influence of igneous rocks. Although some of the differences between these three formations are explained by later alteration, it is believed that the highly amphibolitic and magnetitic character of the Keewatin was partly determined at the time of, or soon after, its deposition, in contrast with the prevailing deposition of ferrous carbonate and ferrous silicate at the later periods. In the discussion of the secondary concentration of the ores it will be shown that the ores of the Keewatin have undergone far less secondary concentration than the later ores. This is certainly in part due to anamorphic changes before the katamorphic agents had an opportunity to work, but possibly in part also to original differences in texture and composition, possibly because the Keewatin as a whole seems to contain a lower percentage of iron than the succeeding formations, and partly because of the small area of the formations exposed to concentrating agencies. (See pp. 474-475.) The Keewatin series had produced only 6.5 per cent of the total shipments to the close of 1909. The Keewatin seems to occupy the same subordinate position in Canada, and as the area of Keewatin in Canada is relatively greater than that of later iron-bearing formations, the chances of finding ore there are relatively smaller than in other parts of the Lake Superior region.

It would be expected also that the iron salts closely associated with the igneous rocks would be less regular in their thickness and more generally separated into different belts by intercalated igneous rocks than those at a distance from the areas of extrusion. The latter seem to be illustrated by the Animikie ores, which attain their maximum development on the north shore of Lake Superior, the nearest known extrusive rocks being west of the lake or possibly under the lake. The remarkably uniform character of the iron-bearing formation and the rest of the Animikie group, distinguishing it from all other pre-Cambrian iron-bearing formations, may well be due to its distance from the contemporaneous volcanic activity, for, in view of the connection of the ores with igneous rocks above outlined, it would seem to be more than a coincidence that the most uniform and widespread of the iron-bearing formations should be the farthest removed from volcanic activity. Variation in the iron-bearing formations with varying distance from the igneous rocks is more definitely shown by the iron-bearing formation of the Gogebic district, which at the east end of the range, where associated with extrusive rocks, is extremely varied in its composition and is broken into different belts by other sediments and by igneous beds. The material of this portion of the formation may also originally have been deposited in small part as magnetite or hematite rather than siderite or greenalite. The irregularity diminishes toward the west, though still existing at Sunday Lake. For many miles west of Sunday Lake the iron-bearing formation was deposited as a continuous thick formation with less amounts of other sediments. These differences may be partly due to varying conditions of temperature and materials present, as discussed on page 526, and are undoubtedly due in part to the fact that near the extrusions there were sudden and violent oscillations in level, requiring frequent alternations of sediments, while farther away these oscillations were less marked and the movement was a comparatively uniform one of sinking, perhaps due to the general extrusion of the lavas from the region.

Moreover, shore conditions of deposition may well have been different from those offshore. It has been noted that the upper Huronian iron-bearing formations in the Mesabi, Gogebic, Menominee, and Felch Mountain districts are clearly defined formations originally containing greenalite and carbonate between quartz sand below and shale above, and that in these districts they come relatively close to the older rocks, suggesting a possible shore condition. In the Cuyuna, Florence, and Iron River districts the iron-bearing members, originally sideritic, are in numerous layers and lenses in the slates. These are probably higher in the series and may also represent offshore conditions.

It may be argued that similar basic igneous rocks elsewhere extruded near or under the sea are not accompanied by deposition of iron-bearing formation on such a scale. That iron-bearing rocks are present on a smaller scale in such association elsewhere is shown on pages 508–510. It should be remembered that only very exceptionally do igneous rocks of any sort carry ores with them. There are many areas of Tertiary eruptive rocks and but few Goldfield camps. So far as the Lake Superior iron-bearing formations derive their materials from direct magmatic contribution of igneous rocks, they are likely to be localized by reason of these exceptional contributions. This may explain why all of the similar pre-Cambrian basalts in Canada or elsewhere in the Lake Superior region are not associated with iron ores, though the geologic conditions are apparently the same. It follows from the foregoing statements that the ores are not derived from basic igneous rocks in general but from certain ones.

It may be further argued that while the iron-bearing formations of the Keewatin may have readily been derived from the relatively abundant associated greenstones, the iron-bearing formations of the Huronian are so extensive as compared with the contemporaneous volcanic rocks that they could scarcely have been derived from those rocks. Such an argument would be without definite basis, however, because there is no known quantitative relation between volume of igneous rock and volume of materials derived from it as igneous after-effects. The iron ores of the Iron Springs district of Utah show a wide range in abundance as compared with the parent igneous rocks. The contemporaneous volcanic activity in the middle Huronian was extensive, being represented by the Hemlock, part of the Clarksburg, and other volcanic formations. That in the upper Huronian was less in amount, but is represented by most of the Clarksburg, in the eastern part of the Gogebic district, and some of the greenstones of the Menominee district; moreover, it may well be that the present Lake Superior basin was the locus of much more abundant upper Huronian flows, for reasons which are mentioned on pages 507–508.

CHEMISTRY OF ORIGINAL DEPOSITION OF THE IRON-BEARING FORMATIONS.

NATURE OF THE PROBLEM.

The experiments specifically described in the following paragraphs, if not otherwise credited, have been made in the geological and chemical departments of the University of Wisconsin, principally by M. E. Diemer, in cooperation with W. J. Mead, R. D. Hall, and others, to meet conditions specified by the authors.

The problem is to explain the original deposition in thick formations of greenalite ([FeMg] $SiO_3.nH_2O$), siderite ($FeCO_3$), chert (SiO_2), and perhaps some hematite, magnetite, and limonite, in intercalated layers of varying proportions, under conditions, if our preceding conclusions are valid, ranging from ordinary cycles of weathering, transportation, and deposition to direct contribution of iron solutions from the hot igneous extrusives to the water in which the sediments were deposited.

Obviously a wide range of chemical processes has been involved in the development of the iron ores. It is unlikely that all are known. It is the aim of the following paragraphs to indicate as definitely as possible certain processes which seem likely to have been important, without implication that these are necessarily the only ones contributing toward the observed results.

The iron may have been carried as a ferrous salt of silicic, carbonic, sulphuric, hydrochloric, or other acids present, or as FeO in presence of H_2O at high temperatures it may have been in excess of the available acid radicles. It appears now as an original constituent of basic extrusive rocks in the form of sulphides, magnetite, hematite, chlorite, and the pyroxenes and amphiboles. The absence of greenalite and ferrous carbonate as such among these original constituents, and also the absence in the ferrous silicate and carbonate of alkalies, which are associated with the iron as original constituents in the igneous rocks, seem to preclude the direct contribution of the iron as ferrous silicate or ferrous carbonate from the igneous rocks and to require certain sifting and simplifying reactions by outside agencies to explain the composition of the original iron-formation rocks. It will be assumed in the following discussion that the iron is carried as a ferrous salt. From the abundance of iron sulphides in the original igneous rocks and in their pegmatitic after-effects it will be assumed further that the acid radicle is sulphuric. This is done also for convenience in experimenting. It is not meant to exclude other possible combinations of the iron above mentioned. Carbonic acid was doubtless present. Other combinations than these would serve fully as well in the essential steps of the process below outlined.

FORMATION OF IRON CARBONATE AND LIMONITE.

The close association of many of the thinner carbonate bands of the upper Huronian with black carbonaceous and pyritiferous slates, an association similar to those found in the "Coal Measures" and elsewhere, suggests that the iron carbonate may be the result of reduction of ferric hydrate by organic material buried with it in deltas, bogs, or other similar places. Hydrogen sulphide characteristic of these conditions would react upon part of the carbonate of iron, producing the iron sulphide, thereby giving both iron carbonate and iron sulphide in association with carbonaceous rocks.

Van Hise [a] says:

As to the form in which the iron salts enter the seas, we can judge only by analogy, but if the present be a guide to the past, the iron was chiefly as a carbonate and to a subordinate extent as a sulphate, although it might have been in part in the form of other salts. When the iron salts reach the lagoon, they are precipitated under favorable conditions as ferric hydrate or possibly in part as basic ferric sulphate. Supposing the iron salt to be carbonate, it would be precipitated according to the following reaction:

$$4FeCO_3+3H_2O+2O=2Fe_2O_3.3H_2O+4CO_2.$$

Where this process goes on, on an extensive scale, limonite bodies are built up.

It was formerly supposed that this reaction took place as a result of the work of oxygen and moisture alone, and this is true to some extent. But recent observation has shown that where in lagoons iron carbonate is abundant the oxidation is largely performed through the agency of a class of bacteria called the iron bacteria. It has been found that these bacteria are unable to exist without the presence of iron carbonate or manganese carbonate, but the iron carbonate is the chief compound used. This material they absorb into their cells. There the iron carbonate is oxidized and the limonite is precipitated. Says Lafar:

"The decomposing power of these organisms is very great, the amount of ferrous oxide oxidized by the cells being a high multiple of their own weight. This high chemical energy on the one hand, and the inexacting demands in the shape of food on the other, secure to these bacteria an important part in the economy of nature, the enormous deposits of ferruginous ocher and bog iron ore, and probably certain manganese ores as well, being the result of the activity of the iron bacteria."[b]

Evidence is furnished of the precipitation of the limonite of bog iron-ore deposits in this manner by the discovery in some of them of large numbers of the sheaths of the iron bacteria.[c] Further evidence of the importance and activity of these bacteria is furnished by their partly or completely closing water pipes of cities where the water contains a considerable amount of iron carbonate.[d]

The iron part of the salts carried down to the sea as a sulphate would be likely to be thrown down as basic ferric sulphate,[e] according to the following reaction:

$$12FeSO_4+6O+(x+9)H_2O=Fe_2(SO_4)_3.5Fe_2O_3.xH_2O+9H_2SO_4.$$

The material thrown down as a hydrated ferric oxide and basic ferric sulphate is mingled with more or less of organic material, and a deposit of considerable thickness may thus be built up. This deposit is below the level of ground water and is therefore in the zone of incomplete oxidation, or is under the conditions of the belt of cementation. The oxygen required for the partial oxidation of the organic material is derived in part from the ferric oxide, and the iron is reduced to the ferrous form; but probably this reaction does not take place on an important scale at the surface. The reducing agent may be regarded as carbon, carbon monoxide, or some of the hydrocarbons, such as methane. The result is the same in any case. The oxygen and the carbon produce carbon dioxide, and thus the conditions are reproduced for the production of iron carbonate. A representative reaction may have been as follows:

$$2Fe_2O_3.3H_2O+3CO_2+C=4FeCO_3+3H_2O.$$

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[a] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 825-827.

[b] Lafar, F., Technical mycology, vol. 1, Lippincott & Co., 1898, p. 361.

[c] Fischer, A., The structure and functions of bacteria, trans. by A. Coppen Jones, Clarendon Press, Oxford, 1900, p. 69.

[d] Lafar, F., op. cit., p. 361.

[e] Pickering, S. P. U., On the constitution of molecular compounds; the molecular weight of basic ferric sulphate: Jour. Chem. Soc. London, vol. 43, 1883, p. 182.

Beck summarizes the conditions of solution, transportation, and deposition of iron under weathering processes, especially with reference to organic agencies. In his discussion of the origin of lake and bog ores, he says:[a]

What was the nature of the solutions? The following are the chief solvents:

1. Sulphuric acid formed by the decomposition of iron-bearing sulphides.

2. Carbonic acid supplied by the air and by decaying organisms, and to some extent by the living animals. This enables it to attack various silicates.

3. Organic acids also play a part. These are, moreover, transformed into carbonic acid by oxidation, when vegetable masses decompose. In the presence of decaying vegetable matter deprived of an adequate oxygen supply, iron sesquioxide is reduced to ferrous oxide, which forms soluble double salts, with humus acids and ammonium.

The precipitation of iron from these dilute solutions may take place in various ways.

In solutions of iron sulphate the mere addition of ammonium humate, which is always present in the brown waters of peaty areas, effects a precipitation of iron oxide and later on of ferric hydrate.

From carbonated solutions the iron is precipitated as ferric hydrate by the escape of carbonic acid into the air, or by its absorption by plant cells. The deposition of iron carbonate is only possible when the air is excluded or in the presence of organic matter, which seems to harmonize with the known facts concerning spherosiderite and black-band ores.

From humates and other organic compounds the ferric hydrate is precipitated by the oxidation of the humus acids and their decomposition into carbonic acid and water. Here, too, the plant cell accelerates this process by furnishing oxygen. Lastly, by the mingling of iron humates and sulphates, the sulphuric acid, which kept the iron sesquioxide in solution, unites with ammonium, and iron is precipitated as hydroxide or as ferric humate.

In this action, the life processes of plants take a part, entirely independent of any products of plant decay. According to Ehrenberg, the algæ, especially the so-called iron algæ, *Galionella ferruginea* Ehrenb., are active ore precipitants, coating their cell walls with ferric hydrate and opaline silica. This alga is abundant on the sea bottoms. According to the recent works of Molisch and Winogradsky, these and most other supposed algæ are ciliated bacteria of different kinds, especially *Leptothrix ochracea*.[b]

The silica of these ores may originally have been held in solution as alkaline silicates, which are supposed to be decomposed by carbonic acid. This silica is precipitated simultaneously with the ferric hydrate. The phosphoric acid was certainly present as ammonium phosphate and is precipitated at first as iron phosphate and as calcium phosphate in calcareous ores. * * *

We saw that in the case of lake ores the deposition took place quite slowly. This process is more rapid where the drainage from the gossan of a large pyrite deposit is carried into a lake basin, or into the sea, or where mining operations produce an inflow of great quantities of iron-bearing mine waters. Thus the bottom of Lake Tisken, near Falun, is covered with a layer of ocher mud several meters thick that has been furnished by the neighboring pyrite stock. The bed of the Rio Tinto carries ocher mud and diatoms derived from the waters of the copper mines as far as Palos in Huelva Bay. That this was the case even before mining began at that locality is proved by the deposit of iron ore on the Mesa de los Pinos and the Cerro de las Vacas. These limonite deposits were formed in a bog which was afterwards dissected by the river. The ironstones contain plant remains of the same character as the present flora. Slabs of this ore were used by the Romans for tombstones.[c]

Iron carbonate is known to be directly precipitated when a ferrous salt comes into contact with calcium carbonate, as, for instance, when ferrous solutions from intrusives penetrate a limestone. The presence of any calcium carbonate in the waters or sediments at the time of the deposition of the Lake Superior iron formations may have reacted with any ferrous salts present to produce carbonate, but we have no direct evidence of this.

The above-noted processes do not seem adequate to account for all the iron carbonates of the Lake Superior region, for some of them, as, for instance, in the Gogebic district, are in much thicker masses than have been found elsewhere associated with carbonaceous seams, are comparatively free from carbon and sulphides, and, moreover, show remarkably close association with certain iron silicates called greenalite, to which they are partly secondary and which are thought to develop in another way. Laboratory reactions between iron silicates, iron carbonates, and carbon dioxide, discussed under another heading (p. 526), suggest other processes of iron carbonate deposition.

NATURE OF CARBONATE PRECIPITATE.

The precipitate of ferrous carbonate is apple-green in color, is flocculent, settles slowly, and shows a distinct tendency in settling to segregate into bands separated by greater or less

[a] Beck, Richard, The nature of ore deposits (tr. by W. H. Weed), vol. 1, 1905, pp. 101–103. See also Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 550.

[b] Weed, W. H., Geological work of plants: Am. Geologist, June, 1894. Walther, Einleitung in die Geologie, Jena, 1893–94, p. 655.

[c] Louis, H., Ore deposits, 2d ed., 1896, p. 41.

amounts of free silica. No tendency is observed in this substance toward the development of globular forms, and in this connection it is suggested, in view of Lehmann's inferences cited on page 525, that the iron carbonate has a strong tendency to crystallize.

PRECIPITATION OF GREENALITE.

PROCESSES.

Evidence has been presented elsewhere (pp. 166–168) to show that greenalite ($Fe(Mg)SiO_3.nH_2O$) is different from glauconite and probably from other green silicate granules which have been described. It may be reproduced in the laboratory.

In all the reactions and experiments in which silicic acid was used, it was in aqueous solution along with sodium chloride. This was for two reasons: (1) The silicic acid was prepared by neutralizing sodium silicate of the composition $Na_2O.3SiO_2$ with hydrochloric acid. Thus:

$$Na_2O.3SiO_2 + 2HCl = 2NaCl + 3SiO_2.H_2O.$$

(2) The methods of experimentation chosen approximated the natural conditions under which the greenalite was deposited, and, to our belief, this was in the presence of sea water. On starting with a soluble ferrous salt, for convenience ferrous sulphate, the following reactions are found to be significant with reference to the origin of greenalite:

1. A solution of ferrous salt when boiled with silicic acid (prepared as above stated) produces (in the absence of air) no precipitate, showing that silicic acid and a ferrous salt do not react to form greenalite.

2. Ferrous sulphate reacts directly with solutions of silicates of the alkalies, producing a granular precipitate corresponding in composition to the water glass used in the precipitation. Thus:

$$FeSO_4 + Na_2O.3SiO_2 = FeO.3SiO_2 + Na_2SO_4.$$

It is shown on page 522 that this precipitate is composed of ferrous silicate ($FeSiO_3$) and free silica.

If a soluble magnesium salt is present with the ferrous salt in the above reaction, it will be precipitated as $MgSiO_3$ (or the silicate corresponding to the composition of the water glass used), explaining the presence of some MgO in the greenalite.

3. That the precipitate $FeO.3SiO_2$ consists of ferrous silicate ($FeSiO_3$) and free silica is shown by the following experiments:

When the precipitate ($FeO.3SiO_2$) formed under the given conditions is dissolved in strong NaOH and reprecipitated by neutralization of the large excess of alkali by hydrochloric acid, the composition of the resulting precipitate is $FeSiO_3$ (by analysis), and the remaining silica of the $FeO.3SiO_2$ is held in solution as colloidal silicic acid.

Furthermore, when $FeO.3SiO_2$ is boiled with water silica is taken into solution, while the iron remains in the precipitate, and the ratio $1FeO:3SiO_2$ becomes gradually less and approaches $FeO:SiO_2$. This process can not be carried to the extent of $FeO:SiO_2$, however, as the iron of the compound oxidizes, and when it oxidizes the combined silica becomes soluble, so that no distinction can be made between the silica of the compound and the uncombined excess silica. When greenalite ($FeO.SiO_2$) alone is boiled with water no silica goes into solution.

The composition of the greenalite is shown further by the fact that when boiled with water through which carbon dioxide is being passed, iron and silica go into solution in the proportions 1:1.

4. When the proportions of silica and alkali are varied in the water glass, there is variation in the total amount of silica precipitated.

5. When the ferrous salt is in excess, in the precipitate the proportion of the iron to total silica precipitate is relative to that of the sodium silicate, but when the water glass is in excess, the proportion of iron and silica is variable, depending on the temperature at which it is formed. This is shown by the precipitates resulting from mixing solutions of ferrous sulphate and water glass.

The precipitates are mixtures of ferrous silicate and free silica:

(*a*) The precipitate from cold solutions with ferrous salt in excess may be expressed as $FeO.3SiO_2$.

(*b*) The precipitate from cold solutions with water glass in excess may be expressed as $FeO.5SiO_2$.

(*c*) The precipitate from hot solutions with ferrous salt in excess may be expressed as $FeO.3SiO_2$.

(*d*) The precipitate from hot solutions with water glass in excess may be expressed as $FeO.10SiO_2$.

6. Regardless of the various proportions of iron to total silica obtained under the conditions stated in paragraphs 4 and 5, the iron silicate formed has the character of greenalite and the variation in composition is entirely in the amount of free silica precipitated.

7. The precipitation of ferrous silicate requires neutral or slightly alkaline conditions. The substance is soluble in acids and strong alkalies. When water glass is added to a ferrous solution which is acid with hydrochloric or sulphuric acid, there is no precipitation, but when this is neutralized with alkali, a ferrous silicate precipitate results. Under strongly alkaline conditions it will not precipitate, being held in more or less of a colloidal solution, which has a greenish muddy appearance.

Thus the materials necessary to make greenalite might be carried for some distances in acid or alkaline solutions before precipitation. Hydrochloric acid is formed simultaneously with the sodium silicate. This would act as a solvent. If the solution were alkaline, deposition would come by neutralization with an acid, such as carbon dioxide.

8. The iron of the ferrous silicate precipitated in the absence of oxygen is entirely in the ferrous condition. The freshly precipitated ferrous silicate was thoroughly washed, dissolved in sulphuric acid, and the ferrous iron titrated. This gave the ferrous iron of the salt—0.154 per cent. Then the total iron was calculated as FeO, the result being 0.159 per cent.

9. When oxygen is available, variable percentages of ferric oxide develop in the silicate.

10. Greenalite may also be produced by using other ferrous salts as chloride, according to the reaction—

$$FeCl_2 + Na_2SiO_3 = FeSiO_3 + 2NaCl.$$

11. As first precipitated the greenalite and silica are hydrous. If they are allowed to stand and dry, out of contact with the air, the percentage of water becomes progressively less. Presumably this loss may go on for an indefinite time and to an indefinite extent. Analyses of greenalite rocks of the Mesabi district show considerable variation in the amount of combined water.

12. Greenalite may be formed by the reaction of alkaline silicate and iron bicarbonate.[a]

NATURE OF GREENALITE PRECIPITATE.

When formed by any of the processes above mentioned the greenalite and associated silica first constitute a green, flocculent precipitate. As this precipitate settles a granular structure practically identical with that observed in the Mesabi slides is developed. The optical properties also are the same. The precipitate has been pressed and dried, a slide cut from it, and a photomicrograph taken (Pl. XLII, *B*). A comparison of this plate with one taken of the greenalite rock (Pl. XLII, *A*) shows identity of textures which can not be mistaken, in spite of the imperfections of the granules developed artificially in cutting the slides. As the precipitate settles, there is also to be observed a distinct tendency toward banding.

The only feature in which the artificial greenalite granules differ from those of the Mesabi district is in lacking the small percentage of magnesia found in Mesabi granules. No attempt was made to introduce magnesia artificially, but there would seem to be no inherent chemical difficulty in the association of the magnesium with the iron, an association characteristic of silicate rocks.

[a] Bischof, Gustav, Elements of chemical and physical geology (tr. by B. H. Paul), vol. 2, London, 1855, p. 71.

PLATE XLII.

PLATE XLII.

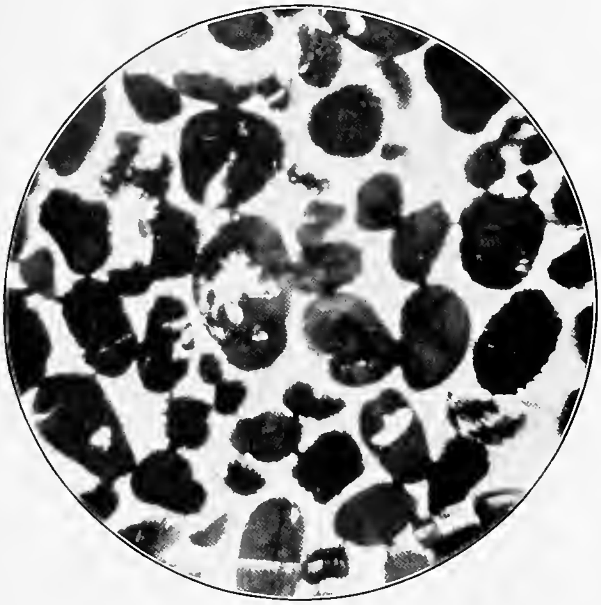
PHOTOMICROGRAPHS OF NATURAL AND ARTIFICIAL GREENALITE GRANULES, CHERTY SIDERITE, AND CONCRETIONARY FERRUGINOUS CHERT.

A. Greenalite granules (specimen 45765, slide 16395) from Cincinnati mine. Without analyzer, × 40. The granules are for the most part unaltered, and are dark green, light green, or yellow. Some of them show alterations to iron oxide and to dark-green chloritic material. Where altered they become dark brown, black, or dark green. The matrix is entirely chert. Evidence of crushing is to be observed in minute cracks ramifying through the slide. Note the remarkable similarity in shapes of these granules to those of the green granules in Clinton ores, illustrated in Plate XLV (p. 536).

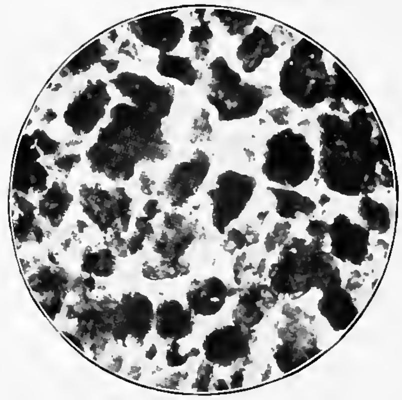
B. Greenalite granule in matrix of silica artificially produced in the laboratory. Without analyzer. See description (pp. 522–523).

C. Photomicrograph of cherty siderite altering to ferruginous chert (specimen 6138, slide 1173), from north shore of Gunflint Lake, T. 65 N., R. 3 W., Minnesota; Animikie group. In ordinary light, × 25. The figure illustrates the formation of iron oxides, pseudomorphous after siderite. A background of chert contains numerous small roundish and rhombohedral areas of siderite and iron oxide. Between the little-altered and wholly-altered siderite a complete gradation is seen.

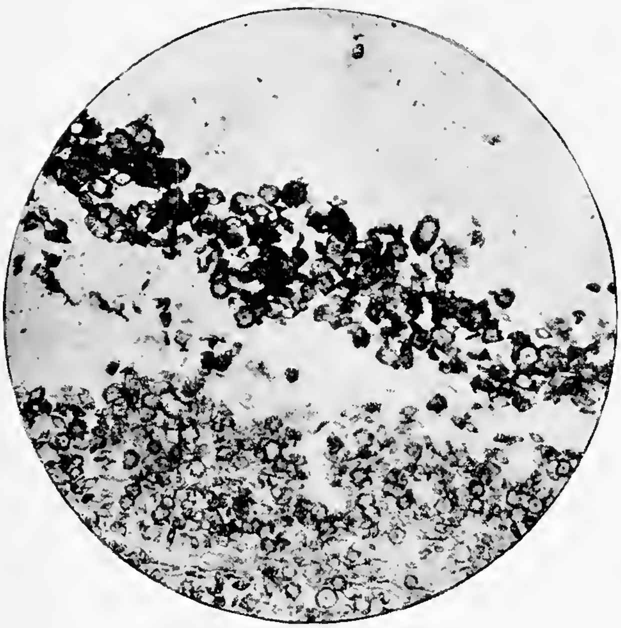
D. Concretionary ferruginous chert, developed from alteration of cherty siderite (specimen 9048, slide 2886), from the SE. ¼ sec. 27, T. 46 N., R. 2 E., Wisconsin. In ordinary light, × 25. In a cherty background are beautiful concretions, which are composed of concentric rings of iron oxide and chert. One concretion particularly is very fine, showing many closely packed concentric rings. Silica is seen breaking across these rings in a few places.



A.



B.



C.

D.

PHOTOMICROGRAPHS.

The reason for the greenalite taking the globular form is probably found in the surface tension between the precipitate and the liquid, which tends to make the smallest possible surface of contact between them, just as mercury in contact with the air will tend to take a globular form in response to surface tension. Such forms are commonly observed in precipitates. Lehmann [a] has investigated them extensively and finds them to develop characteristically in precipitates which lack strong crystallizing tendency. He also finds such forms in other precipitates to be intermediate steps toward crystal form, and presents interesting photomicrographs of incipient development of these forms from these intermediate globular stages. He has used the expressive term "liquid crystals" for these intermediate globular stages. Correlating the development of liquid crystals as intermediate steps in the formation of crystals, where the substances are of strong crystallizing power, with the fact that similar forms and not crystals are likely to be the permanent form taken by substances of low crystallizing power, he is led to suggest that the permanent retention of globular forms is a consequence of low crystallizing power, the substance in its attempt to organize itself having reached the stage of a liquid crystal but not having gone further.

Hydrated iron oxide also tends to take on globular forms when precipitated.

SOURCE OF ALKALINE SILICATES NECESSARY TO PRODUCE GREENALITE.

The above-described reactions indicate that it is necessary to account for the presence of alkaline silicate rather than free silicic acid to produce the desired results. Soluble alkaline silicates are known to be one of the common results of rock decay, but a comparison of the amount of silica available from the basic rock by weathering with that concentrated in the iron formations shows such an excess in the iron formations, as well as absence of alkalies, as to lead us to search for another possible source for the alkaline silicates. Sodium silicate is furnished by the reaction of sea water upon hot silicate magmas of extrusive basalts or porphyries or upon the siliceous solutions coming from these extrusives as igneous after-effects or forming a part of them. Abundant vein quartz inclosing iron sulphides in the basalts and porphyries is taken to represent remnants of siliceous solutions which did not escape. These reactions were suggested by the common practice in pottery making of producing a water-glass glaze by spraying salt water against the hot silicates. Under ordinary conditions hydrochloric acid is much stronger than silicic acid, decomposing many of the silicates, but when heated hydrochloric acid is volatile and silicic acid is not, hence silicic acid may then displace hydrochloric acid from its salts and produce alkaline silicates.

By neutralization of water glass with hydrochloric acid a solution of silicic acid is obtained, along with sodium chloride formed in the reaction. To obtain the neutral point—that is, the point where the sodium silicate is just decomposed—methyl orange may be used as an indicator. This solution is boiled for some time, and the indicator shows that the solution has become alkaline, showing that alkaline silicate has formed. If again neutralized by hydrochloric acid and strongly boiled, the alkalinity returns. A solution of sodium chloride when boiled without the addition of the silicic acid shows no such alkalinity.

A solution of silicic acid and sodium chloride, if evaporated to dryness and heated, but not to fusion, has considerable alkalinity when redissolved in water, showing that alkaline silicate has formed.

From these experiments it appears that sodium chloride can be slightly decomposed by silicic acid or silica in boiling solution, forming sodium silicate, but when heated to a higher temperature sodium chloride decomposes more readily.

In addition to conducting the reactions with free silicic acid, salt water was sprayed upon a hot Keewatin basalt, with the result that a water-glass glaze was produced by reactions similar to those above described.

[a] Lehmann, O., Flüssige Kristalle sowie Plastizität von Kristallen im Allgemeinen, molekulare Umlagerungen und Aggregatzustandsänderungen, Leipzig, 1904.

REACTIONS BETWEEN GREENALITE AND IRON CARBONATE, OR CARBON DIOXIDE.

1. A source of the iron carbonate appears in the reaction of carbon dioxide upon the ferrous silicate (greenalite), either cold or hot, as follows:

$$FeSiO_3 + CO_2 = FeCO_3 + SiO_2.$$

2. Solid $FeSiO_3$ and free silica boiled with water through which carbon dioxide is passed shows iron and silica in solution in the ratio $FeO:SiO_2::0.0320:0.0362$, indicating that the greenalite, and free silica to only a slight extent, are taken into solution.

3. If carbon dioxide is passed through water in the cold containing solid greenalite ($FeSiO_3$) for twenty hours, iron and silica are taken into solution in about the proportions 1 to 1. Less, however, is dissolved than when the solution is hot.

4. If precipitated ferrous carbonate and precipitated ferrous silicate of the composition $FeO.3SiO_2$, instead of ferrous silicate and carbon dioxide, are boiled in water, carbon dioxide is given off and greenalite remains according to the following reaction:

$$2FeCO_3 + FeO.3SiO_2 = 3FeSiO_3 + 2CO_2.$$

In the cold solution both remain. This reaction is similar to 5, below, as it is probable that part of the silica is in the form of silicic acid and not combined with the iron.

5. A solution of silicic acid was boiled with precipitated ferrous carbonate. The composition of the precipitate from several determinations was variable but in each case showed decomposition of the ferrous carbonate by the silicic acid, producing greenalite. This decomposition continues until the silicic acid is entirely precipitated as ferrous silicate.

6. Alkaline silicate and iron bicarbonate react to form iron silicate.[a]

These results show that carbon dioxide will break up precipitated ferrous silicate, either cold or hot, producing iron carbonate, which is probably in solution as the soluble bicarbonate. The precipitation of the iron carbonate would follow from the loss of carbon dioxide.

The experiments show further that when carbonate is actually thrown out it may be reacted upon by silicic acid or alkaline silicates when heated, driving off carbon dioxide, indicating that the silicate is the more stable under such conditions. In the cold no reaction takes place; the silicate and carbon dioxide may exist side by side. In short, there is a constant tendency for the development of a bicarbonate and the precipitation of a carbonate of iron in the presence of carbon dioxide, but the precipitate is stable only when cold.

It appears, therefore, that the probable chemical result of the extrusion of the igneous rock into salt water carrying ferrous salts, with or without free silicic acid, is the formation of ferrous silicate with the simultaneous precipitation of free silica in proportions varying with conditions; that of the soluble salts of the bases which may have been simultaneously delivered the salt of magnesia would form an insoluble compound with the alkaline silicate and be precipitated with the iron; that such iron silicate is the first and most stable salt to form under conditions of heat; that so far as carbon dioxide is present it will tend to decompose the silicate, taking the iron into solution as iron bicarbonate, which, however, will remain as iron carbonate after precipitation only when cold, being decomposed when hot by reaction with silicic acid, or alkaline silicates. The first precipitate after the extrusion of the lava would therefore tend to be greenalite, unless the solution is acid or strongly alkaline, preventing precipitation until neutralized. It is likely to be acid from the presence of hydrochloric acid formed as a by-product of the reactions above described. Removal of this acid by heat would lead to precipitation of greenalite. The presence of a large amount of carbon dioxide, also, would prevent the precipitation of greenalite, holding the substance in solution until loss of carbon dioxide from the bicarbonate allowed the precipitation of the carbonate. The deposition of greenalite therefore depends on the absence of carbon dioxide or other acid; the deposition of carbonate depends on the abundant presence of carbon dioxide. In the last analysis the law of mass action determines which of the two shall form. Iron carbonate replacing greenalite is often observed in the Mesabi district.

[a] Bischof, Gustav, Elements of chemical and physical geology (tr. by B. H. Paul), vol. 2, 1855, p. 70.

SOURCE OF CARBON DIOXIDE FOR REACTIONS WITH GREENALITE.

The reactions above described require a source for the carbon dioxide. One source may be the carbonaceous slates so abundantly associated with the carbonates. Their distillation during the period of deposition of the carbonates would furnish carbon dioxide for these reactions. Another source may be the igneous rock from which the greenalite solutions are held to have come. To quote Chamberlin and Salisbury,[a] "The data now at command seem to indicate that carbon dioxide increases greatly in relative abundance as volcanic action dies away. Great quantities of this gas are often given forth long after all signs of active volcanism have disappeared."

DEPOSITION OF HEMATITE, MAGNETITE, AND SILICA DIRECTLY FROM HOT SOLUTIONS.

Certain facts have been described for the Keewatin iron formations indicating that the present hematitic and magnetic jaspers may not be the result of alteration of earlier ferrous compounds, but are original precipitates in the present form. The same kinds of solutions from these igneous rocks being postulated as seem to be required to produce the greenalite and carbonate, the iron oxides could be produced by the following reactions:

$$6FeSO_4 + 3O = 2Fe_2(SO_4)_3 + Fe_2O_3.$$
$$9FeSO_4 + 4O = 3Fe_2(SO_4)_3 + Fe_3O_4.$$

Magnetite may be formed in high temperatures by the reaction of ferrous iron and water, according to the following reaction:

$$3FeO + H_2O = Fe_3O_4 + H_2.$$

This reaction is reversible. As it does not require change in volume, probably pressure does not control it. As the development requires evolution of heat, the formation of magnetite is favored by lowering of temperature. Travers [b] and, later, R. T. Chamberlin [c] have shown that the free hydrogen in rocks may be developed in this manner by artificial heating.

This carries us a step farther back toward the direct pegmatitic after-effects and magmatic segregations producing the magnetites discussed on pages 561–562.

DEPOSITION OF IRON SULPHIDE.

Iron sulphides are exceptionally abundant in connection with the carbonaceous slates and iron carbonates, presumably deposited in bogs or deltas. Hydrogen sulphide characteristic of these conditions would react upon iron carbonate and produce iron sulphide.

Hydrocarbon distillates from muds or shales, such as are commonly given off in marshes, would accomplish direct reduction of soluble iron sulphates to iron sulphides.

The existence of iron sulphides as magmatic segregations and deep-seated contact minerals points to another mode of origin of iron sulphide. The ferrous sulphate and silicic acid solutions coming from extrusives being again postulated, the reduction of ferrous sulphate directly to the sulphide could be brought about in the presence of hydrogen sulphide or hydrogen, both of which might be emanations from the same mass.

The reaction of ferrous sulphate and magnetite would produce iron sulphide, according to the following reaction:

$$FeSO_4 + 8Fe_3O_4 = FeS + 12Fe_2O_3.$$

CORRELATION OF LABORATORY AND FIELD OBSERVATIONS.

It appears, therefore, that the principal original iron-bearing constituents of the iron formations, greenalite and carbonate, as well as the subordinate ones, may be produced in the laboratory with comparatively simple reactions under conditions ranging from those similar

[a] Chamberlin, T. C., and Salisbury, R. D., Text-book of geology, vol. 1, 1904, p. 590.
[b] Travers, M. W., Proc. Roy. Soc., vol. 64, 1898, pp. 130-142.
[c] Chamberlin, R. T., The gases in rocks: Pub. Carnegie Inst. No. 106, 1908.

to weathering, transportation, and deposition at ordinary temperatures, aided by organic reducing materials, to conditions of direct contribution of iron-bearing salts from the hot igneous rocks to the locus of deposition. Carbonate or greenalite might develop under either set of conditions, but on the whole the former set seems to be more favorable chemically to the development of iron carbonate associated with the carbonaceous slates and the latter set more favorable to the development of greenalite. It also appears that iron carbonate may develop from reactions of greenalite with carbon dioxide, and this is regarded as an adequate though not necessary means of precipitation of iron carbonate known to be more or less free from carbonaceous material and in close association with greenalite. Iron carbonate secondary to greenalite is commonly observed. It may be noted that when carbon dioxide reacts upon greenalite, carbon dioxide is introduced and nothing is taken away. The percentage of silica in the cherty carbonate is therefore less than the percentage of free silica in the original cherty greenalite. The exact difference in percentage will depend on the proportion of greenalite to free silica chosen for the reaction. An average of all the iron carbonate analyses available from the Lake Superior iron formations gives iron 24.56 per cent, silica 41.15 per cent. An average of all the greenalite-chert analyses gives iron 25.05 per cent, silica 55.80 per cent. These figures are derived from a sufficiently large number of samples to make them fair averages. Their validity is strengthened also by their accordance with the composition of the alteration products, the ferruginous cherts and jaspers, the average composition of which has been closely ascertained. The lower relative silica content of the iron carbonates is thus suggestive though not decisive evidence of the derivation of some of the carbonates from the greenalite rocks.

A condition also pointing to reactions between iron silicate and carbon dioxide to produce iron carbonate is the conspicuous absence in the greenalite and in some of the iron carbonate of the bases which form soluble compounds with the silicates, especially calcium and the alkalies, and the presence in the greenalite and iron carbonate of magnesia, a substance which forms an insoluble compound with the alkaline silicates. The average content of these minor constituents in the greenalite and carbonate is as follows:

Average magnesium, calcium, sodium, and potassium content in greenalite and cherty carbonate.

	Greenalite rock.	Cherty carbonate.
	Per cent.	*Per cent.*
Magnesium	4.20	5.20
Calcium	.08	.86
Sodium and potassium	None.	None.

The above argument will not apply to the exceptional iron carbonates which show gradations into limestones and ferrodolomites, as, for instance, at Gunflint Lake and at the east end of the Gogebic district.

Whether iron carbonate develops by reaction of greenalite upon carbon dioxide or under the ordinary surface weathering conditions in the presence of organic material, when we look into the probable sequence of events following the extrusion of the original iron-bearing igneous rocks and leading up to the deposition of the iron formations, we note that in either case the probable tendency would be to develop greenalite first and then carbonate. Also so far as the two are precipitated at the same time, the higher density of the greenalite would make it settle first, the carbonate following later, as shown by laboratory experiment. When the ingredients of the upper Huronian (quartz sand, mud, greenalite, and iron carbonate) are shaken up together in a vessel of water and allowed to settle, a clean layer of sand is formed at the bottom, showing a most distinct contact with the layer next above. Then follows greenalite with some carbonate and mud, then carbonate and mud with some greenalite, and finally mud with some carbonate.

Thus, whatever emphasis is put upon the different ways of producing iron carbonate, it seems probable that in any iron-bearing formation greenalite materials would be more abundant near the bottom of the formation, or near shore, and the carbonate higher up, or offshore.

The distribution of the greenalite and carbonate rocks in the upper Huronian is remarkably in accord with inferences drawn from the chemistry of their deposition. Greenalite is as yet known only at the lowest horizons of the upper Huronian and is exposed in the Mesabi, Felch Mountain, and Menominee districts and to a slight extent in the Gogebic district. In the upper part of the iron formation of the Mesabi district iron carbonate becomes relatively more abundant, and just beneath the overlying Virginia slate forms a layer up to 20 feet in thickness. In higher parts of the upper Huronian associated with the slate in the Cuyuna, Crystal Falls, Iron River, and Florence districts the iron formation consists dominantly of iron carbonate.

The presence of the carbonate near the base of the series in the Gogebic district would imply under the above principles a proportionally greater abundance of carbon dioxide there than in the Mesabi district, for unknown reasons.

SECONDARY CONCENTRATION OF THE ORES.

GENERAL STATEMENTS.

The secondary alteration of the iron formations to ore has been accomplished by both chemical and mechanical processes, under conditions of weathering, with modifications due to folding, deep burial, and proximity to igneous intrusions.

All the ores are partly the result of secondary concentration, but some have suffered more and some less concentration. Layers of iron formation originally rich in iron hav become iron ores by less concentration than have layers of iron formation originally poor in iron. In a few places in the region, as in the east end of the Gogebic district and in parts of the Mesabi district, there is evidence that certain layers of iron formation were originally nearly rich enough in iron to be mined as iron ores, after only a slight amount of secondary alteration. In such places the shape and dimensions of the original layers determine essentially the shape and dimensions of the iron ore deposits. Where secondary concentration has been largely effective in producing the iron ore, as it has in most of the larger deposits of the region, the shape and distribution of the ore bodies are determined by the structural conditions which localize the secondary concentration, rather than by the primary bedding of the iron formation.

The essential secondary changes in the development of the ores have been effected by weathering. The ores once formed, alterations effected by dynamic action, igneous intrusion, or redeposition as fragmental sediments may be regarded as for the most part subsequent and modifying factors, tending to change somewhat the character of the ores and ore deposits, but adding little to their size or richness. Dynamic and igneous metamorphism acting before the concentration of the ores tends to inhibit ore concentration by making the iron formation refractory to weathering agencies. In the following treatment emphasis will be placed accordingly.

CHEMICAL AND MINERALOGICAL CHANGES INVOLVED IN CONCENTRATION OF THE ORE UNDER SURFACE CONDITIONS.

OUTLINE OF ALTERATIONS.

It requires only the most general field observation to bring out the fact that the iron formations are being and have been rapidly altered by percolating waters carrying oxygen, carbon dioxide, and other constituents from the surface and that the present characteristics of the formations are considerably different from those they had when they first became consolidated. Now they consist mainly of ferruginous chert and jasper, with subordinate quantities of iron ore, paint rock, greenalite, iron carbonate, amphibole-magnetite rock, etc. Formerly they were more largely cherty iron carbonate or greenalite. Fortunately the alterations have not everywhere gone far enough to obliterate all the original phases of the iron formations. Gradations may be observed between original cherty iron carbonate or greenalite phases of the formations and the dominant alteration products, ferruginous cherts and jaspers and iron ores. The former are found in protected places beneath slate or other impervious cappings; the latter occur in portions of the formations exposed to percolating oxidizing waters. The former are ferrous compounds, unstable under conditions of surface weathering; the latter are the stable oxides, end products of weathering. The ferruginous cherts, jaspers, and iron ores furthermore retain textures characteristic of carbonate and greenalite, thereby betraying their derivation from these substances. This is especially noticeable in the ores and cherts derived from greenalite, the peculiar granular shapes of the greenalite being conspicuous in its derivatives. The red, brown, and yellow colors of the altered phases of the formations, the ores and ferruginous cherts, contrast strongly with the gray and green of the original cherty carbonate and greenalite, making the alterations conspicuous to the eye, especially along fissures in the original rocks.

The secondary alterations of iron carbonate and greenalite rocks to iron ore involve (1) oxidation and hydration of the iron minerals in place, (2) leaching of silica, and (3) introduction of secondary iron oxide and iron carbonate from other parts of the formations. These changes may start simultaneously, but the first is usually far advanced or complete before the other two are conspicuous. The early products of alteration therefore are ferruginous cherts—that is, rocks in which the iron is oxidized and hydrated and the silica not removed. The later removal of silica is necessary to produce the ore. The secondary introduction of iron oxide and iron carbonate in cavities left by the leaching of silica is of little importance in the alteration of the greenalite rocks to ore. In the alteration of the carbonates to ore it is frequently a conspicuous feature. The alteration of the original rocks of the iron formations to ore may therefore be treated under two main heads—(1) oxidation and hydration of greenalite and siderite, producing ferruginous chert; (2) alteration of ferruginous chert to ore by leaching of silica, with or without secondary introduction of iron.

OXIDATION AND HYDRATION OF THE GREENALITE AND SIDERITE PRODUCING FERRUGINOUS CHERT.

The oxidation of the cherty iron carbonates and greenalites to hematite or limonite produces ferruginous cherts of varying richness. (See Pls. XLII, *C*, *D*; XLIII–XLV.) During these changes the iron minerals for the most part are altered in place, but iron may also be transported and redeposited. Evidence of this is abundant in the stalactitic and botryoidal ores lining cavities or incrusting secondary quartz crystals and numerous veins of ore cutting across the bedding of the formation. It will be shown in the following discussion, however, that the principal enrichment of the ore takes place in connection with the removed silica, although in several districts the introduction of iron is very important. The oxidation and hydration of the original iron minerals are expressed in the following reactions:

$$4FeCO_3 \text{ (siderite)} + nH_2O + 2O = 2Fe_2O_3.nH_2O + 4CO_2.$$
$$4Fe(Mg)SiO_3.nH_2O \text{(greenalite)} + 2O = 2Fe_2O_3.nH_2O + 4SiO_2.$$

The alteration of the iron minerals is facilitated by small amounts of acids carried by percolating waters. Carbonate of iron is soluble with difficulty in pure water and not easily soluble with an excess of carbon dioxide. On the other hand, it is easily soluble in either of the stronger acids, sulphuric or hydrochloric. Sulphuric acid results from the decomposition of the iron sulphide in the original carbonates and in the adjacent pyritiferous greenstones and slates. The reaction may be—

$$FeS_2 + H_2O + 7O = FeSO_4 + H_2SO_4 .$$

This is aided in turn by carbon dioxide in the water. Thus the iron sulphide is oxidized to ferrous sulphate, with the simultaneous production of sulphuric acid, which attacks the iron carbonates and changes them to soluble ferrous sulphate. In the Michipicoten district, where glacial erosion has cut deep, sulphides are found abundantly with the carbonates. Sulphate of iron is present in veins in the ores of the Iron River district. Bayley[a] found the white efflorescence characteristic of Menominee ores to be essentially sodium sulphate with the formula of Glauber salt, $Na_2SO_4 + 10H_2O$, which he regards as the result of decomposition of pyrite

[a] Bayley, W. S., The Menominee iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 46, 1904, pp. 390–391.

PLATE XLIII.

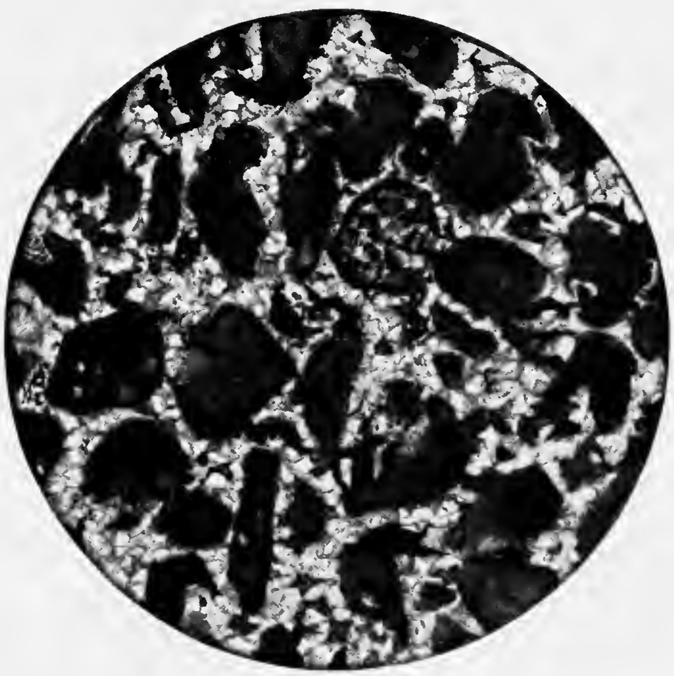
PLATE XLIII.

Photomicrographs of greenalite granules.

A. Greenalite rock (specimen 45178, slide 15652) from 100 paces north 500 paces west of the southeast corner of sec. 22, T. 59 N., R. 15 W., Mesabi district, Minnesota. Without analyzer, × 50. The slide is selected to show both the fresh and the slightly altered granules. Note the peculiar greenish-yellow color of the grauules, their irregular shape, and their curving tails, some of which seem to connect with adjacent granules. The homogeneous greenish yellow colors represent the unaltered parts. The hright-green and dark-green colors represent grünerite which has been developed from the alteration of the greenalite. The dark green is perhaps in small part iron oxide. Described on pages 165–168.

B. The same with analyzer, × 50. The unaltered portions of the granules are nearly or quite dark under crossed nicols. Where the granules have altered to grünerite the polarization colors appear. The matrix consists of fine-grained chert in which the individual particles are very irregular in shape and size. Described on pages 165–168.

(A)



(B)

PHOTOMICROGRAPHS OF GRUNALITE GRANULES.

PLATE XLIV.

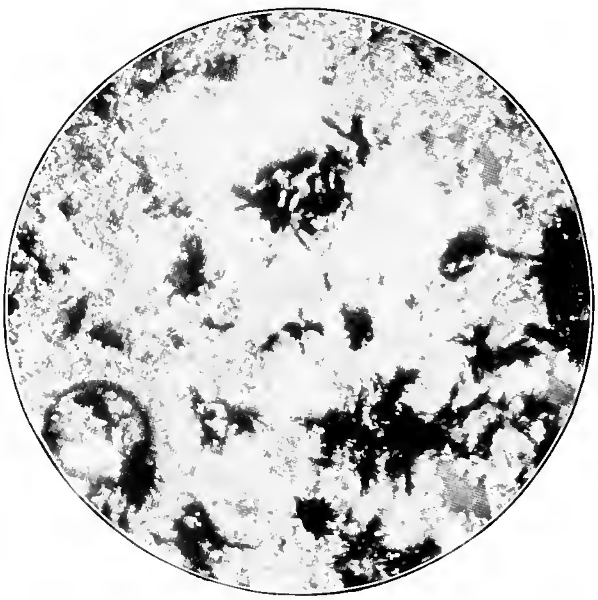
PLATE XLIV.

PHOTOMICROGRAPHS OF FERRUGINOUS CHERT SHOWING LATER STAGES OF THE ALTERATION OF GREENALITE GRANULES.

A. Ferruginous chert with granules (specimen 45063, slide 15563) from near center of sec. 22, T. 60 N., R. 13 W. Without analyzer, × 50. The granules are outlined and in part replaced by iron oxide. The matrix is chert. The complex nature of one of the granules is to be noted. Apparently one complete small granule is entirely inclosed in another large one. Described on pages 168–170.

B. Grüneritic ferruginous chert (specimen 45603, slide 15974) from Clark mine. With analyzer, × 50. The rock consists of chert and iron oxide and grünerite. The iron oxide is a yellowish-brown hydrated variety, which is with difficulty distinguished from the grünerite. The granules have been entirely obliterated. Described on pages 168–170.

A.



B.

PHOTOMICROGRAPHS.

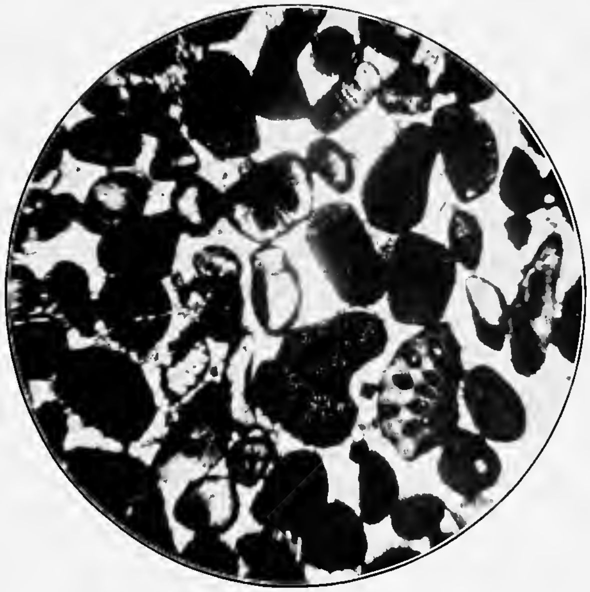
PLATE XLV.

PLATE XLV.

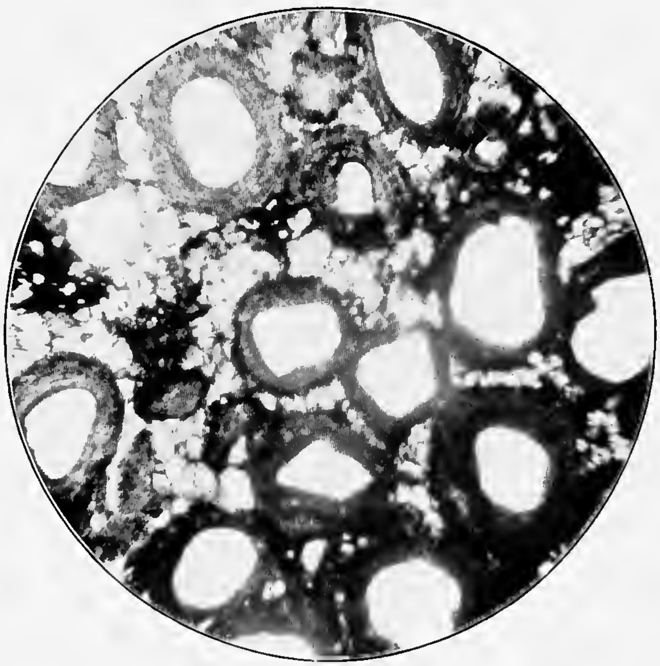
PHOTOMICROGRAPHS OF GRANULES AND CONCRETIONARY STRUCTURES IN CLINTON IRON ORES.

A. Granules in Clinton iron ore, from lower bed, Sand Mountain, New England City, Ga. Loaned by C. H. Smyth, jr. Without analyzer, × 40. Granules of black and dark-brown hydrated hematite stand in a matrix of calcite. The latter areas within the granules are also calcite. Traces of organic shells in these slides are abundant. The granule a little to the right of the center shows this especially well. There can be no doubt as to the fact that the granules are for the most part replacements and accretions about shells and particles of shells. It is apparent also that there is a marked tendency for the granules to take on rounded and oval forms regardless of the shape of the original particles of shell. Note the remarkable similarity of these granules in shape to the greenalite granules illustrated in Plate XLII, *A*, *B*.

B. Green oolites in Clinton ore, from Clinton, N. Y. Loaned by C. H. Smyth, jr. With analyzer, × 40. Concentric layers of chloritic and siliceous substance, of various shades of green and yellow, surround angular, subangular, and rounded grains of quartz. The concentric greenish and yellowish bands under crossed nicols show black crosses characteristic of concretionary structures. The matrix is mainly calcite, but there are present also small particles of quartz.



A.



B

PHOTOMICROGRAPHS.

and muscovite. Iron sulphides and chalcopyrite are also common as vein fillings. Sulphates are found in mine waters. (See pp. 543–544.) Humus acids are also well known to aid in the solution of the iron.

Precipitation of the iron from ferrous solutions would be caused (1) by direct oxidation and precipitation as limonite; or (2) by reaction with alkaline carbonate, producing iron carbonate, which in this form in the presence of oxygen alters almost immediately to hydrated iron oxide; or (3) by loss of carbon dioxide. A small amount of secondary iron carbonate, where iron is carried in solution as bicarbonate, observed locally in each of the districts, is incidental to the main process of oxidation producing ferruginous cherts.

The oxidation of the iron in the carbonate and greenalite goes on much more easily and rapidly than the removal of the silica and may affect most or all of the carbonate or greenalite, producing ferruginous cherts, before the removal of the silica has gone far enough to be appreciable. An epitome of the story for the formation is presented by almost any hand specimen of iron carbonate or greenalite. The ferruginous cherts are, therefore, intermediate phases between the original greenalite or siderite and the ore, and the principal removal of the silica is subsequent to the formation of the ferruginous cherts. Given sufficient time and the other necessary favorable conditions and any part of them may become ore. In districts where greenalite is the dominant original iron compound, so far as can be determined, the layers of chert in the ferruginous cherts prior to their alteration to ore are not very different in number, iron content, and degree of hydration from those in the greenalite rocks, indicating but little transfer of iron, though locally the segregation of silica and iron oxide into bands is more accentuated. In districts where carbonate is an important original iron salt, the rearrangement, transportation, and introduction of iron salts are quantitatively important. This is probably due to the structural conditions described on page 538. Slight rearrangements of the iron ore are to be seen in the concretions composed of alternate concentric layers of chert and iron oxide developed during the alteration. These develop both from the iron carbonate and from the greenalite.

Not uncommonly oxidized greenalite cherts are found alongside of unoxidized iron carbonate cherts. At first thought this would seem to indicate the readier oxidation of the greenalite than the carbonate, but it is not certain that this is the case, for it is sometimes found that the carbonate in these relations is secondary, and another possibility is that the greenalite was oxidized at the time of its precipitation rather than secondarily.

ALTERATION OF FERRUGINOUS CHERT TO ORE BY THE LEACHING OF SILICA, WITH OR WITHOUT SECONDARY INTRODUCTION OF IRON.

PROCESSES INVOLVED.

Ore may be formed (1) by taking away silica from the ferruginous cherts, leaving the iron oxide; (2) by taking out silica and introducing iron in its place; or (3) by adding iron to an extent sufficient to make the percentage of silica a small one. In the last case there would necessarily be a large increase in volume. Quantitative tests show that (1) is of greatest importance, that (2) is effective only in some of the ores derived from carbonates, and that (3) is practically negligible.

Measurements of pore space of the ores derived from the alteration of ferruginous cherts of greenalitic origin bring out the facts that pore space approximates the volume of silica which has been removed (see pp. 184–185), when there has been little slump; in other words, the filling of the pore space in the ores by silica would nearly reproduce the composition of the ferruginous cherts. It will be shown also that the leaching of silica from the ferruginous cherts derived from greenalite alterations does not materially affect the character of the iron oxides, especially their degree of hydration, and that therefore the nature of the ore of the deposit is primarily determined by the changes which the greenalite undergoes when it alters to the oxide bands of the ferruginous cherts.

Measurements of pore space in ores derived from ferruginous cherts, which in turn have been derived from the alteration of iron carbonate, show that the pore space is less than the volume of the silica which has been removed. (See p. 241.) This is due partly to slump, but mainly to the fact that secondary iron oxide partly fills the openings.

The range in which there is conspicuous absence of evidence that iron has been transported to any considerable extent is the Mesabi, where the flat dip exposes a large portion of the formation directly to oxidizing waters, and oxidation works down more or less uniformly from the surface, leaving few unoxidized portions to contribute soluble iron salts to be carried down and mixed with deeper oxidizing solutions following channels from the surface. In the other districts, where the evidence of the carrying of iron is plain, the formations are so tilted that the underground courses of oxidizing waters from the surface pitch deeply, leaving unoxidized iron formation above as a source for soluble iron salts, which may be taken into solution and carried down, and, by reaction with oxidizing waters, precipitate the iron oxide. This deep circulation of oxidizing waters afforded by steeply tilted formations permits the leaching of silica at depth, thus providing openings in which the iron carried in solution from the upper unoxidized portions of the formation may be deposited. It is in this essential that the Mesabi conditions differ from those of the other ranges.

Silica dissolved from the iron formations has been in small part redeposited in veins, both in ore and rock and in the crystallized quartz linings of many cavities in the ore, and in part has joined the run-off. The process is going on to-day, for mine and surface waters carry silica (see pp. 540–544), and quartz linings of cavities may be seen to have developed since mining explorations began. It has been suggested that the abundant chert in the ferruginous cherts themselves might represent materials previously leached from other parts of the formations and redeposited. As the cherts are very dense (see p. 545), there would be no room for the addition of secondary silica except that made by the volume change in the alteration of iron minerals or by the previous leaching of silica. Undoubtedly cavities of both sorts have been filled to a certain extent by silica. But the process of the average increase of silica would involve a reversal of the one which is actually observed to occur—that is, the leaching of silica from the ferruginous cherts, producing the ores. We are forced to the conclusion that while as in any metamorphic process in the belt of weathering silica is removed and silica is deposited, the former change is predominant. A parallel may be cited in the development of caves in limestone by solution and deposition, the process of solution predominating.

CONDITIONS FAVORABLE TO LEACHING OF SILICA.

The loss of silica from the ferruginous cherts on a large scale requires exceptionally favorable conditions. These conditions seem to be (1) the ready access of dissolving solutions to large surfaces of the chert and (2) the alkaline character of the dissolving solutions.

The fine and irregular grain of the quartz in the ferruginous cherts affords large surfaces of contact with the water, thereby favoring solution. It is noted that where the cherts have been coarsely recrystallized under the influence of intrusives there is much less tendency for the silica to go into solution. Much of the silica in the cherts is cherty or opaline and thus easily soluble.

The conditions favorable to rapid and abundant flow of water are due largely to structural causes, which are discussed on pages 474–475. A large amount of water is needed to effect the removal of silica. Merrill[a] estimates that the removal of a unit of silica requires 10,000 times its weight in water. The removal of a large amount of silica from the iron formations which has been necessary to produce the ore deposits has therefore required a large amount of water for each unit removed—in other words, free and vigorous flow. Thus is explained the concentration of the ores along zones of easy flow where water is abundantly concentrated.

SOLUTION OF SILICA FAVORED BY ALKALINE CHARACTER OF WATERS.

The solution of silica is favored by the alkaline character of the waters. Alkaline carbonates react upon quartz, forming soluble alkaline silicates with release of carbon dioxide. Sodium carbonate may not stand in a glass bottle without dissolving it. Well waters in the

[a] Merrill, G. P., Rocks, rock weathering, and soils, New York, 1897, p. 238.

vicinity of Ironwood, Mich., obviously the same waters that are entering the formations, are throughout alkaline in their reactions. Many solution cavities left by the leaching of silica are lined by adularia crystals (potassium feldspars), as in the cavities left by the leaching of quartz pebbles from the ore at the base of the upper Huronian of the Marquette district.

All the ore deposits of the Lake Superior region are close enough to igneous rocks to have been altered by waters which have probably derived an alkaline content from the leaching of the igneous rocks. In the Mesabi district all the waters entering the iron formation have previously come down across the Giants Range granite and in a few places have met granite dikes within the formation and thoroughly leached them of their bases. In the Gogebic district the dikes (see analyses, p. 246) closely associated with the ores have been so thoroughly leached of their bases that the residual clayey material is known as paint rock or soapstone. A glance at the map of the Marquette district (Pl. XVII, in pocket) will show the abundance of basic intrusive rocks in the iron-bearing areas. These again near the contact with the ores have been altered to soap rock and paint rock, thereby delivering their bases to the solutions which have developed the ore. In the Crystal Falls district the relation is not less obvious. The ores are throughout not far from the basic eruptive rocks. In the Cuyuna district intrusive rocks are everywhere associated with the ores. In the Menominee district the relation is not so obvious, although the igneous rocks appearing on both sides of the Menominee trough may well have affected the character of the water in the ores. Probably, however, the waters have been rendered effective principally by solution of the dolomite associated with or immediately underlying nearly all the deposits. It is noted in nearly all the districts that where the ore comes into contact with slate the slate has been altered to paint rock. A comparison of the composition of paint rock and the unaltered slate shows that alkalies have been taken out in the development of the paint rock. Here again, then, is a factor favoring the alkaline character of the waters.

TRANSFER OF IRON IN SOLUTION.

So far as iron is carried in solution it is probably in the early stages of the alteration of any particular part of a formation, when there are still ferrous compounds to work upon. When nothing but ferric iron remains, this is insoluble and the principal further alteration is the removal of silica. If the iron finds lodgment in the formation before the silica is taken out it can be only on a small scale, for the voids are not large enough to contain much ore. When iron is introduced after all the silica is taken out, its introduction may not materially change the percentage of iron in the ore. It will merely reduce the pore space.

SECONDARY CONCENTRATION OF THE ORES CHARACTERISTIC OF WEATHERING.

Quartz is ordinarily regarded as practically insoluble in surface waters. It might be argued that the conditions above cited are not peculiar to iron formations alone but may be found elsewhere, and the question is raised whether elsewhere quartz is largely taken into solution. We believe that quartz is taken into solution under ordinary conditions of weathering to a larger extent than is generally recognized, and that it is apparently stable because it is usually associated with more soluble constituents, thereby contrasting with the iron formations, where the quartz is associated with less soluble constituents against which the loss of quartz may be measured. A series of three analyses of fresh granite, partly altered granite, and much weathered granite from Georgia published by Watson,[a] when recalculated in terms of minerals, shows that in the early stages of the alteration the quartz is but little affected, but that in the last stage there is unquestionable evidence of considerable leaching of free quartz.

In general comparison of analyses of fresh and weathered igneous and other rocks shows that iron and alumina are the two most stable constituents and that in weathering under oxidizing conditions silica is lost more readily than the iron. The iron formation, consisting principally of iron minerals and silica and lacking alumina, would therefore be expected to retain its iron

[a] Watson, T. L., Granites and gneisses of Georgia: Bull. Geol. Survey Georgia No. 9A, 1902, p. 302.

under weathering to a greater extent than the silica, and in so doing has followed the general laws of katamorphism. The absence of evidence of transfer of iron during secondary concentration on a large scale is in strong contrast with its transportation in large amounts in the primary concentration. The secondary local transfers of iron in the ferrous condition before it is oxidized to the stable form are characteristic of both the iron formation and igneous rocks and do not disprove the general principle above stated.

In general the same processes of weathering that have produced residual clay from igneous rocks are the ones which have secondarily concentrated the iron ores. Most igneous rock contains so little iron and so much alumina and silica that secondary concentration fails to produce an iron ore directly from it; it produces an iron-stained clay. Exceptionally, however, as from the serpentine rocks of Cuba, which have a low content of alumina, secondary concentration has produced a mixture of iron ore and clay, and the clay, by extreme weathering at the surface, has broken down further, by loss of silica, to bauxite. The result is a lateritic iron ore.[a]

MECHANICAL CONCENTRATION AND EROSION OF IRON ORES.

The loosening of silica grains by solution locally makes it possible for them to be carried mechanically by the meteoric waters. This process becomes one of some importance when the openings have been made sufficiently large by solution. Where the mine waters are dammed, there is very commonly a considerable sediment of fine-grained chert sand. This process probably also explains the occurrence of finely granular chert sand in seams and crevices in certain Mesabi ore deposits. The process is probably more conspicuous now than it was before mining openings gave a chance for the accumulations of these silica sands. It is difficult to see where, under original conditions, these sands could have been deposited. They are found filling openings underground only to a very small extent, and it is unlikely that they would follow the underground waters into the run-off.

So far as pore space has been lessened by mechanical slump anywhere through the iron formation, this amounts to a decrease in volume and increases the amount of iron in a given volume of iron formation. It is shown in the chapters relating to the different districts that this process has gone on to a considerable extent.

Locally, as at the base of the Vulcan formation in the Menominee district, at the base of the Goodrich quartzite in the Marquette district, and in the Cretaceous of the Mesabi district, there is fragmental detritus derived by the processes of disintegration, transportation, and sedimentation from earlier-formed iron-bearing formations. Where this includes sorting, it amounts to mechanical concentration (Pl. XLVI).

Artificial concentration of ore by removal of the chert through washing is now being practiced on the western Mesabi, where the chemical processes have gone just far enough to loosen the chert. There is an enormous mass of material available. In fact, this is the partly altered iron-bearing formation itself, rather than concentrations within the formation. A considerable amount of iron is lost during the process, because the iron and chert are attached to each other. Much of the silica in the ferruginous cherts is so very fine grained and so intimately associated with the iron that it could probably never be separated by crushing and washing. That separation is possible on the western Mesabi is due to the banded nature of the ferruginous chert and the fact that the finer-grained portions have been removed by solution, leaving the larger pieces of chert loose.

GENERAL CHARACTER OF MINE WATERS.

The mine waters of all but the deepest parts of some of the mines are characterized by considerable contents of carbonates of the alkalies and alkaline earths, together with silica. Iron is usually present only in traces or entirely lacking.

The shallower mine waters are represented by the following analyses:

[a] Leith, C. K., and Mead, W. J., Origin of the iron ores of central and northeastern Cuba: Bull. Am. Inst. Min. Eng. No. 51, 1911, pp. 217-229.

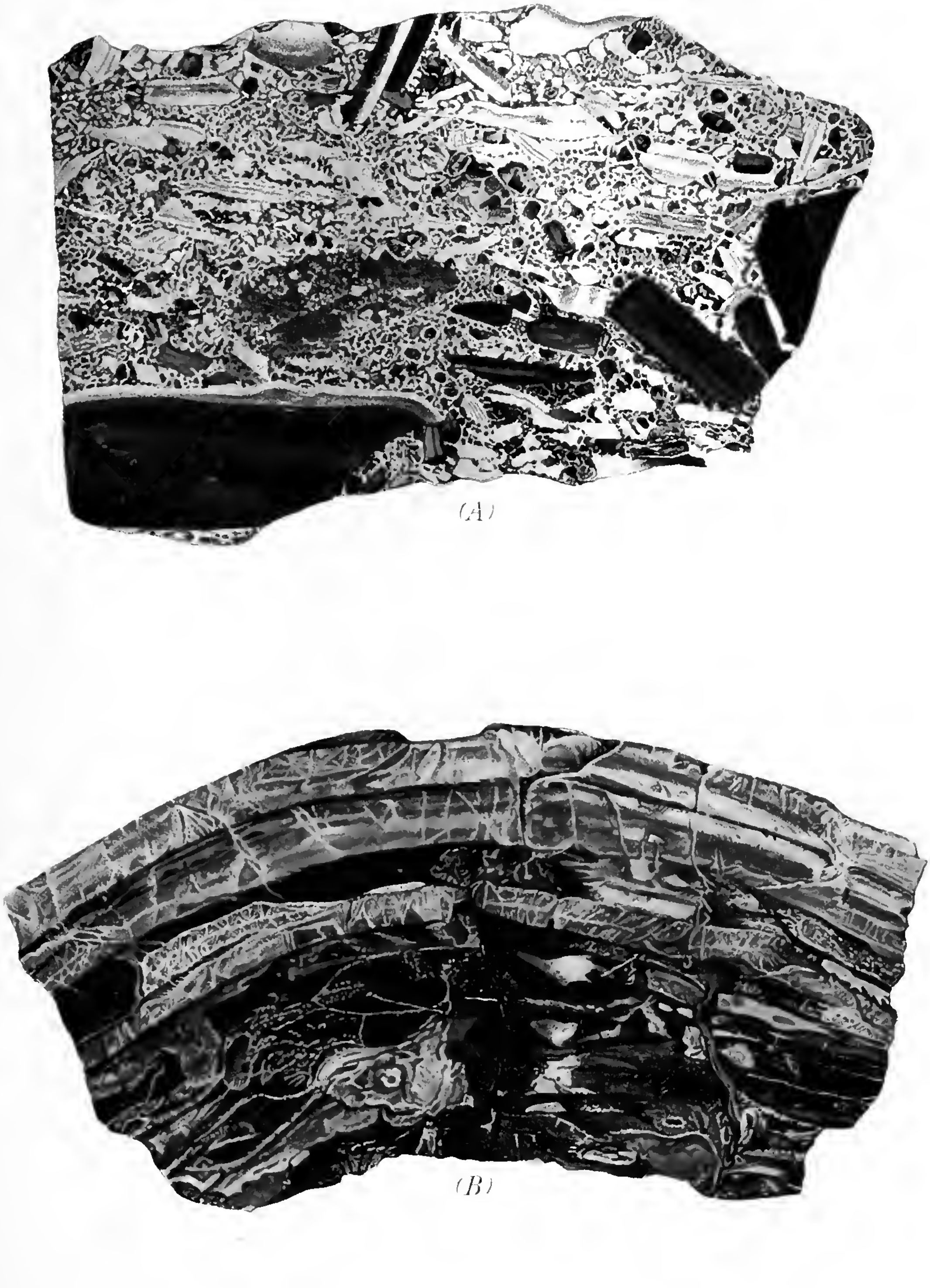
PLATE XLVI.

PLATE XLVI.

Ore and jasper conglomerate and ferruginous chert.

Ore and jasper conglomerate from Saginaw range, Marquette district, Michigan. This is a typical basal conglomerate of the Goodrich quartzite of the upper Huronian. The detritus consists almost wholly of various materials derived from the Negaunee formation, including jasper, chert, and ore. There is present, however, some quartz derived from the Archean. A close examination of the illustration shows that secondary hematite and magnetite have largely formed in the spaces between the grains about many of the jasper fragments, and, indeed, have partly replaced the jasper fragments themselves. This is beautifully shown at the lower left-hand corner of the figure. In the places where the basal conglomerate is fine grained these replacements by iron oxide may be almost complete, in which case an iron-ore deposit is formed. Of such an origin is the iron ore of the Volunteer and some other mines.

Ferruginous chert from point south of Jackson mine, Marquette district, Michigan (sec. 1, T. 47 N., R. 27 W.). The iron oxide and chert were largely concentrated into bands before the last folding. At the time of the folding radial cracks were formed, especially in the chert layers, owing to the position of the rock on the crown of an anticline. Along these cracks the silica has to some extent been leached out and iron oxide introduced. One light-colored area of chert appears to be a secondary infiltration, but it was apparently present before the last folding, as it is fractured in the same way as the other layers. Natural size.



(A) ORE AND JASPER CONGLOMERATE FROM MARQUETTE DISTRICT, MICHIGAN
(B) FERRUGINOUS CHERT

Analysis of water from a drift between the Hull and Rust mines west of Hibbing, Mesabi district.[a]

[Parts per million.]

CO_2	71
SiO_2	22.35
SO_4	2.2
PO_4	Trace?
Fe	Not a trace.
Ca	10.1
K	.97

Analysis of water from Newport mine, Gogebic district.

[Parts per million. Analyst, R. D. Hall, University of Wisconsin.]

SiO_2	8.43
Fe_2O_3	1.23
Al_2O_3	.6
CaO	21.3
MgO	16.1
Na_2O	5.4
K_2O	1.83
Cl	6.0
SO_3	10.8
CO_2 (combined) as carbonate	30.5
CO_2 (free) as bicarbonate	18.0
P_2O_5	None.
Drying at 100°	108.3
Ignited	68.6

Some of the deep mine waters have been found to be highly concentrated solutions of calcium and sodium chlorides, according to the following analyses. Such waters are extremely corrosive in boilers and pumps.

Analyses of Michigan iron mine waters.[a]

	Vulcan.			Ishpeming.	Ironwood.	Hurley.	Bessemer.	Champion.	Republic.
Total solids (soluble)	0.340	0.344		0.232	0.142	1.493	0.309	7.15	45.59
Nonvolatile, or solids after ignition	.250				.0876				
Organic	.052			(.020)			.055		
Carbonate ion (CO_3)	.051	.163	.171	.046	.070	(.037)	(.050)		
Chlorine (Cl)	.061	.019	(.007)	.034	.016	.638	.060	3.061	25.36
Calcium (Ca)	.060	.062	.062	.022	.025	.220	.040	.817	7.202
Sodium (Na)	(?)	.006	.011	(.047)	.003	.081	(.039)		7.29
Magnesium (Mg)	.038	.028	.030	.005	.009	.073	.008		.560
Potassium (K)	Tr.	.013	.004	{With ?Na}	(?)	Tr.			
Silica (SiO_2)	.006	.010	.011	.010	.012	.010			
Alumina (Al_2O_3)	.004	.018	.002	.001	.001	.020	.003	Not det.	.700
Iron oxide (Fe_2O_3)	Tr.							0	Tr.
Sulphate ion (SO_4)	.043	.013	.011	.040	.005	.058	.040	.37	1.045
Sum	.263	.332	.309	.205	.141	1.137			
Ratios:									
Ca : Cl_2	.99	3.2	8.9	.65	1.56	.345	.66	.27	.31
Na : Cl_2	0	.315	1.8	1.38	.187	.127	.65		.284
SO_4 : Cl	.70	.68	(1.47)	1.18	.31	.092	.66	.12	.41

[a] Furnished by A. C. Lane, State geologist of Michigan, March, 1909.

Highly mineralized waters have also been found on the eighth level of the Great Western mine, in the Crystal Falls district of Michigan. No analyses are available, but tests by the mine chemists showed the presence of calcium chloride and magnesium sulphates.

The upper carbonate waters are abundant, rapidly flowing, dilute, and more or less direct from the surface, carrying gases of the atmosphere. They are the waters which accomplish the major part of the secondary concentration of ore, as shown by the limitation of the ore deposits to places of rapid circulation of these waters and further by the known chemical effects of waters of this type upon the original iron-bearing formation.

[a] Mon. U. S. Geol. Survey vol. 43, 1903 p. 264.

The deep chloride waters are relatively minute in quantity and highly concentrated. Their distribution is very irregular. Small reservoirs may be tapped and exhausted alongside of flows of fresher water. Waters of very similar characteristics are found in the deep copper mines of the Lake Superior region, in the deep levels of the Silver Islet silver mine,[a] on the north shore of Lake Superior, in deep wells in the Paleozoic of the upper Mississippi Valley, in the granites of the Piedmont area of Georgia, and elsewhere. Their characteristics seem not to be related to certain kinds of rocks or ore deposits, but to depth and stagnant conditions. Chlorine is present in minute quantities in original igneous rocks and in nearly all surface waters. Its salts tend to remain in solution, while the salts of other acids are more largely precipitated. With a given amount of water, there seems likely to be, therefore, a progressive relative accumulation of chlorine salts. Such is the case in salt waters at the earth's surface, where a large factor in the accumulation is the lack of sufficient circulation to carry off and dilute the salt waters that are developing by evaporation. In deep underground waters there is essentially the same condition of stagnancy, and therefore we suggest progressive accumulation of soluble chlorine salts. In the shallower mine waters the rapid circulation and accession of fresh waters from the surface prevent such accumulation of salt.

The proportion of sodium chloride to calcium chloride in deep mine waters in the Lake Superior region becomes relatively less with increase in depth, indicating that the increasing content of chlorine is able to hold not only all sodium present but larger amounts of calcium. The materials in solution under any conditions must be regarded as representing the residual solutions from which all possible insoluble minerals have already crystallized out. All the Lake Superior mines, both iron and copper, are associated with basic rocks in which calcium greatly predominates over the sodium, so that whenever the sodium is taken care of by the chlorine present there should always be a considerable excess of calcium available.

Lane, who has given special attention to deep mine waters and who has brought together the analyses above quoted, offers quite another explanation for the characteristics of these deep waters. He believes them to be connate or fossil sea waters, included in the rocks, both igneous and sedimentary, during submarine deposition. The fact that they differ from present sea water in having so large a proportion of calcium chloride he ascribes to a possible change in composition of the sea water during geologic time in the direction of increasing the proportion of sodium chloride as compared with calcium chloride to the present known proportion of sea water. We do not follow him in this conclusion because of the fact, already cited, that these peculiar salt waters seem to be characteristic not only of marine sediments but of sediments of subaerial origin, of surface eruptives, and of plutonic igneous rocks. They are related to depth and stagnancy rather than to kind of rock or geologic horizon. There seems to be no adequate reason for regarding these waters as fossil sea waters, for all the essential kinds of conditions which produce the salt water of the ocean are present.

LOCALIZATION OF THE ORES CONTROLLED BY SPECIAL STRUCTURAL AND TOPOGRAPHIC FEATURES.

From the foregoing discussion it appears that the iron ores constitute concentrations in the exposed parts of the iron-bearing formations accomplished on the average mainly by the removal of associated silica, leaving the iron oxidized and in larger percentage, but to an important extent accomplished also by solution, transportation, and redeposition of the iron when it was still in its soluble ferrous condition. The agents of alteration are surface waters carrying oxygen and carbon dioxide from the atmosphere. The accessibility to the iron-bearing formations of these agents therefore determines the location, shape, and size of the deposits. The structural conditions favoring such accessibility have been summarized in the earlier part of this chapter (see pp. 474–475), and are discussed in some detail in connection with the ores of the individual districts. They may be merely mentioned here. The most favorable condition is afforded by wide area of exposure of the formation, which in turn is a function of the dip. Fractures,

[a] Ingall, E. D., Report on mines and mining on Lake Superior: Ann. Rept. Geol. Survey Canada for 1887-88, vol. 3, pt. 2, 1889, p. 28H.

impervious basements, and varying porosity also serve to concentrate the circulation. Ores are not found, however, in some places where area, fractures, and impervious basements seem to be favorable for ore concentration. This is believed to be due in some part to the denseness of the cherts in these places, preventing access of water. Wherever the rocks are dense the silica is not removed. The amphibole-magnetite cherts, the unaltered greenalite and siderite rocks, and the quartzites associated with the iron-bearing formations all have very little pore space, as shown by a considerable number of determinations. Silica is not removed directly from these rocks. On the other hand, the ferruginous cherts, resulting from the alteration of cherty iron carbonates and greenalites, contain pore space averaging about 5 per cent, developed by the lessening of the volume of the iron minerals during their alteration from the ferrous to the ferric form. This pore space is so distributed as to give the water access to all parts of the rock mass. The size of grain is so small that for each grain there is a large surface in proportion to volume. But even the ferruginous cherts are locally so dense that they do not allow ready access of water. Several possible reasons may be suggested for this unusual density. (1) The ferruginous cherts at these places may not have been derived by alteration from cherty carbonates or greenalites but may have been deposited directly in their present form as chemical sediments with small pore space. It has been shown that this could easily go on with the deposition of greenalite and carbonate. This explanation would seem to be especially likely to hold for certain of the amphibolitic cherts of the Keewatin, which are intimately associated with basalt flows both above and below and which it is entirely conceivable might have been originally deposited in a condition different from those of the cherty carbonates and greenalites of the later iron-bearing formations. (2) Metamorphism of the cherts under pressure after pore space had been developed by oxidation of the iron minerals may have closed the openings before the silica had been taken out. Cherts which have been much folded and contorted at so great depth as to be deformed without fractures are almost invariably dense. The Keewatin iron-bearing formations are the oldest and have naturally suffered more from such metamorphism than the later formations, and this may be a factor in the barrenness of the Keewatin. On the other hand, larger areas of the upper Huronian are comparatively little deformed and pore spaces formed by the oxidation of the iron minerals have remained substantially open since upper Huronian time. (3) The openings may have been closed by infiltrated silica and iron. In the Marquette jasper, secondary materials completely heal the rock. The relative importance of these conditions affecting pore space varies from place to place and between the different iron-bearing formations, and this variation is believed to account in large measure for the marked differences in enrichment of different formations and different parts of formations.

Undoubtedly the processes of secondary concentration above described tend to affect to a greater or less degree all the exposed surface of the iron-bearing formations. It is not unlikely that in long periods of slow denudation ores may have actually covered all of this surface. It is equally obvious, however, that the covering had various depths, depending on a considerable variety of structural conditions. The glacial denudation has scraped off ore which may once have developed at the surface, and little has developed since. There remain only the lower parts of the deposits left by denudation. A discussion of the structural conditions governing the ore deposits is therefore really a discussion of the conditions determining their lower limit and configuration. The structural and topographic conditions of each of the districts are summarized in other chapters.

QUANTITATIVE STUDY OF SECONDARY CONCENTRATION.

The nature of the secondary concentration of Lake Superior iron ores has been in the past inferred almost entirely from qualitative evidence. The extensive commercial development of the ores of this region during recent years now makes available data for quantitative study of the origin and concentration of the ores. Although there is a great similarity in the secondary concentration of all the iron ores of the Lake Superior region, certain local differences require that each of the several districts be discussed independently. This is done in the chapters on the several districts.

The average change in secondary concentration, based on all available analyses (see p. 181), is graphically expressed in figures 20 (p. 189) and 31 (p. 245).

ALTERATIONS OF IRON-BEARING FORMATIONS BY IGNEOUS INTRUSIONS.

ORES AFFECTED.

The changes described in the foregoing sections have completed the development of the ore deposits of the Mesabi, Gogebic, Menominee, part of the Marquette, Crystal Falls, Iron River, Florence, and Cuyuna districts, which yield roughly 93 per cent of the total ore mined annually in the region. Other ores, such as the hard ores of the Marquette and Vermilion districts and the magnetic rocks of the Mesabi and Gogebic, have suffered certain additional vicissitudes of anamorphic alterations by igneous intrusion, thus becoming the hard, dense, recrystallized, more or less magnetic, dehydrated, and silicated ores described below. (See Pls. XXXV, p. 470, and XLVII.) The development of some of these characteristics may have been synchronous with the deposition of the iron-bearing formation under the influence of contemporaneous igneous extrusives, discussed on page 527, but whatever the probability of this there is no doubt that characteristics of this kind have been developed mainly by later intrusives.

The intrusion of small masses of igneous material, as the dikes in the Gogebic district and certain of the bosses in the Marquette district, has apparently but slightly metamorphosed the iron-bearing formation. Where great masses of igneous material have come into contact with the iron-bearing formation, however, marked results have followed, as near the Duluth gabbro, the gabbro of the western Gogebic district, and the intrusives of the western Marquette district.

POSSIBLE CONTRIBUTIONS FROM IGNEOUS ROCKS.

The characteristic features of the amphibole-magnetite rocks of the iron-bearing formations described above become more accentuated in approach to the igneous rocks, leaving no doubt that they are the metamorphic result of the intrusion of the gabbro. The facts available indicate to some extent also the processes through which this result is accomplished. The question first to be answered is whether or not the iron-bearing formation owes its characteristics near the contact to direct contribution from the hot intrusives or to the recrystallization of substances already in the iron-bearing formation. The essential similarity of composition of the amphibole-magnetite rocks with that of the ferruginous cherts (see p. 204) argues against large introduction of materials from the gabbro. Had such materials been introduced on a large scale they would probably have considerably changed the proportions of the elements present, for otherwise it would be necessary to assume that the materials contributed from the gabbro had been in the same proportion as those originally present in the iron-bearing formation. The magnetite in the gabbro is titanic, while that in the adjacent iron formation is not. The higher sulphur content in the amphibole-magnetite rocks may indicate direct contribution of sulphur, though this may also be original in the iron-bearing formation. (See pp. 550, 552.) Whether or not there was some small introduction of materials from the gabbro, the bulk analyses of the amphibole-magnetite rocks are so similar to those of the other phases of the iron-bearing formation as not to require the assumption of delivery of hot solutions from the gabbro to the iron formation.

Furthermore, there is no regular variation in the composition of metamorphic phases of the iron-bearing formation through the several hundred feet from the contact for which these phases are known in many places to extend. Finally, the very fact that the metamorphic phases of the iron formation extend so far and so uniformly from the gabbro contact argue against their development by accession of materials from the gabbro.

It is concluded, therefore, that the principal effect of the intrusion of the gabbro into the iron-bearing formation was that of recrystallization of substances already present and not by contribution of solutions.

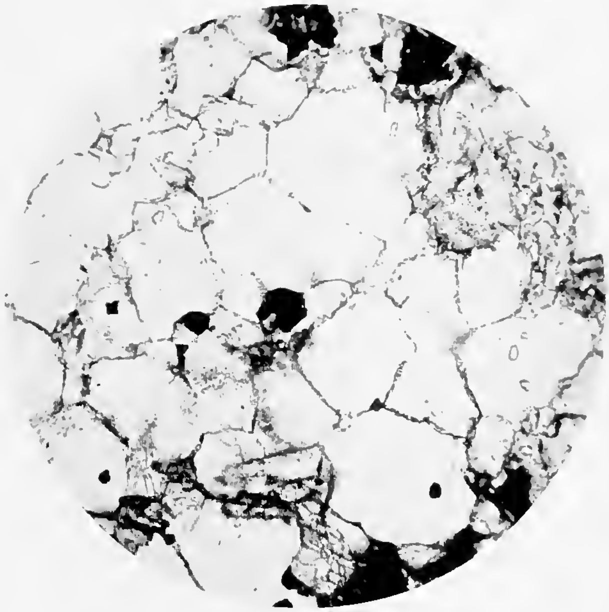
PLATE XLVII.

PLATE XLVII.

Photomicrographs of ferruginous and amphibolitic chert of iron-bearing Biwabik formation near contact with Duluth gabbro.

A. Actinolitic, grüneritic, and magnetitic chert (specimen 45141, slide 15621) from southeast of center of sec. 17, T. 60 N., R. 12 W., Mesabi district, Minnesota. Without analyzer, × 50. This rock is close to the contact with the Duluth gabbro and shows the typical alterations characteristic of the contact. The chert is in much larger particles than in the western portion of the range away from the contact. The particles fit in somewhat regular polygonal blocks. The iron oxide is magnetite instead of hydrated hematite, and actinolite and grünerite are present. The amphiboles are in small quantity in the slide shown, but the short actinolite needles may be seen inclosed in the quartz. (See Pl. XXXV.)

B. Actinolitic slate (specimen 9555, slide 3190) from Penokee Gap, NW. ¼ sec. 11, T. 44 N., R. 3 W., Wisconsin. In polarized light, × 165. The section is a typical actinolitic slate. The quartz is completely crystallized. The magnetite has mostly well-defined crystal outlines and is manifestly the first mineral to crystallize, being scattered uniformly through the section without any regard to the actinolite and quartz and therefore included by both of them. The actinolite is in its characteristic blades and sheaf-like forms, having a radial arrangement of its fibers. It is as plainly the second mineral to crystallize, as needles of actinolite everywhere penetrate the quartz, but never the magnetite. The quartz constitutes a background for the magnetite and actinolite and includes them in such a manner as to make the conclusion certain that it must in the main have crystallized subsequently to the formation of the magnetite and actinolite. (See Pl. XXXV.)



(A)

(B)

PHOTOMICROGRAPHS OF FERRUGINOUS AND AMPHIBOLITIC CHERT OF IRON-BEARING FORMATION NEAR CONTACT WITH DULUTH GABBRO.

TEMPERATURE UNDER WHICH CONTACT ALTERATIONS WERE EFFECTED.

The significant discovery by Wright and Day,[a] of the geophysical laboratory of the Carnegie Institution of Washington, that quartz crystallized below 575° differs in its properties from quartz crystallized above this temperature affords a satisfactory means of determining the temperatures at which the quartz of the iron-bearing formation has crystallized. Doctor Wright has kindly determined for us the properties of the quartzes in specimens from different parts of the Lake Superior iron-bearing formations, some of them clearly developed under katamorphic conditions, some of them near the contact with the gabbro. His observations are as follows:

Properties of quartz crystals from iron-bearing formations.

Specimen No.	Number of sections cut.	Average diameter (mm.).	Circular polarization.				Twinning, etch figures.[a]		
			R.	L.	R.+L.	Character of intergrowth.	Number not twinned.	Number twinned.	Character of twinning.
A	5	7	....	4	1	Regular....	2	3	Regular large patches.
B	6	5	....	....	6	.....do.....	....	6	Do.
29955	4	1.5	3	1	....	....	....	4	Regular.
29450	6	2.0	3	3	....	....	2	4	Often irregular and small.

[a] Etched 1½ hours in cold commercial hydrofluoric acid.

A. Crystalline quartz in ore from Vermilion district.

B. Crystalline quartz in ore from Mesabi district.

29955. Coarsely recrystallized iron-bearing formation, 300 feet from gabbro contact, northwest of Paulson mine camps, Gunflint district, northeastern Minnesota.

29450. Coarsely recrystallized iron-bearing formation in actual contact with Duluth gabbro at east end of Fay Lake, Gunflint district, northeastern Minnesota.

The quartz of Nos. A and B occurs in clear crystals and free from fractures. The usual + and — unit rhombohedrons are present; also the prism faces. On A crystals there is also present the rhombohedron (11$\bar{2}$1) and a trigonal trapezohedron form; this in itself is proof that the A quartz was formed below 575°.

The above observations show conclusively that the A, B, and 29955 quartzes [distant from gabbro contacts] have not been heated above 575°; that they were formed below that temperature. Specimen 29450 [at gabbro contact] is less regular in its behavior and resembles in that respect the quartz of some pegmatites. It is not as shattered as granite quartzes usually are and yet is not so regular as the definitely lower temperature quartzes. I concluded that in the pegmatites such quartz was formed probably near the inversion temperature 575°, because pegmatite dense quartz is definitely the low *a* form while some pegmatite quartz is definitely high *b* quartz. This was proved on one and the same dike.

It seems to me probable, therefore, that the temperature of formation of the quartz band in specimen 29450 was not far from 575°.

It is obvious from these results that the iron-bearing formation as a whole has not been fused, for its fusion temperature is certainly higher than 575°. This conclusion, together with the one above referring to the lack of transfer of material from the gabbro to the iron-bearing formation, emphasizes strongly the probability that the metamorphism of the iron formation near the gabbro was primarily the result of recrystallization below fusion temperature, with the aid of heat from the gabbro.

CHARACTER OF IRON-BEARING FORMATIONS AT THE TIME OF INTRUSIONS OF IGNEOUS ROCKS.

What were the constituents originally present in the iron-bearing formations at the time of the intrusion? Were they the ferruginous cherts earlier developed from the alteration of cherty carbonates or greenalite rocks, or were they the cherty carbonates and greenalite rocks themselves? If prior to the intrusion of the igneous rock the iron existed as ferric hydrate, then the change to magnetite involved deoxidation. This, according to Moissan,[b] will occur at 300° in 30 minutes in a hydrogen atmosphere. The presence of an actively reducing agent of this type along igneous contacts, while perhaps locally probable, can not be proved on any

[a] Wright, F. E., and Larsen, E. S., Quartz as a geologic thermometer: Am. Jour. Sci., 4th ser., vol. 27, 1909, pp. 421-427.

[b] Moissan, H., Compt. Rend., vol. 84, p. 1296.

large scale. If prior to the intrusion of the igneous rock the iron was in the ferrous condition, either as greenalite or carbonate, then moderate heat was sufficient to produce magnetite by robbing the associated water of part of its oxygen. (See p. 526.) This alteration is thought in general to be a more common one than the reduction of iron to magnetite from the ferric state. In the Lake Superior region there is field evidence also that the development of the amphibole-magnetite rocks has been more largely accomplished by partial oxidation of the ferrous iron than by the reduction of ferric oxide. In places in the Lake Superior region, where there is good field evidence that the iron-bearing formation had been exposed and altered to ferruginous cherts before the introduction of igneous rocks—as, for instance, in the eastern part of the Marquette district or at Sunday Lake in the Gogebic district—it is found that the contact effect of the intrusives has been to produce the bright-red banded specular jaspers or black magnetitic jaspers rather than amphibole-magnetite rocks. In the Marquette district it was long ago noted that the lower parts of the Negaunee formation in contact with intrusives developed amphibole and magnetite, while the upper parts developed the banded specular jaspers. The cement in these rocks is usually magnetite. Smyth[a] argued that this present difference in the character of the rocks at upper and lower horizons, especially for the Republic trough, is so uniform as to indicate an original difference in the beds at these horizons. The magnesia content of the amphibole-magnetite rocks for the most part seems to be like that of the original greenalites and carbonates rather than that of their altered derivatives, ferruginous cherts. In the alteration of carbonates or greenalites to cherts magnesia is lost. (See p. 528.) Had the amphibole-magnetite rocks developed from the ferruginous cherts, it would be necessary to assume that magnesia had been introduced in just the percentage of the original siderite and greenalite rocks.

Sulphur is also more abundant in the original phases of the iron-bearing formation than in its katamorphosed products, though no figures are available to show what the average sulphur content is, because analyses have ordinarily been made of the greenalite and siderite where free from sulphur. Contact or deep-seated metamorphism would not remove this sulphur, and this is thought to be the probable explanation of the high sulphur in the amphibole-magnetite rocks. The alternative explanation is that sulphur had been introduced directly from the igneous rocks.

CHEMISTRY OF ALTERATIONS.

The chemistry of the alterations from original ferrous compounds, greenalite and siderite, to amphibole-magnetite rocks presents less difficulty than that of the alteration of ferruginous cherts, or ferric compounds, to the amphibole-magnetite rocks. The former alteration requires partial oxidation of a ferrous compound; the latter requires reduction of a ferric compound, which is thought to be much less common.

On the assumption that the amphibole-magnetite rocks had developed directly from the cherty iron carbonates and greenalites, the changes would be substantially as follows:[b]

Where the carbonate is nearly pure siderite, grünerite is produced, according to the following reaction:

$$FeCO_3+SiO_2=FeSiO_3+CO_2,$$

with a decrease of volume of 32 per cent, provided the silica be a solid and the carbon dioxide escape. Where the original material was hydrous ferrous silicate, greenalite, simple dehydration only is necessary to form the grünerite.

Where the iron-bearing carbonate bears calcium and magnesium in considerable quantity, instead of grünerite being produced sahlite or actinolite may be formed. Supposing the carbonate to be normal ankerite, sahlite is produced, according to the following reaction:

$$CaFeC_2O_6.CaMgC_2O_6+4SiO_2=Ca_2MgFeSi_4O_{12}+4CO_2,$$

with a decrease in volume of 37 per cent, provided the silica be solid and the carbon dioxide escape.

From ankerite actinolite may be produced, according to the following reaction:

$$3(CaFeC_2O_6.CaMgC_2O_6)+8SiO_2=Ca_2Mg_3Fe_3SiO_{24}+8CO_2+4CaCO_3,$$

with a decrease in volume of 23 per cent, provided the silica bo a solid, the $CaCO_3$ formed remain as a solid, and the carbon dioxide escape.

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, p. 530.
[b] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, pp. 834-837.

If a more ferriferous and less calcareous iron-bearing carbonate be taken, it would not be necessary to suppose any calcium carbonate to have separated.

The iron-bearing carbonates may be very impure, just as limestones may be impure; and in this case there may develop various other minerals. In proportion as impurities are mingled with the carbonates, other amphiboles and the pyroxenes, micas, garnets, and other heavy minerals such as olivine may abundantly develop; and thus there may be produced a great variety of rocks, such as garnetiferous magnetite rocks, micaceous grünerite rocks, etc. As the impurities become abundant and the silicates other than grünerite, sahlite, and actinolite more prominent, the alterations become nearly those of the fragmental rocks. Between the two there are, of course, all gradations.

But as a matter of fact, the two silicates which most extensively form by the alterations of the iron-bearing carbonates in the zone of anamorphism are actinolite and grünerite. Where these reactions are complete we may have, in place of the iron-bearing carbonate, actinolite rocks, grünerite rocks, and all gradations between them.

Where the iron-bearing formation is originally greenalite, the alteration to the amphiboles would be simply one of dehydration.

The development of magnetite directly from the iron carbonates is possible by the following reactions:

$$2FeCO_3 + FeS_2 + 2H_2O = Fe_3O_4 + 2H_2S + 2CO_2,^a$$
$$3FeCO_3 + H_2O = Fe_3O_4 + 3CO_2 + H,$$
$$3FeCO_3 = Fe_3O_4 + CO + 2CO_2,^a$$
$$3FeCO_3 + O = Fe_3O_4 + 3CO_2.^a$$

Carbon dioxide is driven off at temperatures probably as low as 400°. At these and higher temperatures the ferrous iron remaining will rob the water of its oxygen, forming magnetite.

Siderite at red heat passes into a magnetic oxide with the formation of both carbonic acid and carbonic oxide. According to Döbereiner this reaction takes place as follows:[a]

$$5FeCO_3 = 3FeO.Fe_2O_3 + 4CO_2 + CO.$$

Glasson,[b] however, says that $4FeO.Fe_2O_3$ results, at first giving two parts of CO_2 and one of CO, but that later the proportion changes to five parts of CO_2 and one of CO.[c]

Van Hise[a] says, again:

Observation in the field shows beyond question that the change from iron carbonate to magnetite takes place on an extensive scale. Which of the above reactions is the more important may be an open question.

The alteration of greenalite to magnetite is possible by the following reaction:

$$3FeSiO_3nH_2O + O = Fe_3O_4 + 3SiO_2 + nH_2O.$$

Which of the above rocks develops at a given place depends not only upon the original composition of the rocks, but upon the nature of the alteration. For instance, where in the original rock silica is subordinate and nearly pure siderite abundant, a quartzose magnetite may develop, as at various places in the Lake Superior region. Where the conditions are such that the silicates form, the development of the actinolite or grünerite uses up both the iron carbonate and the silica, and an actinolite rock or a grünerite rock may be produced. Where silica was originally an abundant constituent both magnetite and the silicates are likely to develop. Thus we have various proportions of all the minerals, producing the magnetite-quartz rocks, the actinolite-magnetite-quartz rocks, the grünerite-magnetite-quartz rocks, the actinolite-quartz rocks, and the grünerite-quartz rocks.[d]

BANDING OF AMPHIBOLE-MAGNETITE ROCKS.[e]

Usually a given formation, or member, does not show a perfectly homogeneous arrangement of the mineral particles. The original sedimentary rock is banded, and the different bands have different compositions. Naturally the transformation of these bands produces different combinations of minerals. Moreover, during the recrystallization there is a tendency for minerals of the same kind to segregate. Hence, in any of the above cases, where as a whole a certain set of minerals are dominant within a rock, a single mineral, or two combined, may be largely segregated in bands; and in the alternate bands the other minerals be largely segregated. Thus a banded rock, consisting mainly of magnetite and quartz, may have a banded appearance as the result either of the segregation of the quartz and magnetite in separate bands or, more commonly, the segregation of more quartz and less magnetite in one band and less quartz and more magnetite in another band. In a similar manner alternate bands may be made up of actinolite or grünerite with quartz

[a] Van Hise, C. R., op. cit., p. 838.
[b] Cited by Gmelin-Kraut, Anorganische Chemie, vol. 3, p. 319.
[c] Chamberlin, R. T., The gases in rocks: Pub. Carnegie Inst. No. 106, 1908, p. 51.
[d] Van Hise, C. R., op. cit., p. 839.
[e] Idem, pp. 839-840.

in various proportions, and of actinolite or grünerite with magnetite in various proportions. In still other instances the banding may be due to the combining of actinolite or grünerite, magnetite, and quartz in various proportions. In general, therefore, the alterations of the rock do not destroy the original sedimentary banding, but, on the contrary, emphasize it. The striking banded appearance of actinolitic and grüneritic rocks is one of their most characteristic features.

RECRYSTALLIZATION OF QUARTZ.

The recrystallization of quartz under these anamorphic reactions has multiplied the size of the grain many times, as mentioned in the discussion of the individual districts. The recrystallization of quartz has largely followed the development of magnetite, for magnetite with crystal outlines is often observed to be completely inclosed in large clear quartz crystals with no strain effects.

HIGH SULPHUR CONTENT OF AMPHIBOLE-MAGNETITE ROCKS.

The amphibole-magnetite rocks usually carry a higher percentage of iron sulphide than other phases of the iron-bearing formations. If iron sulphide plays the important part assigned to it in the early portion of this discussion (see pp. 518–519), iron sulphides may be supposed to have been locally deposited throughout the iron-bearing formations with the carbonates and greenalites. These would be the first substances to be altered by the surface waters and, going quickly into solution, would greatly accelerate the concentration of the ore, but during the alteration of iron carbonate or greenalite to amphibole-magnetite rocks there is no opportunity for oxidizing solutions to get at the sulphides and hence they remain. The refractoriness of the amphibole-magnetite rocks also prevents subsequent oxidization. In the Gunflint Lake district of Minnesota the sulphide is in the form of pyrrhotite, which, according to Moissan[a] and Allen,[b] is developed through the application of heat to pyrite.

An alternative explanation of the high sulphur is that it was secondarily contributed by the hot intrusives. For this there is no direct evidence.

SECONDARY IRON CARBONATE LOCALLY DEVELOPED AT IGNEOUS CONTACTS.

In a few localities, as at Gunflint Lake, Minnesota, in the Animikie district, and at Sunday Lake, in the Gogebic district, coarsely crystallized iron carbonate is found close to the igneous rock, this material doubtless being produced by recrystallization of the original finer carbonate.

CONTACT ALTERATIONS NOT FAVORABLE TO CONCENTRATION OF ORE DEPOSITS.

The anamorphic changes above described do not favor the transfer and segregation of constituents of the iron-bearing formations. They tend rather to combine them. Locally there is evidence that iron is carried in solution under these conditions, in the fact that cements in fractures are largely magnetite and the iron is usually in coarser bands. If the intrusions come before the original iron-bearing formation has become porous through the loss of its silica, the rocks do not have the openings for the transfer of solutions. Even had openings existed in some places, the deep-seated pressures exerted by great batholiths, like the Duluth gabbro, have been sufficient to make the rock undergo rock flowage, thereby closing openings. If other conditions were favorable there would still be the lack of abundant surface waters to leach the silica. So far as the iron-bearing formation had been previously altered and concentrated to ore under weathering conditions, the intrusions of the igneous rocks would have the effect of dehydrating and recrystallizing the ores, but not of further concentrating them.

There are but two highly magnetic deposits in the Lake Superior country which have been mined as ore. In the Republic district of Michigan magnetitic specular hematite is interlayered with bright-red and black jaspers in which the iron oxide is hematite and magnetite. Near the base of the formation amphiboles are abundant and the formation is lean in iron. The upper part of the formation seems to be essentially the result of anamorphism of a previously

[a] Moissan, H., Traité de chimie minérale, vol. 4, Metamorphism, p. 565.
[b] Allen, E. T., Sulphides of iron: Summary in Ann. Rept. Geophys. Lab. Carnegie Inst., 1910, pp. 104-105 (reprint).

formed iron oxide and jasper zone in which there has been some concentration of iron ore. The lower portion of the formation is regarded as the result of the anamorphism of an original carbonate formation not exposed to weathering prior to the introduction of the igneous rocks. In both cases conditions of rock flowage incident to the folding and intrusion have aided the direct contact effects. The upper part of the formation has suffered most from the readjustment along the surface of the contact between the unconformable middle and upper Huronian. The probable sequence of events is discussed on pages 277–279.

At Champion, Mich., in the Marquette district, the development of the magnetite-ore deposit is explained in much the same way. These ores have been found to contain a larger percentage of titanium than is usual in the Lake Superior ores of the sedimentary type, some samples of the Champion ore containing as much as 1.66 per cent of TiO_2. It is possible that this may represent a direct contribution from the intrusive.

The titaniferous magnetite deposits in the Lake Superior region are not results of the contact alteration of an iron-bearing formation, but are rather magmatic segregations in the igneous rocks. Also certain of the black magnetite rocks of the iron-bearing formations closely associated with surface extrusive rocks may have been the result of direct contribution from the igneous rocks and not contact metamorphism, as already indicated. (See p. 527.)

The alterations above described are essentially constructive or anamorphic in their nature, tending to produce more complex mineral substances, and do not accomplish simplification and segregation sufficiently to develop ore deposits, in these respects contrasting markedly with weathering alterations which the formation undergoes at the surface away from the influence of igneous rocks.

Therefore, so far as the amphibole-magnetite rocks contain ores, these ores are probably originally rich iron layers in the iron formation which may have been partly concentrated during katamorphism preceding anamorphism. The anamorphic processes have not aided their concentration.

SURFACE ALTERATIONS OF AMPHIBOLE-MAGNETITE ROCKS.

After the grüneritic or actinolitic rocks have developed in the zone of anamorphism, in consequence of denudation they may pass into the zone of katamorphism, or even into the belt of weathering. Then will begin the processes of oxidation, hydration, and carbonation, as a result of which the magnetite is slightly changed to hematite or limonite and the amphibole or other silicates may decompose into chlorite, epidote, and calcite. However, as magnetite and the iron-bearing amphiboles are very refractory, this process is exceedingly slow and usually has affected only comparatively thin layers of materials adjacent to the surface or adjacent to openings in the rock. Indeed, the reactions of the belt of weathering and the upper part of the belt of cementation, which may produce large iron-ore bodies where they have the original iron-bearing carbonates or the hydrous ferrous silicates to work upon, have nowhere in the Lake Superior region formed large ore bodies where they are working upon the grüneritic and actinolitic rocks.

The iron content of the amphibole-magnetite rocks is not materially different from that of the ferruginous cherts, allowance being made for a slight difference in degree of oxidation and hydration of iron. The leaching of silica from this rock would produce an ore as rich as that derived from the alteration of cherts, but as a matter of fact the silica is usually not leached from these rocks and ore deposits derived from them are small and rare. The external conditions for their alteration are essentially the same as those for the alteration of the cherts, topographically, structurally, and chemically, and so the failure of the waters to leach the silica from them and concentrate the iron must be ascribed to the condition of the rock. Microscopic examination shows that the quartz is much more coarsely crystallized than in the ferruginous cherts. The grains will average a thousand times the mass of those of the cherts. (Compare Pls. XLIV and XLVII.) It has undergone marked recrystallization, which has completely obliterated the minute particles or any pore space that the cherts may have had, and also crystallized any amorphous chert originally present. The pore space is less than 1 per cent, as compared with about 5 per cent in the ferruginous cherts. The result is that the waters have fewer openings into which to penetrate and far less surface of quartz upon which to work. This fact alone is believed to be sufficient to account for the lack of leaching of silica. However, it may be also pointed out that some of the silica has combined with the iron in resistant amphiboles which do not yield readily to the surface waters. The rocks are hard, dense, and crystalline, being obviously much more difficult for the waters to attack either mechanically or chemically than the ferruginous cherts. They usually stand at a higher elevation, other structural conditions being approximately the same, indicating their resistance to erosion. In the Mesabi district the elevation of the upper Huronian iron-bearing formation where it is altered to amphibole-magnetite rock at the east end of the district is fully 200 feet higher on an average than that farther west, where the rock is altered to ferruginous chert.

It follows from the foregoing that anamorphic processes of the original iron carbonates and greenalites producing amphibole-magnetite rocks are not only unfavorable to the direct development of ores, but they put the formation in condition to resist the action of ordinary katamorphic concentrating agencies.

SUMMARY OF ALTERATIONS OF IRON-BEARING FORMATIONS BY IGNEOUS INTRUSIONS.

As a result of igneous intrusions, iron-bearing formations become recrystallized and coarser in grain.

The average chemical composition is not essentially changed except by dehydration, and perhaps locally by introduction of sulphur or other constituents, but the mineral composition is greatly changed.

The density has been increased and the pore space lessened.

The alterations of the carbonate and greenalite rocks have produced amphibole-magnetite rocks. The alterations of the ferruginous cherts and soft ores have produced banded red jaspers and hard ores.

The changes under the influence of intrusions are those of anamorphism unfavorable to the development of ore deposits, but originally rich iron layers may remain as ores. The anamorphic products, once formed and exposed at the surface, are found to be too refractory to undergo alterations to ores.

ALTERATION OF IRON-BEARING FORMATIONS BY ROCK FLOWAGE.

Mechanical deformation has accomplished different changes in the iron-bearing formations, depending on whether it is effected by fracture or by flowage and whether the iron-bearing formation was in its original carbonate or greenalite form at the time of the deformation, or had been altered to ferruginous chert and ore or to actinolitic and grüneritic rocks. Fracturing has opened up avenues for water circulation, as discussed on pages 474–475. Here is considered the effect of rock flowage only.

The iron carbonates and greenalites were not considerably altered by rock flowage, for subsequent to the folding they underwent the normal alterations to ores and ferruginous cherts. This is especially well illustrated by the folded upper Huronian iron-bearing formation, in which original carbonates are still found where the surface alterations have not reached them.

The alterations of the ferruginous cherts and ores under mechanical pressure have been very conspicuous in the Keewatin ores of the Vermilion district, in parts of the Negaunee formation nearest the contact with the upper Huronian in the Marquette district, and elsewhere. (See Pl. XXXIX, *B*, p. 480.) The Vermilion ores have been rendered hard, crystalline, dehydrated, locally somewhat schistose, more or less magnetic, locally brecciated, and cemented by vein quartz and later by iron oxide (hematite and magnetite). As the ores stand in the Ely trough they contain much pore space because of their coarsely brecciated condition. The ferruginous cherts of the Vermilion district have simultaneously been recrystallized and cemented, and the iron minerals have gone through the same series of physical and chemical changes as in the ores. The net result is the production of a rock having a composition similar to that of ferruginous chert, with a large proportion of magnetite and with a small amount of pore space.

In the Marquette district the post-Huronian folding developed a marked shear zone at the contact of the Negaunee formation with the overlying detrital ferruginous base of the upper Huronian, with the result that the ore was dehydrated and rendered crystalline, developing coarsely crystalline specular hematite or micaceous hematite and porphyritic magnetite, accompanied by a marked elimination of pore space. The extent of the mashing is best indicated by the quartz pebbles in the detrital base of the upper Huronian, some of which are much flattened.

The effect on the ferruginous cherts or jaspers has been to make the iron bands brightly specular.

Aside from these effects noted near the contacts of the upper and middle Huronian, the later folding has not essentially changed the characters of the iron-bearing formation. Smyth [a] discusses it thus:

It has been said that the grünerite, quartz, and iron oxides of the iron-bearing member have a very distinct banded arrangement and yet are not original minerals, and that this banding is parallel to the upper and lower boundaries of the formation. It is probable that a set of parallel structural planes has controlled the segregation of the present constituent minerals during the changes through which the rock has passed, and that these planes must have been original bedding planes. As the parallel banding is confined to this one direction, it is certain that during its development no other system of parallel planes existed in the rock. The last severe folding, which has determined the larger structural features of the Marquette district, has also affected the rocks in a more intimate way. In certain localities strong minor, even minute crenulations have been produced, and also parallel cleavage, which sometimes traverses the banding of the rock at right angles. The little folds are often broken and faulted and the siliceous bands reduced to fragments. Along the parallel cleavage planes movement has often taken place, as is shown by the displacement of a particular band on the two sides. Along this secondary cleavage, which dates from the period of general folding after upper Marquette time, no great development of new minerals, except the iron oxides, has taken place, while the displacement which the minute faulting has caused in the banding conclusively proves that this structure was present before the folding.

Allen[b] finds similar conditions in the Woman River district of Ontario, where riebeckite and magnetite are cut by later cleavage.

The effects of mechanical deformation in the zone of flowage may be summarized as follows:

As a result of mechanical deformation the ores have become dehydrated, crystalline, in some places specular and schistose, lacking pore space, locally brecciated, and in part recemented by quartz and iron oxide.

The ferruginous cherts have become recrystallized and dehydrated, in some places slightly deoxidized, tending to produce the banded red and black jaspers. These alterations of the cherts are not certainly discriminated from those due to the intrusion of igneous rocks.

Deformation by flowage does not aid concentration by surface waters, but on the other hand it does not so affect the original carbonates and greenalites that surface waters may not later alter them to ores.

CAUSE OF VARYING DEGREE OF HYDRATION OF LAKE SUPERIOR ORES.

The Lake Superior iron ores include both hydrous and anhydrous varieties—magnetite, hematite, limonite, and several intermediate hydrates. The iron ores of the region as a whole are low hydrates of iron, containing an average of about 2 per cent combined water. The most hydrous of the pre-Cambrian ores are those of the Mesabi range, which average an amount of combined water equivalent to a ferric hydrate having 4.5 per cent. Locally ores containing almost as much water as limonite are found, but this is exceptional. Some of the ores are crystalline hematite and magnetite.

Are the differences in hydration of the different beds due to differences in original character, or to differences in secondary alterations? These questions are answered only in part.

[a] Smyth, H. L., The Republic trough: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 531-532.
[b] Allen, R. C., Iron formation of Woman River: Eighteenth Ann. Rept. Ontario Bur. Mines, pt. 1, 1909, pp. 254-262.

Guy H. Cox has assembled the various experimental data on the subject and supplemented them by laboratory experiments of his own.

From meteoric solutions under ordinary temperatures at the surface the precipitates of iron are ferric hydrates containing 29 per cent of water, which rapidly changes in contact with water into limonite, containing 14.44 per cent of water.

The presence of alumina, lime, and magnesia to combine with the iron may prevent dehydration.[a] If left for several years, the ore becomes dehydrated and crystalline.[b]

Increase in temperature and pressure on the solutions at the time of precipitation will lower the hydration of the precipitated salt. At a temperature of 500° magnetite may be precipitated directly from solution. Slight variations in the degree of hydration in a precipitate are determined by the form in which the iron is held in solution, by the precipitating agents, and by the strength of the solutions, though so far as experimental data go the range of variation due to these causes is small.

Secondary alterations have little effect on anhydrous ores, but hydrous ores may easily lose part of their water by moderate increase in temperature and by pressure such, for instance, as that involved in freezing, where the water is allowed to escape. It appears also that in an ore containing various hydrates, solution will dissolve the highest hydrates, leaving the residue in a lower state of hydration, but that the redeposition of the dissolved part as a higher hydrate may result in net increase of hydration for the residue and dissolved parts combined.

It appears, therefore, that conditions of high temperature and pressure, either during the original deposition of the iron salts or during their secondary alterations, favor the development of anhydrous salts, thereby explaining the occurrence of crystalline hematite and magnetite in the iron-bearing formations near igneous contacts or where dynamically metamorphosed. It is shown elsewhere that magnetite, perhaps even hematite, may have been precipitated directly from the hot solutions coming from some of the basic igneous rocks, or that the iron salts may first have been deposited as greenalite and iron carbonate which subsequently altered under conditions of high temperature and pressure to magnetite and hematite, or that the iron salts were first deposited as greenalite and hematite, subsequently altered to limonite, and then dehydrated by the high temperature and pressure of anamorphic conditions to hematite and magnetite. In all these cases the heat from some adjacent igneous rock or the pressure developed from rock flowage seems, from field evidence, to be an essential factor.

However, hematite and various hydrates are found minutely interbedded in parts of the iron-bearing formations where there is no evidence of the effect of unusual heat or pressure. A hand specimen may show several layers of iron oxides with varying degrees of hydration. These differences persist in the ferruginous cherts and jaspers and in the ores into which the ferruginous cherts and jaspers grade. Moreover, they seem to be independent of distance from rock surface and of dip of beds. In steeply inclined beds layers with different degrees of hydration may be found to continue from the surface to great depth with no relative change in hydration.

These remarkable and persistent variations in hydration in closely associated layers may have been due to—

1. Differences in the original substances in different layers, whether carbonate or greenalite. The iron-bearing formations were originally anhydrous iron carbonate and hydrous silicate, both of which have altered when weathered to hydrous oxides. It has not been ascertained that there is any specific difference in degree of hydration of the alteration products of the greenalite and carbonate, though on the whole the beds in the Mesabi district, containing the most greenalite, are the most hydrous.

2. Difference in time of alteration of the greenalite and carbonate, with accompanying slight variations of temperature and pressure. The hydration of different layers has taken place at

[a] Spring, W., Neues Jahrb., vol. 1, 1899, pp. 47-62 (cited by Moore, E. S., Eighteenth Ann. Rept. Ontario Bur. Mines, pt. 1, 1909, p. 194).

[b] Wittstein, G. C., Vierteljahresschrift für Pharmacie, vol. 1, 1852, p. 275 (cited by Moore, E. S., Eighteenth Ann. Rept. Ontario Bur. Mines, pt. 1, 1909, p. 194).

different times when the temperature conditions and pressure conditions may have been slightly different, although of these differences we have no knowledge.

3. Selective secondary alterations of the hydrates formed by the first alteration of the greenalite and carbonate. Freezing (seasonal and glacial) and moderate depth of cover may tend to dehydrate the ores and probably have contributed to the low average degree of hydration of the bedded hematites. So far as experimental evidence goes, these ores would have their highest degree of hydration at the time of precipitation, and all influences acting upon them subsequently, even moderate seasonal variations in temperature and moderate depth of burial, would tend toward lowering the degree of hydration.

It might be expected that the result of seasonal variations in temperature and the pressure of overlying rocks would result in a uniform variation in hydration from the surface downward. No evidence of this sort has been found in the ore bodies. It should be noted, however, that the effect of freezing would be toward dehydration at the surface and the effect of pressure would be toward dehydration with depth. Instead of uniform change in hydration one way or another from surface to depth, the most conspicuous change in hydration is between closely interbedded layers of the iron-bearing formations.

The selective effect of solution and redeposition might have influence; for instance, waters percolating rapidly along a certain bed or fissure might dissolve the more hydrated ores, carry them off, and redeposit them, leaving the residue with a lower degree of hydration. Slight original variations in hydration would thereby be emphasized. Other unknown causes may be operative.

According to Stremme,[a] hydration is favored by salt content and carbon dioxide content of the altering solutions. The salt and acid content apparently influence the degree of hydration of the iron oxide by lowering the vapor pressure of the solution. Each iron hydrate is supposed to have its own vapor pressure, which is the minimum pressure of water vapor with which the hydrate can remain in equilibrium at any given temperature.

We may conclude in general that the hydrous ores of the Lake Superior region have developed under ordinary conditions of temperature and pressure near the surface, that the anhydrous ores exhibit the effects of heat and pressure, and that the differences in hydration of closely intermingled layers of the iron-bearing formations have required some influence of a selective sort, the nature of which may be suggested but not proved.

SEQUENCE OF ORE CONCENTRATION.

We have touched upon each of the factors going to determine the present character and structural relations of the ores. To complete the picture we have now to dwell upon the chronologic development of the ores.

The beginning of the processes of secondary concentration must be placed for the Archean ores in early Huronian time and for the middle Huronian ores in the time between the middle and upper Huronian. Iron-formation fragments in the basal conglomerates of these divisions tell to some extent what had previously happened to the iron-bearing formations of the older land. At the base of the upper Huronian rich ferruginous detritus was formed at the beginning of upper Huronian time. In certain places the iron-bearing formation within the upper Huronian was exposed by erosion before Keweenawan time and went through a set of changes in the time interval between the Huronian and Keweenawan similar to those that affected the lower Huronian iron-bearing formation in inter-Huronian time. This is shown by the detritus of the Keweenawan basal conglomerate and by the development of red jaspers and hard ores from the soft varieties near the contact of Keweenawan and upper Huronian in eastern Gogebic district. In those districts in which great masses of Keweenawan rocks were laid down upon the Huronian rocks before the iron-bearing formation had been exposed to weathering, the concentration of the ore could not have begun until the Keweenawan was cut through in the erosion

[a] Stremme, H., Zur Kenntnis der wasserhaltigen und wasserfreien Eisenoxydbildungen in den Sedimentgesteinen: Zeitschr. prakt. Geologie vol. 18, No. 1, 1910, pp. 18-23 (reviewed in Econ. Geology, vol. 5, 1910, p. 499).

period preceding Cambrian time, and it is rather probable that this limitation also applies to other districts. Clearly the process in each district began when, as a result of the great orogenic movements and the attendant denudation, the iron-bearing formation was exposed to the weathering forces. In most of the districts this occurred in the great time gap represented by the unconformity between the Keweenawan and the Cambrian. At this time were concentrated most of the great ore deposits of the upper Huronian of the region and the ores at the middle and lower horizons of the Negaunee formation of the middle Huronian.

Wherever the Cambrian remains in or near the iron districts it contains iron-ore fragments, jaspers, and cherts in its basal conglomerate. In the Menominee district these are rich enough to be mined. The process of ore concentration was therefore well advanced before Cambrian time.

In the Mesabi district remnants of Cretaceous beds overlie some of the ore deposits, particularly in the western parts of the range. At the basal horizons of these beds are detrital iron ores derived from the Biwabik formation. Here, then, the concentration was well advanced as early as Cretaceous time, and there is little doubt, from the similar relations of the ores to the Cambrian in other regions, that the ores of the Mesabi district were well concentrated even by Cambrian time.

The process of enrichment has undoubtedly continued until the present time. It therefore appears that the circulating waters have had eras in which to perform their work; indeed, a part of pre-Paleozoic time and all of the Paleozoic, Mesozoic, and Cenozoic.

Frequently during pre-Cambrian time the iron-bearing formations were metamorphosed by igneous intrusions, the principal effect of which was to recrystallize the original phases of the iron-bearing formations, yet unaltered, to refractory amphibole-magnetite rocks able to resist the ordinary katamorphic ore-concentrating agencies. The alteration to ores of portions of the iron-bearing formations so modified was practically stopped at the times of the intrusions.

In all the districts since the beginning of final concentration many thousands of feet of strata have been removed by erosion. During the process of denudation the ore deposits in each district began to be secondarily concentrated shortly after the iron-bearing formation was exposed at the surface and for a long time they continued to increase in size. It is probable that after a sufficiently long period the growth of the deposits practically ceased, for denudation would finally remove the ores at the surface as fast as they formed below the surface. However, change would not stop. The ore deposits formed would continue to migrate downward pari passu with denudation. On account of the pitch, lateral migration would accompany downward migration. At any given time the masses of ore would extend from the surface to the depth at which descending waters were effective. We therefore must conceive of the secondarily concentrated iron-ore deposits as slowly migrating downward through thousands of feet, being always just in advance of the plane of erosion. So far as the original iron-formation layers were rich enough to be ores without secondary concentration, these statements do not apply. The amount of ore existing at any one period through much of preglacial time may have been roughly constant, although there was doubtless considerable variation depending on topographic and climatic conditions.

At times the processes of denudation would go on rapidly; at other times they would be stayed for long periods, depending on the post-Keweenawan history of the Lake Superior region.

The important steps of this history are (1) the great pre-Cambrian mountain making and erosion, (2) subsidence and Paleozoic sedimentation, (3) the post-Paleozoic uplift and denudation, (4) the deposition of Cretaceous rocks upon parts of the region, (5) the post-Cretaceous uplift and succeeding denudation, and (6) the Pleistocene ice incursions.

1. In the pre-Cambrian period of mountain making and denudation the ore deposits probably reached their full development, and indeed they may during the latter part of this ancient time have been of greater magnitude than they are at present, although possibly not so rich. In the Menominee district the Upper Cambrian sandstone and the Ordovician limestone cap the Huronian formations and even some of the ore deposits. The upward extension

of the iron-bearing formation was removed before Upper Cambrian time. It is clear, therefore, that the main concentrations of iron oxide for these deposits must have taken place in pre-Cambrian time. The basal conglomerates of the Cambrian carry ore fragments from previously altered formations. If, as is probable (see below), Cambrian and Ordovician or Silurian strata capped the beds in other iron-bearing districts of the Lake Superior region, it is all but certain that ore concentration was equally advanced in these other districts, although where erosion has extended farther below the Paleozoic than in the Menominee district later events have had a greater influence upon the present condition of the ore deposits. The later stages of this period of denudation were marked by the development of a great peneplain, over which, it may be assumed, the ore-concentrating processes acted slowly.

2. After this period of denudation the Paleozoic sea encroached upon the Lake Superior region. Where the iron-bearing formations were reached by the sea, detrital ores were formed at the base of the Cambrian. The entire region was deeply buried beneath the Paleozoic deposits. Probably so long as the region remained below the sea the processes of concentration practically ceased and the mass of the ore deposits remained nearly stationary. Sea water does not chemically affect the iron oxides.

3. When after Paleozoic time the region was again raised above the sea and denudation began, little enrichment took place until the major portion of the Paleozoic rocks was stripped from the region. Over much of the region these Paleozoic rocks were entirely removed, and the pre-Cambrian Huronian surface again emerged from below the Cambrian deposits. In the Menominee district and the southeastern part of the Crystal Falls district the Paleozoic deposits were not completely removed from the iron-bearing formations, and here considerable quantities of detrital ores are found at the base of the Cambrian. In most of the region erosion did not stop at the Paleozoic but extended downward for a greater or less depth into the Huronian rocks, and it is presumed that where this took place the ore deposits migrated downward precisely as during the pre-Cambrian period of denudation.

4. Erosion continued until the end of the Cretaceous period of base-leveling, when the area was again reduced nearly to an uneven plain and locally was overridden by the sea and capped by Cretaceous rocks, at least as far east as the Mesabi district. The basal strata of these beds carry detrital iron ore from the Biwabik formation. At the end of this period the processes of downward denudation and concentration were greatly diminished in speed.

5. During the period of the post-Cretaceous uplift denudation and the migration of the ore deposits again went on, but to what extent is uncertain. It is highly probable that in the Menominee district the topography of the Huronian rocks is largely pre-Cambrian and the present depressions to a large extent are reexcavated pre-Cambrian valleys. The same is true of the Felch Mountain tongue of the Crystal Falls district. On the borders of the Marquette district, also, Cambrian deposits are found. However, it is now a matter of conjecture as to how far the present topography is redeveloped pre-Cambrian topography and how far it is post-Cretaceous.

6. The last great event in the development of the ore deposits was the glacial incursion of Pleistocene time. So far as the ore deposits are concerned, the work was of two kinds, glacial denudation and glacial deposition. The quantity of ore which was removed during the first stage of Pleistocene time, that of glacial erosion, was enormous. Almost the entire zone of decomposed rocks which must have been adjacent to the ores has been removed. The ore deposits were certainly truncated to at least an equal depth. Glacial erosion also in many places cut deeper into the soft ore bodies than into the adjacent hard rocks, and thus produced subordinate valleys, as is finely illustrated in the Mesabi district. The abundant fragments of hard iron ore in the glacial drift furnish evidence of the large amount of ore which has been removed by the glaciers. It is certain that still greater quantities of soft ore have been removed, although on account of its softness it has been broken into minute fragments and therefore furnishes little evidence of its removal. The foregoing considerations lead to the certain conclusion that the glacial truncation seriously reduced the amount of available iron ore in the Lake Superior region. While the process of concentration has continued since glacial time and has tended to

enrich and deepen the deposits, there is no doubt that the gain since the glacial incursion is insignificant as compared with the loss of rich material during the glacial period. When the glaciers receded, the clean-cut ore bodies were covered to a greater or less depth by deposits of glacial drift. This relation may be seen to the best advantage in the great open pits of the Mesabi district, where the soft, clean ore extends directly to the drift, not derived from the ore but brought from the north. The contacts in many places are of almost knifelike sharpness, there being practically no ore in the basal layers of the drift.

It appears from the foregoing discussion that while the quantity of ore in the Lake Superior region has always been large since Cambrian time, there have been numerous vicissitudes in its history during which the quantity of ore alternately increased and decreased.

ORIGIN OF MANGANIFEROUS IRON ORES.

Manganese exists in a series of minerals remarkably similar to and usually in association with those of iron. The origin and secondary concentration of the manganese minerals have been regarded in general as following very closely those of the iron. The subject has not been specifically studied for the Lake Superior region. It may be noted here merely that the manganese tends to be concentrated in the upper parts of the Lake Superior iron-ore deposits, and that as secondarily concentrated it consists principally of manganese dioxide (pyrolusite) and subordinately of manganese carbonate. In the general study of the manganese deposits of the Appalachians and other parts of the United States it has been found that this is a common but not invariable relation of iron and manganese. In some deposits also the relation is reversed, the iron being above, the manganese below. Where they are associated with clay, not in the Lake Superior region, there seems to be a tendency for the concentration of clay at the surface relative to the manganese. Iron and manganese oxides and clay are the most stable of the common constituents of the belt of weathering, and hence all of them tend to become residually concentrated as compared with other substances originally associated with them. The vertical distribution of these three substances is taken to be a function of their relative stability under various conditions of weathering, but the available information does not seem to warrant more specific statements.

PART OF THE METAMORPHIC CYCLE ILLUSTRATED BY THE LAKE SUPERIOR IRON ORES OF SEDIMENTARY TYPE.

Starting with the ferrous iron and dominance of silicates in the original igneous rocks, the development of the ore deposits is a process of continuous katamorphism. From the original igneous rocks and their included veins containing a small percentage of iron there is developed an iron-bearing formation—cherty iron carbonate or greenalite—containing 25 or 30 per cent of iron, which, on further alteration at the surface, becomes concentrated to 50 or 60 per cent or more. The iron-bearing formation and included ores may themselves be broken up to yield materials for later sedimentary iron-bearing formations. The upper Huronian iron-bearing formations, the greatest and most productive of the Lake Superior region, may be regarded as including materials not only from the chemical alterations of the older greenstones but from the destruction of the older iron-bearing formations of the middle Huronian and Archean. These formations have undergone the extreme of katamorphism. Nature's great concentrating mill has developed a high-grade end product, both chemical and mechanical, through a series of concentrations. The changes have been those of simplification and segregation of mineral compounds, marked increase in volume, when all substances entering into the reaction are taken into account, incoherency of substance, and net liberation of heat, all of them typical of the katamorphism or destructive processes affecting the earth's surface.

No sooner have the ores reached their maximum incoherency through katamorphic changes than constructive agencies begin their work. It may be more correct to say that they begin before the destructive agencies have finished. The ores become cemented and strengthened; they tend also to become dehydrated and more or less magnetic. As they become buried beneath the surface, owing to the deposition of later sediments, and as they become folded, their volume is decreased by an elimination of pore space and moisture, they are recrystallized, are slightly deoxidized to magnetite, in small part combine with siliceous and other impurities to produce silicates, and are frequently rendered schistose, producing the hard specular ores. The mineralogical change is one from simple to less simple compounds. The net change in energy is loss, due to the energy given off in volume decrease. The process is a characteristic one of anamorphism, which affects all rocks under similar conditions. The anamorphic changes in the ores are best shown in the oldest or Archean iron-bearing formations.

More marked anamorphic results are produced under the influence of igneous intrusions.

The contrasting katamorphic and anamorphic changes affecting the ore deposits constitute a partial metamorphic cycle.[a] Beginning with a coherent igneous rock, incoherent ore deposits are developed through katamorphism and in turn a part are rendered coherent again through anamorphism. The mineralogical changes are at first from complex to simple and later from simple to complex. The changes at first are essentially those of simplification and segregation and later this process is arrested and on a smaller scale reversed in the development of the complex silicates. The ores are not essentially dispersed to again become constituents of igneous rocks, although certain of the amphibole-magnetite rocks associated with the ores are not easily distinguishable from igneous rocks. The cycle, therefore, so far as observation goes, is not complete. There is throughout a net loss of energy.

TITANIFEROUS MAGNETITES OF NORTHERN MINNESOTA.

The great gabbro mass of Lake and Cook counties, Minn., contains much magnetite, both disseminated and segregated into ore deposits. Complete gradation may be observed between gabbro carrying little magnetite and magnetite carrying little of the ferromagnesian constituents and feldspars. The known deposits are extremely irregular, with gradations between themselves and the gabbro and containing within themselves much gabbro material. They weather very much like the gabbro and might be easily unnoticed on the weathered surface. There has been little exploration for these ores. A few drill holes have been sunk in the region south of Gunflint Lake, some of them revealing depths of ore aggregating several hundred feet. The known deposits seem to be distributed in irregular zones roughly parallel to the north or basal margin of the Duluth gabbro.

The composition of the ore averaged from 3,556 feet in 14 drill holes is 43.8 per cent of iron. The range is from 54 to 20 per cent. The high titanium content renders the ores of doubtful value for the present.

Where the gabbro comes into contact with the iron-bearing Gunflint formation both formations carry magnetite so similar in texture that it is difficult to tell one from the other. However, on analysis the gabbro magnetite is found to be titaniferous, while that of the Gunflint formation is not titaniferous. This fact seems to argue against any considerable transfer of material from the gabbro to the iron-bearing formation during its alteration.

The titaniferous magnetites of northeastern Minnesota are direct magmatic segregations in the Duluth gabbro, according to all geologists who have studied them, including Irving, Merriam, Bayley, Grant, Winchell, Clements, Van Hise, Leith, and others. The complete gradation from gabbro with a small amount of original magnetite to a magnetite with small amounts of amphibole and other gabbro minerals can be seen in almost any part of the titaniferous magnetite deposits. It is scarcely necessary to repeat the detailed petrologic evidence so fully given by the writers named.

Evidence is given elsewhere for the intrusive character of the Duluth gabbro. It cooled far beneath the surface, where there was not easy escape for its solutions. This fact is taken to explain its retention of its iron oxides. It has been argued under an earlier heading that where basic rocks of similar composition reached the surface large quantities of iron escaped and became available for ordinary sedimentary deposition.

[a] Leith, C. K., The metamorphic cycle: Jour. Geology, vol. 15, 1907, pp. 303-313.

MAGNETITES OF POSSIBLE PEGMATITIC ORIGIN.

The ore in the Atikokan district is a magnetite, highly impregnated with amphiboles and sulphides and showing extremely close and intricate relations to associated diorite. It differs from the magnetite of the gabbro of Minnesota in being nontitaniferous and in being separated by definite boundaries—in many places plane surfaces—from the adjacent wall rock. The apparent absence of iron-bearing formation, the general lack of banding, the high content of amphibole corresponding to that in the associated diorite, the content of sulphides, and the extremely intricate structural association with the diorite are not easy to explain if the ore is sedimentary and owes its character to complex intrusion by the basic igneous masses. Nowhere in the Lake Superior region is intrusion known to completely destroy banding, nor does it develop so much coarsely crystalline amphibole and iron sulphide with lack of parallel texture. On the other hand, both character and relations suggest pegmatitic intrusion or igneous aftereffects, similar to those described by Spencer [a] for the New Jersey magnetites or by Leith [b] for certain western magnetites.

The evidence for pegmatitic origin of the ores of the Atikokan district is weak. This district lies outside of the principal area studied in connection with this report, but from our examination of it we suggest this origin as a plausible one from the facts available. Certainly this district seems to show marked variations from most of the districts of the Lake Superior region—variations which seem to call for another mode of derivation.

Minute pegmatitic veins of quartz or iron oxide or both are common in the ellipsoidal basalts of the Vermilion district. In the coarser phases they may be seen to be intimately and irregularly mixed with the rock, and grading out toward the finer phases they tend to take on more definite vein outlines. In the Keewatin series as represented in the Vermilion district it is in many palces difficult to determine whether the iron-bearing formation is a magmatic segregation of greenstone, a vein material of a pegmatitic nature, or an ordinary iron-bearing sediment derived from them. In Plate XLVIII are shown gradations from the basalt through siliceous and jaspery phases to ordinary banded iron-bearing formation. These intermediate phases seem to be of a pegmatitic nature.

BROWN ORES AND HEMATITES ASSOCIATED WITH PALEOZOIC AND PLEISTOCENE DEPOSITS IN WISCONSIN.

ORES IN THE POTSDAM.

In the driftless portion of the Potsdam area north of Wisconsin River in western Wisconsin there are many small patches of hematite and brown ore, closely associated with upper horizons of the Cambrian (Potsdam) sandstone. Many of these patches lie on the tops and slopes of hills, but some of them follow the valleys. During the early days of mining in Wisconsin these ores were smelted locally at a furnace in Sauk County, but for 30 years they have not been mined, principally because of the small amounts available.

The origin of these ores is not clear. Occurring near the upper horizons of the Potsdam, some of them may represent residual accumulations due to erosion of the overlying Ordovician limestone. Samuel Weidman [c] believes that part of them at least are results of later valley filling by spring and bog solutions.

BROWN ORES IN "LOWER MAGNESIAN" LIMESTONE.

At Spring Valley, in Pierce County, Wis., are nodules and irregular masses of limonite in clays, resting upon the eroded surface of the "Lower Magnesian" limestone, particularly in old drainage courses on the surface of this limestone. Quoting from Allen: [d]

[a] Spencer, A. C., Franklin Furnace folio (No. 161), Geol. Atlas U. S., U. S. Geol. Survey, 1908, pp. 6, 7.

[b] Leith, C. K., Bull. U. S. Geol. Survey No. 338, 1908, pp. 75-89.

[c] Personal communication.

[d] Allen, R. C., statement prepared for this monograph. See also Allen, R. C., The occurrence and origin of the brown iron ores of Spring Valley, Wisconsin: Eleventh Report, Michigan Acad. Sci., 1909, pp. 95-103.

PLATE XLVIII.

PLATE XLVIII.

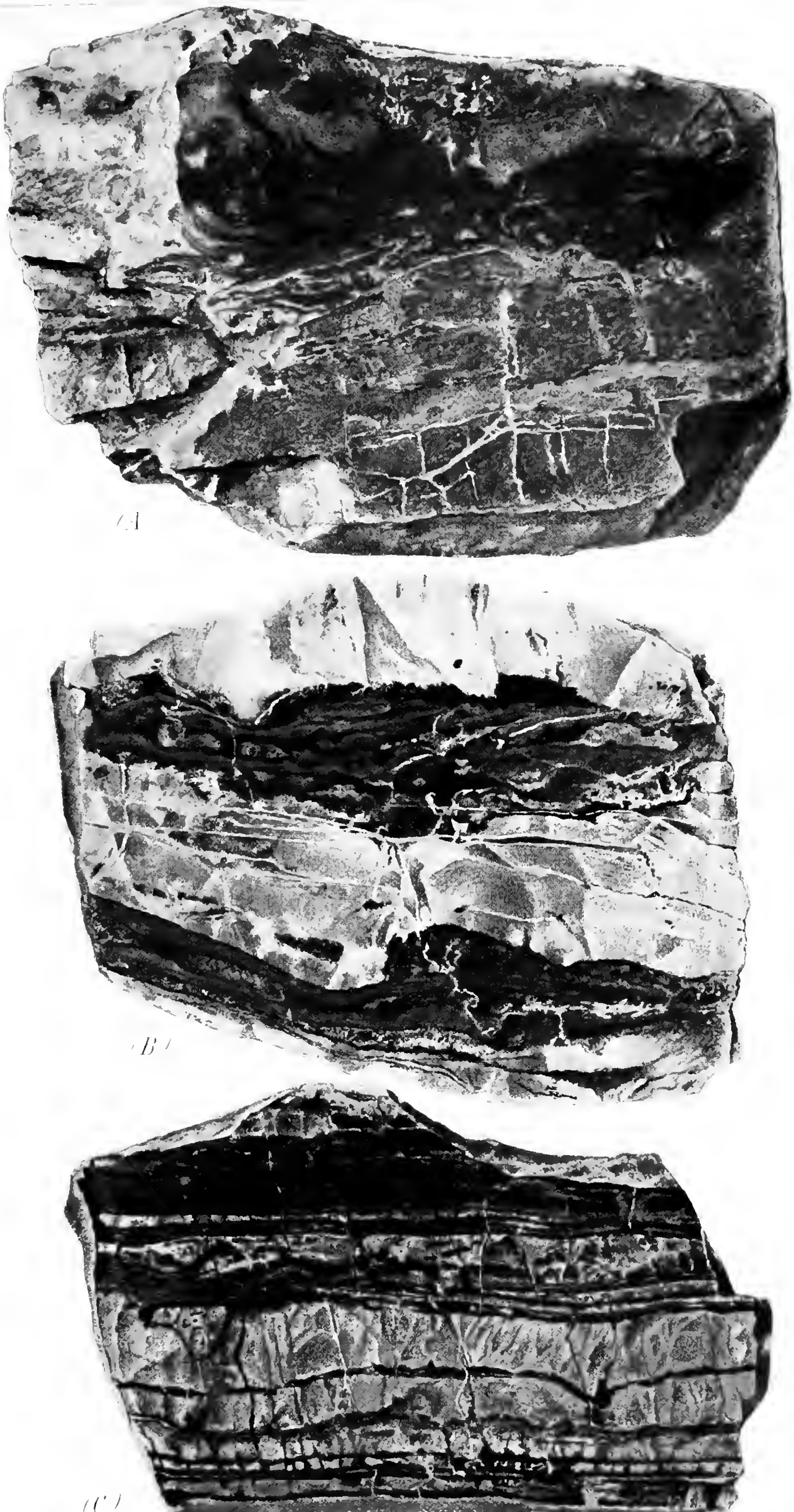
FERRUGINOUS CHERT OR JASPER, OF POSSIBLE PEGMATITIC ORIGIN, IN BASALT.

A. Partly silicified basalt (specimen 28564) from Vermilion district, Minnesota. In the ledge this is observed to grade imperceptibly into the little-altered basalt of the region.

B. Chert, green silicate, and iron oxide (specimen 28565) from Vermilion district, Minnesota, more definitely segregated into bands, grading imperceptibly into the rock shown in *A* on the one hand and into that shown in *C* on the other.

C. Same (specimen 28566), with larger proportion of iron in bands. This is an amphibolitic ferruginous chert or jaspilite of a type often seen in the iron-bearing formations.

In the ledge from which this series of specimens was collected, it was quite impossible to find any plane of separation between basalt and iron-bearing formations.



FERRUGINOUS CHERT OR JASPER, OF POSSIBLE PEGMATITIC ORIGIN, IN BASALT.

Spring Valley is a small town on Eau Galle River reached by a spur from Woodville, on the Chicago, St. Paul, Minneapolis and Omaha Railway. Iron ores were discovered in the vicinity of Spring Valley about 20 years ago. Thorough prospecting developed a number of deposits, two of which, known as the Gilman and the Cady deposits, are being mined. The Gilman was opened about 1890 and has been in operation more or less continuously since that time. In 1893 a furnace was erected at Spring Valley for utilizing the Gilman ores and numerous charcoal ovens were built in the vicinity for supplying fuel for the furnace. Wood soon became scarce and coke supplanted charcoal as a fuel. The original plant has been partly replaced by a more modern one.

GEOLOGY AND TOPOGRAPHY.

The Upper Cambrian sandstone underlies the valleys and lower hill slopes. The uplands are formed by limestone of Lower Ordovician age. The strata are conformable and flat-lying.

The topography is that of the maturely dissected plateau, and is essentially of preglacial origin. Eau Galle River and its tributary creeks are flowing through partly filled valleys. If the valleys were to be filled to the average height of the ridges the resulting surface would be a plain. A plain probably once existed here as part of a greater one which extended over a surrounding broad area. The present topography may be explained as resulting from the uplift of this ancient plain, giving the streams new erosive power. Before glacial time the streams had sunk their valleys through the Ordovician limestone and well into the underlying Cambrian sandstone. During the glacial epoch the valleys were partly filled by glacial wash.

GILMAN BROWN-ORE DEPOSIT.

The Gilman deposit rests upon an eroded surface of the Ordovician limestone, near its base, on the upper slopes of a ridge above the valley of a small creek tributary to Eau Galle River. It is on the railroad and is 1½ miles west of Spring Valley. The deposit covers several acres and in outline is very irregular, as shown by the mine workings, which are open shallow excavations, the deepest being not more than 30 feet. The ore is a brown hydrated hematite and occurs as nodules and concretions mixed irregularly with ocherous clay, sand, chert fragments, and nodular concretions of sand and clay. Locally the deposit shows rough and irregular bedding, but the general absence of bedding is conspicuous. The limestone presents an uneven surface to the bottom and sides of the deposit. In one place a wall of limestone some 6 or 8 feet high, showing undoubted evidence of having been eroded while exposed to the air, abuts directly against the ore. In places the ore comes quite to the surface, but as a rule it is covered by a foot to several feet of clay. All the mining is done by hand. The larger nodules of ore, called "rock" ore, are picked by hand from the clay and sand in which they are embedded. Some of them are very large and need to be broken up by blasting. But most of the ore in the Gilman mine is removed with the impurities in which it occurs and put through barrel washers. The following is the analysis of a three months' sample of "rock" and "wash" ore:

Analysis of ore from Gilman mine.

Fe	43.6	MgO	0.30
SiO_2	24.00	P	.14
Al_2O_3	2.3	S	.018
CaO	.58	Mn	.80

CADY BROWN-ORE DEPOSIT.

The Cady deposit is 2½ miles northwest of Elmwood and about 5 miles southeast of Spring Valley. It covers several acres on the top and upper slopes of a hill that rises steeply some 200 feet above the valley of Cady Creek. As in the Gilman deposit the ore rests on the Ordovician limestone. At the time of visit in 1906 the deposit had not been opened, but the ore was exposed in numerous pits and trenches. According to W. H. Foote, a shaft went down through 80 feet of ore and struck a face of limestone at that depth which was at an angle of 60° with the horizontal. Ore was followed down this face for 40 feet more with no bottom. The following analyses indicate the character of the ore in this shaft:

Analyses of Cady Creek ore.

	Thickness (feet).	Fe.	SiO_2.	Mn.	P.
Blue lump ore	10	59.12	9.0	2.03	0.075
Brown lump ore	10	49.96	14.33	.83	.073
Brown hematite	16	47.79	20.5	1.39	.078
Do	22	32.96	45.25	2.13	.076
Do	28	46.56	22.17	2.47	.077
Do	34	52.02	11.82	2.51	.054
Do	40	37.91	35.34	1.82	.068
Do	45	55.11	....	1.73	.062
Do	50	53.56	....	2.72	.062
Do	55	52.02	....	2.25	.062
Do	60	52.22	....	1.91	.068
Do	65	54.18	....	1.33	.060

The ore contains a somewhat higher percentage of iron, has a greater proportion of rock ore, and is associated with a less amount of impurities (sand, clay, etc.) than the Gilman ore, but is otherwise exactly similar to it. Mining has recently begun. The ore is delivered to the bins at the base of the hill by an aerial tram. The descending loaded buckets return the empties to the top of the hill.

ORIGIN OF SPRING VALLEY BROWN-ORE DEPOSITS.

The ores near Spring Valley are of superficial origin, being deposited upon the eroded surface of limestone and other rocks. Allen has shown, from a consideration of the thickness of the strata once overlying the present ores and their probable content of iron, that the now known deposits were probably not the result of direct downward slump of residual materials but are rather sediments transported laterally along drainage channels after the country had been cut down to the elevation of the ores. Allen shows further that since the formation of these deposits erosion has cut through them and around them, with the result that the adjacent territory has been lowered, leaving the deposits on the tops or slopes of hills. He concludes that the ore deposits of Spring Valley were laid down in lakes or marshes that existed along the drainage courses on the old post-Devonian peneplain, or on the valley bottoms, as may have been the case in the Gilman and Cady deposits, where the ore abuts directly against eroded limestone faces. The marshes and lakes were finally drained as a result of uplift of the land which enabled the streams to erode vertically at a greatly increased rate. Narrow valleys were formed in the older, broader ones. The outer margins of the old valleys correspond with the upper slopes of the hills forming the present valley sides. It is on these upper slopes that the ores characteristically occur. As erosion progressed ore-covered areas would naturally come to occupy higher and higher relative elevations, owing to the resistant nature of the ore beds. In this way would result ore-covered hilltops, as illustrated by the Cady deposit.

Weidman,[a] who has made a survey of the region surrounding Spring Valley, while accepting the general view that the Spring Valley ores are of superficial origin and were deposited upon the eroded surface of the limestone and associated rocks, is inclined to place the date of their origin long after the period of peneplanation of the region. This alternate hypothesis supposes the ore to have been formed in these valleys after they were eroded to a considerable depth—200 to 300 feet—in the peneplain and perhaps even at the still later stage when the valleys were in the process of being filled again with alluvial material. The deposits lie in secondary and tertiary valleys and on slopes opening outward toward larger valleys, and the massive, lumpy character of the ore indicates that it may very well have originated in the manner of iron-spring deposits, accompanied by more or less slope wash and slumping of clay and sand while the valleys were being filled. Since the valleys were partly filled and the ores formed, erosion has removed 30 to 40 feet of alluvial material from the valleys and a variable amount of the ore. This explanation as to the date of origin of the ore—namely, at the time when the valleys were well developed—seems to apply very well to the Gilman ore deposit, where most of the ore has been removed and where the relation of the ore deposit to the topography can be clearly observed, and it probably also applies equally well to the Cady deposit, where mining is not sufficiently advanced to show the actual conditions.

POSTGLACIAL BROWN ORES.

Postglacial iron ores are known in many parts of the Lake Superior region. They are ordinary bog deposits to which iron is being contributed in solution under the influence of organic material and deposited by oxidation. Nowhere is their thickness known to be over a few feet. Lying, however, directly at the surface, they frequently attract attention and for many years have been subject to intermittent exploration.

[a] Weidman, Samuel, Geology of northwestern Wisconsin: Bull. Wisconsin Geol. and Nat. Hist. Survey. (In preparation.)

CLINTON IRON ORES OF DODGE COUNTY, WIS.

OCCURRENCE AND CHARACTER.

Iron ores of Clinton age, similar to ores of the same horizon in the Appalachian region, appear in Dodge County, in southeastern Wisconsin. The shipments to the end of 1909, which figure in the total for the Lake Superior region, have aggregated 570,886 long tons.[a] The ores outcrop in a narrow belt extending for about a mile north and south on a westward-facing scarp caused by the overlying Niagara limestone. The underlying rock is Ordovician shale. The dip is eastward at the rate of about 100 feet to the mile. The beds are lens shaped along the outcrop and range in thickness up to a maximum of 37 feet. Mining operations have followed them 400 feet down the dip, and they are known by drilling to extend farther. Wells have shown the occurrence of ore in the southeast corner of the county and near Hartford in thicknesses ranging from 4 to 20 feet, and a diamond-drill hole near Kenosha, 60 miles to the southeast, cuts 18 feet of ore. The iron beds, if continuous eastward to Lake Michigan, a distance of 35 miles, are nowhere more than 800 feet below the surface, for the Niagara limestone which overlies them has this thickness and it outcrops all the way to the lake.

If we assume an average thickness of 10 feet, an extension down the dip of 2,000 feet, and continuous extension southward to Kenosha (which is doubtful), the amount of ore in these deposits would be 600,000,000 tons.

The ore is a slightly hydrated hematite, running from 29 to 54 per cent in iron and averaging perhaps 45 per cent, high in phosphorus, with the typical granular, oolitic, or flaxseed forms so characteristic of the ores of the Appalachian area. The matrix is calcite. Bedding is distinct and false bedding is common. The granules lie with their flat sides parallel to the bedding. The individual granules have been worn shiny by water action and aggregates of them have been rounded into pebbles.

Under the microscope the iron-oxide granules are found in part to be amorphous and in part to have the concentric structure of oolites. Clastic grains of quartz or of iron oxide commonly form the nucleus, surrounded by alternate layers of iron and silica. On treatment with hydrochloric acid the iron is dissolved, leaving little globular particles of amorphous silica, forming at first casts of oolites but on drying falling in, giving a basin-shaped indentation on one side. In the Clinton formation of the East some of the granules have the structures of replaced marine shells, but these have not been noted in the iron-bearing formation of this horizon in Wisconsin.

The origin of some of the amorphous granules is observed in experimental precipitation of ferric hydroxide in laboratory solutions where the precipitate is allowed to settle slowly. There is then observed a marked tendency for the aggregation of iron oxide into granules identical in shape and size with the granules observed in the Clinton ores. These granules are of the type regarded by Lehmann[b] as liquid crystals, a globular form preceding development of crystal structure and indefinitely grading into it. In materials that have strong crystallizing power this globular stage is soon passed or is not even observed. In substances weak in crystallizing power, such as iron oxide, the tendency inherent in the substance itself to group or crystallize does not go beyond this stage of globular aggregation.

Along the top of the ore body, at the contact with the overlying limestone, is a thin layer, ranging from less than an inch to 6 inches in thickness, of a hard, compact bluish hematite, heavier than the oolitic ore and running about 10 per cent higher in metallic iron than the main body of oolitic ore. In this hard bed there is no trace of the oolitic structure. However, there is an apparent gradation from one to the other.

The contact between the ore and the Niagara limestone might be termed a "knife-edge," as it is perfectly well defined, showing no gradation whatever from the iron into the limestone. The lower contact of the ore body with the underlying calcareous shale is similar to the upper contact. Under the microscope some of the calcite grains in the limestone near the contact are

[a] Lake Superior iron ore shipments for 1909 and previous years, compiled by Iron Trade Review, Cleveland.

[b] Lehmann, O., Flüssige Kristalle sowie Plastizität von Kristallen im Allgemeinen, molekulare Umlagerungen und Aggregatzustandsänder, ungen, Leipzig, 1904.

observed to be partly replaced by iron oxide, while other large calcite grains are the result of recrystallization. However, these are not common. In the lower contact the calcite is discolored by the iron oxide, but where this iron stain occurs we do not always find any evidence of replacement. For the most part the surface of contact of ores and overlying limestone is even, but locally the beds finger into one another.

ORIGIN OF THE CLINTON IRON ORES.

For a fuller discussion of the origin of the Clinton iron ores the reader is referred to the publications of the geologists who have studied the Clinton ores of the Appalachians, especially to the recent work of Burchard in Alabama.[a] The ores are not mined on a large scale in the Lake Superior region and have not been studied in the same detail as those of the Algonkian and Archean.

However, a comparison with the ores of the Algonkian and Archean in the Lake Superior region discloses certain contrasts, which are probably significant of origin. The Clinton ores constitute beds uniform in lithology, with no evidence of local concentration or replacement or residual masses of unaltered material, and the adjacent beds are not altered or iron stained, as they are where secondary concentration has occurred. The hematite is therefore probably not the residual result of the alteration of preexisting rocks. On the other hand the granules and aggregates of granules making up the ore are distinctly weatherworn and lie with their flat sides parallel to the strongly marked bedding and current bedding, pointing strongly to the deposition of the iron in essentially its present mineralogical condition in shallow waters.

The Clinton ores therefore differ from the Lake Superior Algonkian and Archean ores in being deposited as ferric hydroxide under shallow-water or shore conditions rather than as some ferrous compounds in quiet water, as is characteristic of the pre-Cambrian iron deposition. That the waters were marine is indicated by the character of the beds both above and below, carrying marine fossils, and also by the similarity of these ores to Clinton ores of the eastern United States, in which marine fossils are plentiful. It is also clear from the waterworn granules, current bedding, and oolitic structure that the waters were moving, suggesting shore conditions. The discontinuity of the beds and their variation in thickness also suggest locally varying shore conditions. But many features of the history of the deposition of these ores are yet obscure. No satisfactory answer has yet been made to the question why these ores have developed at this particular horizon in the Paleozoic and not at other horizons.

The final answer to this problem must involve the study of the Clinton ores of all of North America.

SUMMARY STATEMENT OF THEORY OF ORIGIN OF THE LAKE SUPERIOR IRON ORES.

The Lake Superior iron ores include the genetic types described in the following paragraphs.

1. Lake Superior sedimentary type: Iron brought to the surface by igneous rocks and contributed either directly by hot magmatic waters to the ocean or later brought by surface waters under weathering to the ocean or other body of water, or by both; from the ocean deposited as a chemical sediment in ordinary succession of sedimentary rocks; later, under conditions of weathering, locally enriched to ore by percolating surface waters. To this class belong most of the producing iron ores of the Lake Superior region, those of the Michipicoten district of Canada, and most of the nonproducing banded iron-bearing formation belts of Ontario and eastern Canada.

2. Magmatic segregation type: Ores brought to the outer part of the earth in molten magmas but were retained in them during crystallization, with the result that the ores form part of the rock itself, just as do the feldspar and other minerals. Such are the titaniferous magnetites, which contain refractory silicates and in places sulphur and phosphorus in deleterious quantities. Although these ores are known in enormous quantities in the Duluth gabbro of northern Minnesota they are not mined.

[a] Burchard, E. F., The Clinton or red ores of the Birmingham district, Alabama: Bull. U. S. Geol. Survey No. 315, 1907, pp. 130-151.

3. Pegmatite type: Ores which are carried to or near the surface in magmas and are extruded from them in the manner of pegmatite dikes, after the remainder of the magma has been partly cooled and crystallized. They are deposited from essentially aqueous solutions mixed in varying proportions with solutions of quartz and the silicates and have had no second concentration. To the pegmatite type are doubtfully assigned the ores of the Atikokan district of Ontario, and possibly also certain magnetites of the Vermilion district. (See p. 562.) No detailed study of the Atikokan ores has been made. Ores of this type have been mined in small quantity in the Atikokan district.

4. Clinton sedimentary type: Sedimentary "flaxseed" ores deposited in shallow waters, presumably from weathering of the land areas in which the iron is either disseminated in igneous rocks or has undergone some of the concentrations outlined in the three preceding paragraphs. They have suffered no essential second alteration. These are the ores in the vicinity of Iron Ridge, Wis.

5. Brown or hydrated ores, associated with Paleozoic and Pleistocene deposits: Residual or bog deposits in limestone as at Spring Valley, Wisconsin, or in glacial drift. Also abundant in ores of the Lake Superior sedimentary type. The associated substance is largely clay and they are therefore not susceptible of second concentration.

Each of these classes of ores has counterparts in ores mined elsewhere in the country, except the Lake Superior sedimentary ores, the only ones which have undergone a second concentration. From this class have been produced 99 per cent of the iron ores shipped from the Lake Superior region and annually 80 per cent of the iron ores mined in the United States, a fact that indicates the great importance of a second concentration.

All the ores have been derived ultimately from the interior of the earth, whence they were delivered by igneous eruptions to points near or at the surface, there to undergo various distributions and concentrations under the influence of meteoric waters and gases. The variations in composition, shape, and commercial availability of an ore have been controlled by variations of conditions under which the ores have reached the surface and have been distributed. The titaniferous magnetites represent ores brought nearly to the surface but not allowed to escape. The pegmatites represent ores which have been crystallized in the act of escape. The pre-Cambrian sedimentary formations of the Lake Superior region were derived largely from basic rocks of not dissimilar composition that reached the rock surface, though usually under water, in which case they crystallized as ellipsoidal basalts.

The eruptions to which is due primarily the introduction of most of the known ores have come up along the zone of the present Lake Superior basin. The copper ores of Keweenaw Point and the silver ores of Silver Islet have been brought up by similar igneous rocks at a little later date along the same zone. Along the strike of the Lake Superior zone during Keweenawan time igneous rocks also brought up the cobalt, nickel, and silver ores of Sudbury and Cobalt. The minerals and petrographic relations of the Keweenawan, cobalt, and nickel ores bear many similarities, suggesting possible differentiation from essentially the same magma. It is suggested that the entire Lake Superior and Lake Huron region is a great metallographic province from which the early extrusions brought up iron salts and the later extrusions were differentiated into the copper, silver, cobalt, and nickel ores.

OTHER THEORIES OF THE ORIGIN OF THE LAKE SUPERIOR PRE-CAMBRIAN IRON ORES.

Whitney,[a] Wadsworth,[b] Winchell,[c] Hille,[d] and others have held the Lake Superior pre-Cambrian ores of the sedimentary type to be of igneous origin. Winchell's arguments are nearly all based on the similarity of the textures of the iron-bearing formations to those of

[a] Foster, J. W., and Whitney, J. D., Report on the geology and topography of the Lake Superior land district, pt. 2, The iron region: Senate Docs., 32d Cong., special sess., 1851, vol. 3, No. 4, 406 pp.

[b] Wadsworth, M. E., Proc. Boston Soc. Nat. Hist., vol. 20, 1881, pp. 470–479; Bull. Mus. Comp. Zool., Geol. ser., vol. 1, 1880, p. 75.

[c] Winchell, N. H., Structures of the Mesabi iron ore: Proc. Lake Superior Min. Inst., vol. 13, 1908, p. 203.

[d] Hille, F., Genesis of the Animikie iron range, Ontario: Jour. Canadian Min. Inst., vol. 6, 1904, pp. 245–287.

igneous rocks. For instance, the concretions are compared with bombs, the spaces left by the leaching of silica are regarded as amygdaloidal cavities, the breccias are regarded as volcanic breccias, the bedding is regarded as flow structure, the slump of the ores in contact with wall rocks is regarded as the result of flow of lava over the bluff represented by the wall rock.

In this view Winchell practically reaches a conclusion similar to that of Wadsworth, who believed that the ores and jaspers are chiefly eruptive and described the jasper and ore as intruded into the country rocks in wedge-shaped masses, sheets, and dikes.

These resemblances between iron ores and igneous rocks are so superficial that they would scarcely be taken seriously by most observers, and conclusions as to igneous origin ignore so many fundamental facts of composition, texture, and structural relations described in these reports that it is not believed necessary to attempt to refute them.

In earlier reports Winchell [a] presents a different view of the origin of the ores, as follows:

A chain of active volcanoes, having explosive emissions, extended across northeastern Minnesota about where the Mesabi iron range is found. This was near the shore line of the Taconic ocean, and was accompanied by land-locked bays and perhaps by fresh-water lakes. Such marginal volcanoes had a chemical effect on the oceanic water, causing the precipitation of silica and probably of iron. Its basic lavas and obsidians were attacked by the hot waters and were converted by encroaching silica into jaspilite. Near the shore such glassy lavas were eroded by wave action and distributed so as to form conglomerates and sandstones. Such action would have distributed lavas wholly silicified as well as those which were yet glassy, and the detritus of both would necessarily mingle with detritus from the Archean. Such lavas would exhibit great contortion and in places great brecciation, the same as later lavas, and these breccias must have been mingled sometimes with the products of detrital action. After prolonged activity of the volcanoes most of the deposits and of the lavas which were submarine would be permeated by secondary silica, but carbonate of iron would permeate the mass where carbonic acid had freer access, as in the lagoons into which streams drained from the land surface to the north.

This view Winchell also applies to the Vermilion range. He argues that the iron of the iron-bearing formation was first deposited as a ferric oxide and that the ferruginous cherts making up the greater part of the formation to-day are original oceanic deposits laid down essentially in the present form.

In volume 6 of the "Geology of Minnesota" he argued that the solutions formed from the igneous rocks accumulated in the rocks to the point of saturation and that precipitation came later as a result of cooling.

This discarded view of Winchell obviously has more points in common with the theory of origin outlined in the present monograph than his more recent views, although important differences are still to be noted.

In a report on the Baraboo range Weidman [b] reached the conclusion that the iron ores of that district were originally precipitated in bogs and shallow waters as limonite and hematite associated with slate, that they were then covered by the dolomite, tilted up, and eroded, and that the deposits to-day are essentially the same in lithology as they were when deposited with the exception of certain minor vicissitudes in the way of dehydration, recrystallization, etc. The deposits might under this theory extend to indefinite depths—indeed, as far as any of the sedimentary formations of the district—and in this way they would contrast with the distribution of the ores determined primarily by a secondary concentration from the surface. In view of the evidence of secondary concentration found in other parts of the Lake Superior region the burden of proof must rest with one who attempts to exclude secondary concentration of the Baraboo ores. Deep drilling in the Baraboo district has seemed to show a diminution in thickness and grade of ore beds and a relative increase of iron carbonate with increase in depth, pointing to secondary concentration from the surface as the agency which has been largely responsible in developing the ore bodies. The difference in opinion as to the origin of Baraboo ores here indicated is really one primarily of emphasis. Weidman emphasizes the primary deposition in rich beds; we believe that the primary deposition, while a large factor in localizing ores, has been supplemented by considerable secondary concentration to develop the commercial ore deposits.

[a] The geology of Minnesota, vol. 5, 1900, pp. 997-998.

[b] Weidman, Samuel, Bull. Wisconsin Geol. and Nat. Hist. Survey No. 13, 1904, pp. 142-146.

GENETIC CLASSIFICATION OF THE PRINCIPAL IRON ORES OF THE WORLD.

Iron ores are known to have been developed by a great variety of igneous and metamorphic processes. In almost any genetic classification of ore deposits iron ores will be represented in each of the divisions, contrasting thereby with the less abundant precious metals. Moreover, it is likely that certain iron-ore deposits would fall outside of any such classification and others would require assignment to two or more of the divisions. The following classification of the iron ores of the world has been constructed with the idea of showing the correlatives of the Lake Superior pre-Cambrian ores and the wide range of conditions under which the larger and better-known deposits have developed.

1. Magmatic segregations, usually in basic rocks. Titaniferous and silicated magnetites, weathering to limonites, epidotic and chloritic magnetites. On disintegration yielding magnetic sands.
   - Titaniferous magnetites of northeastern Minnesota and Adirondacks.
   - Magnetite of Vysokaya Gora and Goroblagadot of the Uralo, Russia.
   - Silicated magnetites and specular hematites of pre-Cambrian of Kiirunavaara, Gellivare, etc., Sweden.
   - Silicated magnetites of Kiirunavaara, Loussavaara, and Tuollavaara, Sweden.
   - Titaniferous magnetites in Taberg, Sweden.
2. Igneous after-effects, usually from acidic rocks (pneumatolytic, pegmatitic, etc.), usually deposited within or near parent igneous mass.
   - Certain silicated magnetites of Vermilion and Atikokan districts of Adirondacks and New Jersey, of Iron Mountain, Missouri, and of Iron Springs, Utah.
   - Contact-silicated magnetites of Christiania, suggested by Backstrom and DeLaunay to be aqueous sediments contributed by associated porphyries.
3. Residual limonites resulting from weathering of igneous rocks.
   - In this class are most of the laterite deposits resulting from the weathering of basic igneous rocks in tropical regions. The limonites of northeastern Cuba, constituting the weathered mantle of serpentine rock, are in enormous tonnage.
4. Sedimentary.
   - *A. Iron oxides, mainly syngenetic.*
     - Crystalline hematites of Minas Geraes, Brazil, the largest and richest known deposits of this type in the world.
     - Cambro-Silurian micaceous hematite and magnetite of Norway.
     - Oolitic limonites, containing subordinate quantities of iron-silicate granules of various descriptions and iron carbonates, in Silurian Clinton rocks of Wisconsin and Appalachians and Newfoundland; in Jurassic of Luxemburg, Lorraine, and elsewhere in Germany and in Cleveland district of England; in Tertiary of Louisiana, Texas, and Bavaria.
     - Bog and lake limonites, sometimes in granules. In glacial lakes and bogs of Lake Superior region. Small and nonproductive. Represented by Scandinavian lake ores, Finnish lake ores, lake and bog ores of eastern Canada, Massachusetts, and elsewhere.
   - *A 1. Iron oxides, developed mainly by secondary surface alterations of sedigenetic carbonates and silicates.*
     - Pre-Cambrian hematites and limonites of Lake Superior region.
     - Paleozoic limonites of Spring Valley, Wisconsin.
     - Brown ores of southern Appalachians, etc.
   - *A 2. Iron oxides, resulting from anamorphic alterations of sedimentary iron-bearing formations.* Specular hematites and silicated magnetites derived from deep-seated anamorphism of oxides, especially of carbonates and silicates by deep burial, intrusion, or both.
     - Marquette specular hematites. Hard blue hematites of Vermilion.
     - Silicated magnetites of Gunflint district of Minnesota, eastern Mesabi, western Gogebic, western Marquette, etc.
   - *B. Iron carbonates.* Usually associated with coal or carbonaceous slates. Also various intermixtures of calcium and magnesium carbonates, with minor amounts of oxides and silicates.
     - Huronian original iron carbonates of Gogebic, Marquette, Menominee, and other districts of Lake Superior region, altering at surface to limonites and hematites, and at depth or by igneous intrusion to silicated magnetites and hematites.
     - Carboniferous black-band ores of Pennsylvania, Ohio, and Kentucky, altering at surface to brown ores or pot ores in clay.

Tertiary black-band ores of Maryland.
Carboniferous black-band ores of Germany.
Carboniferous black-band ores of Wales and Scotland.
Permian black-band ores of district of Erzberg, in the northern Alps.

C. Iron silicates. Greenalite, glauconite, chamosite, thuringite, etc., with minor mixtures of iron oxides and carbonates.
Huronian original greenalite rocks of Mesabi district of Minnesota, derived largely from direct igneous contributions, as indicated under 2. Altering to hematites and limonites at surface and to silicated magnetites at depth or at igneous contacts.
Lower Silurian chamosite ores of central Bohemia and chamosite and thuringite ores of Thuringerwald and vicinity, in Germany.

D. Various combinations of above.

It will be noted that the Lake Superior ores are represented in most of the principal classes here given. They also constitute an important subclass, the greenalite ores, developed by aqueo-igneous processes, not yet certainly identified elsewhere.

Much the largest part of the world's production of iron ore has come in recent years from the sedimentary ores. The largest reserves are in that class. Also important for the future are the residual weathering ores of the laterite type, such as are found in northeastern Cuba. The highest grades are reached in the sedimentary ores which, in addition to some purification by weathering in place in a parent rock, have been sorted and segregated during transportation and deposition as sediments, and in the Lake Superior type, when again exposed to the surface, have undergone further purification through katamorphism. These successive concentrations have removed deleterious constituents, broken up complex silicates, and left the ores with a porous texture better adapted for furnace reduction than the ores of classes 1 and 2.

The iron ores therefore illustrate both a wide range of ore-depositing agencies and the great increase of values effected by the reaction with meteoric waters and the atmosphere in the zone of katamorphism.

One of the most striking features of the ore deposits of the sedimentary class is the prevalence in them of granular textures, both oolitic and amorphous. The principal types of granules are as follows:

Green ferrous silicates:
Greenalite, $Fe(Mg)SiO_3.nH_2O$, amorphous.
Glauconite, hydrous silicate or iron and potassium, amorphous, resembling earthy chlorite, in granules.
Thuringite, $8FeO.4(Al,Fe)_2O_3.6SiO_2.9H_2O$, related to prochlorite, massive and fresh, oolitic when altered.
Chamosite, SiO_2 29 per cent, Al_2O_3 13 per cent, Fe_2O_3 6 per cent, FeO 42 per cent, H_2O 10 per cent. Related to prochlorite. Oolitic.
Oolites with concentric rings of quartz and some green silicate, of chloritic nature, undetermined. Found in Clinton and other ores.

Hematite and limonite:
Oolites consisting of concentric rings of silica and iron oxide.
Amorphous granules representing oxidation of some of the ferrous silicate granules mentioned above or replacing shells.

All the above granules lie in various cements of silica, iron oxide, and calcium carbonate.

The correlation and origin of these various granular forms present an interesting field for monographic study. It is known that some are organic, as, for instance, the glauconite and certain of the amorphous iron-oxide granules replacing shells. It is known further that probably the larger part are inorganic, including the oolites and amorphous greenalite and iron oxide. As shown in another place (p. 525), both the greenalite and iron-oxide granules form in ordinary chemical precipitates, and it is further suggested that they are perhaps related to Lehmann's liquid crystals. It may be of interest to note that of the three common iron compounds, oxides, silicates, and carbonates, the two former appear in granules, while the last does not. The oxides and silicates have weak crystallizing power, which, according to Lehmann, is usually associated with the development of granular or amorphous forms; the carbonates have strong crystallizing power, tending to give the surface definite and angular outlines.

CHAPTER XVIII. THE COPPER ORES OF THE LAKE SUPERIOR REGION.

By the authors, assisted by Edward Steidtmann.

THE COPPER DEPOSITS OF KEWEENAW POINT.

GENERAL ACCOUNT.

Although the authors have studied the copper of the Keweenawan series in many parts of the Lake Superior region and have visited the copper deposits frequently, they have made no systematic investigation of the ore deposits themselves. Since the publication of Irving's monograph[a] on the district by the United States Geological Survey, the detailed mapping done by the Survey in this region has been confined to the iron deposits. It is nevertheless thought desirable to include in this monograph a general account of the copper deposits in order to summarize, as fully as possible, the present state of knowledge of the geology of the Lake Superior region. The portion of this chapter dealing with the origin of the ores contains certain new features.

The following description of the ores is based partly on our own observations and largely on the published descriptions of Irving,[a] Rickard,[b] Lane,[c] Graton,[d] and others.

The copper-producing district of Keweenaw Point follows the axis of the point in a general northeasterly direction for 70 miles and has a width of 3 to 6 miles. The richest portion of the belt is the central portion, in Houghton County, adjacent to Portage Lake (see Pl. XLIX), in association with the upper lava flows.

The copper is metallic. With the exception of the comparatively small amount of coarse copper—"mass" and "barrel work"—sorted out at the mines, all the ores are subjected to crushing by steam stamps, followed by concentration.

The principal gangue minerals of the copper of this district are calcite, quartz, prehnite, and laumontite, with smaller but still considerable quantities of analcite, apophyllite, natrolite and other zeolites, orthoclase, datolite, epidote, chlorite (delessite), and native copper. Rarer associates are, according to Prof. A. E. Seaman, of the Michigan College of Mines,[e] adularia, agate, anhydrite, algodonite, azurite, aragonite, argentite, amethyst, annabergite, amphibole, ankerite, barite, braunite, biotite, bornite, cerargyrite, chalcocite, chloanthite, chrysocolla, chalcopyrite, chlorastrolite, cuprite, covellite, clinochlore (?), dolomite, domeykite, fluorite, gypsum, hematite, iddingsite, jasper, kaolinite, keweenawite, limonite, magnetite, martite, marcasite, malachite, melaconite, muscovite, mohawkite, niccolite, pyrite, pyrrhotite, phillipsite, powellite, saponite, selenite, stibiodomeykite, semiwhitneyite, serpentine, silver, siderite, talc, whitneyite, thomsonite, wad, and wollastonite. Though this group of minerals

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883.

[b] Rickard, T. A., The copper mines of the Lake Superior region, New York, 1905.

[c] Lane, A. C., The geology of Keweenaw Point—a brief description: Proc. Lake Superior Min. Inst., vol. 12, 1907, pp. 81–104; The geology of copper deposition: Am. Geologist, vol. 34, 1904, pp. 297–309.

[d] Graton, L. C., Silver, copper, lead, and zinc in the Western States: Mineral Resources U. S. for 1907, pt. 1, U. S. Geol. Survey, 1908 (Michigan, pp. 496–523; Copper, pp. 571–644).

[e] Personal communication, 1910.

is characteristic of the deposits in general, they may vary in importance in the different types as well as in the different parts of the district. Calcite is the most abundant associated mineral in the transverse veins and conglomerates; epidote is the most abundant in the dipping veins. The genetic sequence of these minerals is discussed under the origin of the ores.

The copper constitutes (1) veins intersecting the northwestward dipping beds of the Keweenawan series described in Chapter XV and (2) bedded deposits formed by infiltration or replacement of both the conglomerate and amygdaloidal beds of the Keweenawan series, chiefly in the beds below the "Great" conglomerate, which is the dividing line between the lower part of the Keweenawan, where traps predominate, and the upper part, where sediments predominate. (See fig. 75.) Copper deposits have not been found in felsitic beds and compact traps, except in minute quantities in the latter, where they are closely associated with amygdaloid beds. Rich cores of native copper are reported to have been drilled on the Indiana property, in Ontonagon County, from a very dense felsite, which appears to be intrusive. Development, however, has not reached the productive stage. Only one bed above the "Great" conglomerate contains copper, and this is the Nonesuch shale, which carries a little disseminated copper throughout its extent and has been worked in the Porcupine Mountain district.

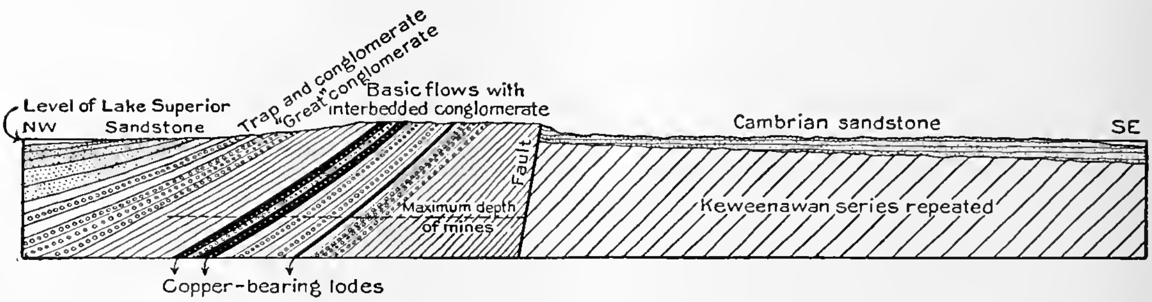
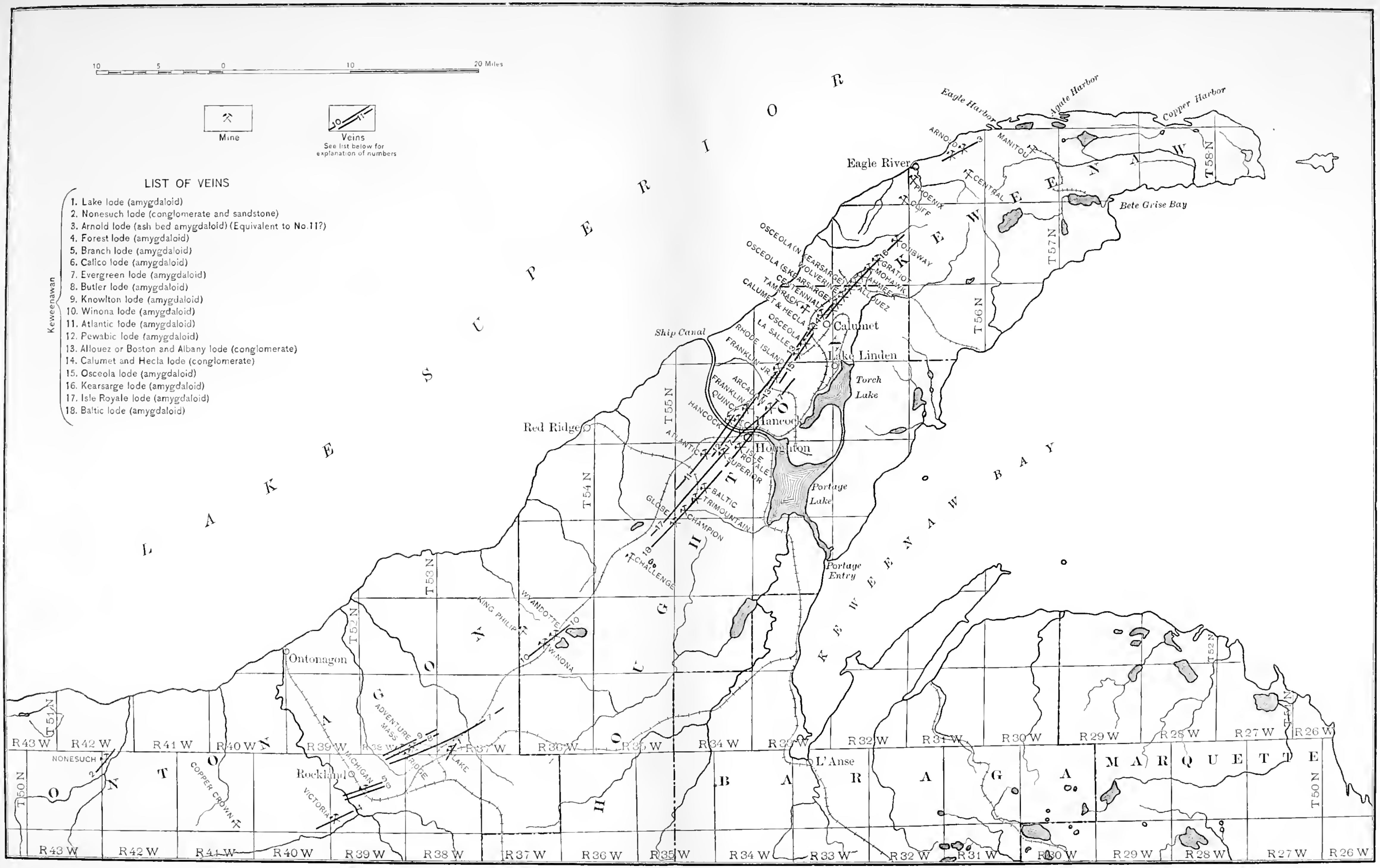


FIGURE 75.—Cross section of Keweenaw Point near Calumet, showing copper lodes in conglomerates and amygdaloids.

The deposits earliest exploited were the veins transverse to the strike of the beds in the Eagle River area at the northeastern extremity of the district; the next were the veins parallel to the strike, though not uniformly to the dip, in the Ontonagon area at the southwest end of the district. The vein deposits, especially those in the Ontonagon district, are characterized by masses of copper, being in this respect distinguished from the amygdaloidal and conglomerate copper deposits, in which the copper is, as a rule, much more minutely disseminated. The amygdaloidal deposits were the next to be opened, principally in the central portion of the district, but also in the Ontonagon area. The conglomerate deposits occurring only in a small area in the vicinity of Calumet, in the central portion of the district, were the last to be opened. (For summary of history see pp. 35–37.) In 1907 73.1 per cent of the ore mined came from amygdaloidal lodes and 26.9 per cent from conglomerate lodes, the vein deposits at present being practically nonproducing, although of the total production from the district approximately 3 per cent is sorted out at the mines as coarser mass material.

The grade of the ores is low and is becoming lower. In the early days of mining much ore above 3 per cent was mined. In 1906 the average grade for the district was 1.26 per cent, and in 1907 it dropped to 1.1 per cent, and to 1.05 per cent in 1908. Only four mines in 1908 worked ore yielding an average of 1 per cent or more in metallic copper. In 1908 the richest lodes mined carried less than 2 per cent metallic copper, while the poorest yielded but little over 0.5 per cent. The grades and amounts mined from the principal mines in 1907 are as follows: [a]

[a] Mineral Resources U. S. for 1907, pt. 1, U. S. Geol. Survey, 1908, p. 500.



MAP SHOWING LOCATION OF COPPER-BEARING LODES AND MINES ON KEWEENAW POINT.

See page 573.

Ore output and grade of the principal Michigan lodes in 1907.

Lode.	Ore (tons).	Grade (per cent).
Calumet	2,400,000	1.835
Baltic	1,900,000	1.06
Kearsarge	2,350,000	.87
Pewabic [a]	1,250,000	.79
Osceola	750,000	.895
Actual total and average	8,641,361	1.67
All other lodes	1,250,853	.62

[a] Partly estimated.

A little native silver occurs with the copper in some lodes. Averaged on the total tonnage in 1908, the silver yield was 0.023 ounce to the ton. Native silver is present in all the deposits, but is particularly characteristic in the veins of the Eagle River and Ontonagon areas, where also mass copper is abundant.

The amygdaloidal and conglomerate deposits have great extent along the strike, the Kearsarge lode, for example, being actively mined almost without break for a distance of 12 miles and other lodes being mined for 2 miles along their strike. They have been followed down the dip to a maximum distance of more than 1½ miles and a vertical depth of about a mile, making these mines among the deepest in the world, and are still found to be productive, although of somewhat lower grade. The depth to which mining may be carried is not yet known. That it should be possible to mine at a profit ores as low as 0.5 per cent at a depth of a mile is due to the remarkable uniformity and continuity of the deposits along both strike and dip. Shoots of richer ore pitching parallel to the strike of the beds—as, for instance, the northward-pitching shoot of the Calumet and Hecla conglomerate—are known in a few places, but these are themselves so extensive that their existence and alternation with leaner portions of the beds have been ascertained only after years of extensive mining.

TRANSVERSE VEINS OF EAGLE RIVER DISTRICT.

The veins of the Eagle River district, in the northern part of Keweenaw Peninsula, cut vertically across the strike of the beds of sediments, traps, and amygdaloids. The veins are not commonly formed by the filling of a simple fissure, but by a large number of subparallel, anastomosing fissures with blocks of small rock inclosed between, forming rather a fracture zone. The productive zone is in the amygdaloid beds immediately below the Allouez conglomerate and above the greenstone. The veins vary from mere seams to those 20 or 30 feet wide, being widest where they cut across loose-textured amygdaloidal beds and not exceeding a width of 3 feet where they are in contact with compact traps. The greatest depth reached in the mining of transverse veins is 1,600 feet, in the Cliff mine. The texture of the rock traversed by the veins also controls the ore content, the veins being rich where they cut porous amygdaloidal layers and poor where they cut compact layers. Many of the amygdaloid beds themselves are rich enough to be productive adjacent to transverse veins.

The gangue materials associated with the copper of the Eagle River veins are mainly calcite, quartz, prehnite, and laumontite, but analcite, apophyllite and other zeolites, orthoclase, datolite, epidote, natrolite, and other minerals are found. Native silver is present. Veins containing only calcite are generally bare of copper.

The copper is scattered through the gangue in thin films penetrating other minerals or in coarser fragments filling interstices between other minerals, or occurs in lenses, in this occurrence usually with a crystalline form. Mass copper also is found here, the masses ranging up to many tons in weight and many of them containing fragments of wall rock.

Irving[a] believes that these veins are replacements along fissured zones rather than fillings of open fissures. As evidence he cites the gradation between vein and wall rock, the replacement of wall rock by copper masses, the occurrence of fragments of wall rock in the vein and in the

[a] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 422-426.

copper masses, and the greater width of the veins adjacent to amygdaloidal beds than of those in contact with dense traps. The origin of the copper ores is discussed on pages 580 et seq.

Transverse fissure veins are not restricted to the Eagle River district, but are present in nearly every mine on Keweenaw Peninsula. In the southern districts, however, these veins, as a rule, contain no copper, or at least not enough to make them productive. Many of them are barren even where they cross productive beds of amygdaloids.

No mines are now operating in the Eagle River district. Explorations have recently been conducted there with a view to further mining. The mines which have produced ore in this district are the Ætna, Empire, Delaware, Amygdaloid, Copper Falls, Central, Phoenix, and Cliff.

DIPPING VEINS OF ONTONAGON DISTRICT.

The dipping veins of the Ontonagon district are noted chiefly for the great amount of mass copper that has been removed from them. The principal "mass" deposits are in the group of amygdaloids, traps, and conglomerates corresponding roughly to the strata between Portage Lake and the area covered by the upper sediments. The veins are fillings of fractures following the strike of the beds. Many of those within weaker portions of the bed—for instance, along amygdaloidal layers—have a dip steeper than the bedding. Those that lie between two different beds are likely to dip at the same angle as the beds.

The veins vary in width from a few inches to many feet. The veins between different beds are more likely to be narrow; those cutting amygdaloidal beds may consist of a wide fracture zone, with fragments of rock interspersed with vein minerals. Slickensided walls locally bound the veins, but on the whole the contact is irregular. Irving[a] believed these veins, as well as the transverse veins of the Eagle River district, to be largely replacements of wall rock.

Transverse veins (crossing the strike) are present also throughout the mines of the Ontonagon district, but they are unproductive except where they cross dipping veins.

The chief vein materials associated with the copper are epidote and calcite, but the other minerals above named as generally associated with copper are present. The copper occurs in irregular hackly masses, some of which are many tons in weight. One mass found in the Minnesota mine in 1857 weighed 420 tons. The large proportion of mass copper originally mined in this district gradually decreased and the production of amygdaloidal copper increased. In 1908 the production was derived wholly from amygdaloid lodes. The principal producing mines are the Adventure, Mass, Michigan, and Victoria. Recent explorations have shown additional copper deposits.

AMYGDALOID DEPOSITS.

The copper deposits in amygdaloids are by far the most numerous and most productive in the Keweenaw Point region. The amygdaloids are the upper, and in some places the lower, vesicular portions of the many lava flows, with here and there an interbedded detrital layer. The thickness of the productive portion of the amygdaloids varies from a few feet to 35 or 40 feet. The depth to which amygdaloid beds are productive has not been determined; the greatest depth yet reached is shown in the Quincy mine—5,280 feet along the incline, or 4,008 feet vertically.

The copper deposits in the amygdaloids, though lean in places, are much more continuous along the strike than those in the conglomerates, several mines miles apart working the same bed. There are very unusual variations in strike in the vicinity of the Baltic, Trimountain, and Champion mines.

The dip of the amygdaloids flattens out below and also to the northeast along the strike. The Quincy lode has a dip of 55° at the surface and 37° at a depth of about 5,000 feet along the incline. The Atlantic lode dips 54°, the Wolverine 40°, and the "Baltic" 70°, the dip thus showing a considerable variation even in a small area, though in general being steeper in the southern part of the region.

[a] Irving, R. D., Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 422-426.

In amygdaloidal beds the copper occurs in cavities in amygdules partly filled by other minerals, along cleavage or fracture planes within these minerals or replacing them partly or completely. The minerals associated with the copper are prehnite, chlorite, calcite, and quartz. According to Irving,[a] considerable portions of the beds have lost all semblance to their original amygdaloidal structure and now consist of chlorite, epidote, calcite, and quartz intimately associated or forming separate masses of the most indefinite shape merging into one another. In places portions of partly altered prehnite occur associated with copper, but as a rule prehnite has given way to its alteration products. In these highly altered masses copper crystallized free where it had a chance, but more commonly it replaced other minerals. In calcite bodies it formed those irregular, solid branching forms locally known as horn copper, some of them many hundred pounds in weight; in epidote, quartz, and prehnite bodies it occurs as thread and flakelike impregnations; in foliaceous, lenticular chloritic bodies it forms flakes between cleavage planes and oblique joints, or here and there—this is more particularly true of fissure veins—it replaces the chloritic selvage-like substance till it forms literally pseudomorphs, some of which are several hundred tons in weight.

In the Baltic and adjacent mines are considerable quantities of black sulphides near the surface, but even here they are not in sufficient amount to have economic value. The amount of these sulphides decreases greatly with increasing depth.

The amygdaloids are productive only where broken. Usually they have both strike and dip fractures in addition to very irregular fracturing. Commonly the strike fractures are not exactly parallel to the beds but cut across them at acute angles. Many of these fractures show slickensiding, proving considerable differential movements. At the Quincy and Baltic mines the amygdaloid is lean where there are cross fractures, but a little distance away from the cross fractures it is rich.

In some places the copper goes down into the compact rock beneath the amygdaloid, following zones of fissuring, alteration, and replacement.

In a number of places productive amygdaloid occurs below a heavy trap bed, as at the Winona, Quincy, Atlantic, Wolverine, and Baltic mines.

The mines operating in the amygdaloidal deposits and producing 60 per cent of the total output of the Keweenaw Point district in 1908 were the Calumet and Hecla, Tamarack, Osceola, Quincy, Centennial, Wolverine, Tecumseh, Franklin, Isle Royale, Atlantic, Baltic, Trimountain, Champion, Winona, Allouez, Ahmeek, Mohawk, Adventure, Mass, Michigan, and Victoria. The distribution of these mines and the lodes upon which they are operating are shown on Plate XLIX (p. 574). The Calumet and Hecla, Osceola, Ahmeek, Wolverine, and Mohawk are on the so-called Kearsarge lode, which has been developed for an extent of about 14 miles, the largest deposit in the district. The Wolverine has the richest deposit, running about 1.35 per cent of refined copper. The ore runs as low as 0.7 per cent in other mines. Below 0.7 per cent it has not been found profitable to mine. South of Portage Lake the only lode which has a large production is the Baltic. Its surface extent is about 4 miles and the yield averages about 1.1 per cent.

COPPER IN CONGLOMERATES.

Only two workable beds of conglomerate have been found among thirty or more beds distributed through the Keweenawan series underneath the "Great" conglomerate—the Allouez ("Boston and Albany") conglomerate and the Calumet and Hecla conglomerate—and even these are workable only in a small area. A number of other conglomerate beds have been found to contain small impregnations of copper but not enough to be productive. The Allouez conglomerate is being worked by the Franklin Junior mine and the Calumet and Hecla conglomerate by the Calumet and Hecla and Tamarack mines. (See Pl. XLIX.)

The Calumet and Hecla conglomerate is the richest and largest copper lode in the district and ranks among the first two or three large copper deposits of the world. It is famous as the principal source of copper of the Calumet and Hecla Company, which has been the greatest

[a] Op. cit., pp. 421-422.

dividend payer in the history of mining. This conglomerate thins both to the north and south. At the North Hecla mine it is not more than 3 feet wide in one place. It thins so rapidly to the south that on the Osceola property it has not been discovered. Thus the Calumet and Hecla conglomerate is essentially a lens.

The Calumet and Hecla conglomerate bed is productive only in the 2 miles covered by the Calumet and Hecla and Tamarack properties. North of this area the bed was mined by the Centennial mine without success, and to the south it was mined by the owners of the Osceola before they sunk down to the Osceola amygdaloid.

The conglomerate dips 39° W. at the surface, flattening to 36° with depth. It is followed down the dip from the outcrop to a maximum depth of 8,100 feet by the Calumet and Hecla Company, representing a vertical depth of 4,748 feet. A vertical shaft belonging to the same company about a mile from the outcrop on the hanging-wall side passes through the lode at a depth of 3,287 feet and goes to a depth of 4,900 feet. One of the Tamarack shafts reaches a depth of 5,229 feet, being the deepest shaft in the world. The conglomerate lode has increased in thickness from 13 feet at the surface to 20 feet in the deepest workings. The upper half (stratigraphically) is richer than the lower half of the bed.

The copper content of the Calumet and Hecla conglomerate was formerly about 4 per cent near the surface, and now a mile vertically below the surface is 1 to 1½ per cent and averages for the mine shipment 1.83 per cent. The copper is of lower grade and less regularly distributed in the Tamarack part of the same bed. This decrease in grade of the ore worked with increase in depth is partly a real one and partly due to improvements and lower costs, enabling lower-grade ores to be worked. The richer ores of the Calumet and Hecla conglomerate constitute a shoot pitching to the north and extending to the Centennial ground. The upper half of the conglomerate bed is finer grained than the lower half. It contains more interstratified sandstone layers, called sandstone bars, which are usually barren but in places are very rich. In some places they separate the conglomerate into two parts and in such places the values may be either above or below the sandstone. The conglomerate is well cemented to both foot and hanging walls.

Below the conglomerate are several amygdaloidal beds. Immediately over the conglomerate is a trap, 300 or 400 feet thick, which separates it from the first amygdaloid. The cross-section maps of the formations, made from the drifts of the deep shafts intersecting the beds for thousands of feet above and below the conglomerate, divide the lavas into two classes, traps and amygdaloids. The traps form the greater part of the sections and many of them are hundreds of feet in thickness. The amygdaloids compose a much smaller portion of the sections and are usually thin. The copper values are very small in the trap and amygdaloids, both above and below the conglomerate.

The rich portions of the conglomerate are usually light colored; the poor portions are dark. This is a practical distinction by mining men, who speak of the lean conglomerate as "black" and mean by this that wherever it is in this condition the values are low or lacking. This difference in color is due to the fact that the alterations, a part of which resulted in the deposition of the copper, have bleached the conglomerate. In many places in the rich conglomerate aureoles of lighter-colored material may be seen at the outer parts of pebbles and bowlders.

The Allouez conglomerate, worked by the Franklin Junior mine, varies between 8 and 25 feet in thickness, with 3 to 4 feet of sandstone at the base. It is of lower grade than the Calumet and Hecla conglomerate, averaging about 0.5 per cent in copper.

The pebbles in the conglomerates are mainly porphyritic felsite with diabase and amygdaloids in subordinate amounts. Locally, as in the Calumet and Hecla conglomerate, granitic and quartz porphyry pebbles are abundant. The original cementing materials were siliceous and feldspathic particles, but these have been replaced largely by secondary calcite and epidote, with chlorite, and where the conglomerates are productive the copper is an important or the chief cementing material. Copper also replaces pebbles to varying degrees. In this process the pebble first becomes porous and discolored and is altered to a mass of epidote and chlorite with a spongelike skeleton of copper associated with calcite. As a rule epidote and chlorite first replace the matrix and porphyritic feldspars and later copper replaces them, but often copper replaces feldspar directly, penetrating in thin films along cleavage planes. Pebbles like these, some of them as large as a man's head, are found in both the Calumet and Hecla and the Allouez conglomerates, being composed of copper in various degrees up to nearly solid bowlders of metal. In some pebbles the copper has almost entirely replaced the original material as well as the epidote alteration, but more commonly the copper skeleton contains in its cavities unaltered crystals of orthoclase and quartz, surrounded by a crust of epidote and chlorite.

Few fractures are noted in the conglomerate, nor is there evidence of slipping or faults at contacts with walls. The hanging wall is not safe, tending to fall down. Whether this is due to the weakness of the rock when the stopes are taken out so that new fractures are formed, or whether incipient fractures were present, has not been determined. Certainly the distribution of values is not a function of exceptional shattering.

In the Nonesuch shale of the Porcupine Mountain district copper is found as a cementing material, as a replacement of cementing material, and as a replacement of rock particles. Many of the copper fragments in this bed are peculiar in having minute cores of magnetite.

COMPOSITION OF COPPER-MINE WATERS.

Lane has assembled a large number of analyses of copper-mine waters. He finds that in the upper levels of the mines, to depths varying from 500 to 1,000 feet, the waters are abundant and fresh, though on the whole somewhat softer than the river waters of the Mississippi Valley. Below these depths the waters are much less abundant and more highly concentrated and contain principally chlorides of soda and calcium. At the deepest levels the calcium and soda may be in about equal proportions, or the calcium may predominate over the soda. At intermediate levels the soda predominates over the calcium. The contrast in composition of the upper and lower waters slightly resembles that of the waters of the upper and lower levels of the iron mines. Reference is made on pages 543–544 to possible causes of this difference in composition.

Of the several analyses available, three are selected as typical of the three classes of water.

Analyses of copper-mine waters.[a]

[Parts per million.]

	1. Deep water.	2. Intermediate water.	3. Surface water.
Cl	134,916	702	[b] 3.5+
SO_4	2,123	75	6 +
CO_3	2,123	....	40 +
PO_4	None.	....	....
Na	11,592	414	[b] 2.3+
K	None.	....	....
Ca	65,346	91.2	19
Mg	2,123	....	4
Al	None.	....	....
Fe	None.	....	....
Mn	None.	....	....
SiO_2	2,123	35	10
$(FeAl)_2O_3$	....	....	1.5
Fe_2O_3, Al_2O_3	....	30	....
Sum	....	1,347.2	86.3
Difference	....	2.8	....
Total solids determined	212,300	1,350	....

[a] Lane, A. C., Mine waters: Proc. Lake Superior Min. Inst., vol. 13, 1908, pp. 74–126.

[b] If contaminated.

1. Water from one of the lower levels of the Quincy copper mine, Hancock, Mich. Analysis by George Steiger. Cited in Bull. U. S. Geol. Survey No. 330, 1908, p. 144.
2. Water from South Kearsarge mine, Keweenaw Point, No. 1 shaft, ninth level, dripping collected by F. W. McNair and C. D. Hohl. Analysis given by Lane, A. C., Proc. Lake Superior Min. Inst., vol. 13, 1908, p. 116.
3. Water from Tobacco River, Michigan. Analysis given by Lane, A. C., op. cit., p. 90.

COPPER IN KEWEENAWAN ROCKS IN PARTS OF THE LAKE SUPERIOR REGION OTHER THAN KEWEENAW POINT.

Copper is known in small quantities in the Keweenawan traps and sediments in Douglas County, Wis., in adjacent parts of Minnesota, on Isle Royal, on Michipicoten Island, and elsewhere. These occurrences are not essentially different from those of Keweenaw Point in their mineralogical and geologic associations. The copper occurs principally in fissure veins cutting the bedding of the traps and to a less extent in the amygdaloidal openings and interbedded sediments. Exploration has been carried on intermittently in all the areas named. On Isle Royal a considerable amount of metallic copper has been mined. (See pp. 37–38.) None of these districts are now producing copper.

ORIGIN OF THE COPPER ORES.

COMMON ORIGIN OF THE SEVERAL TYPES OF DEPOSITS.

The copper ores of the Lake Superior region are in part replacements of conglomerates and cementing material filling the original openings in the conglomerate, in part fillings of amygdaloidal openings and replacements in traps, to a slight extent fillings of veins and replacements of adjacent wall rock, and finally cement and replacements of a basic sandstone high in the series. The copper is an integral part of the cementing material of these rocks.

In a discussion of origin the three types of deposits must be considered as essentially a unit. Irving [a] sees in them—

> simply the results of a rock alteration entirely analogous to that which has brought about the deposition of copper and its associated vein-stone minerals within the cupriferous amygdaloids. They are alteration zones which traverse, instead of following, the bedding, simply because the drainage of the altering waters has been given this direction by the preexisting fissures. * * * Thus the differences in origin of the several classes of copper deposits—conglomerate beds, cupriferous amygdaloids, epidote veins parallel to the bedding, and "fissure" veins transverse to it—which at first sight seem to be great, on closer inspection for the most part disappear.

That much of the copper was introduced as filling and replacement of wall rocks admits of no doubt. Several hypotheses are still open as to the source of the copper and the manner in which it was transferred and redeposited.

PREVIOUS VIEWS OF NATURE OF COPPER-DEPOSITING SOLUTIONS AND SOURCE OF COPPER.

Irving,[b] Wadsworth,[c] and nearly all other geologists who have studied the copper-bearing rocks believe that the source of the copper was in the basic igneous rocks, and that so far as it was derived from the sediments, its ultimate source was still the basic igneous rocks, because the sediments came from those rocks. This belief is founded principally on the uniform and close association of copper with the basic igneous rocks and the known existence of copper sulphides minutely disseminated through some of the coarser igneous rocks. The source of the copper was believed by Pumpelly [d] to be in the overlying sediments.

Smyth[e] believed that the ores did not come from the adjacent wall rocks but from a deep-seated source, the nature of which does not appear from his report.

The conditions and agents under which the copper has been supposed to have been taken from the adjacent rocks and concentrated have been variously interpreted. Irving,[f] Pumpelly,[g]

[a] Irving, R. D., The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, 1883, pp. 424–425.

[b] Idem, pp. 425–426.

[c] Wadsworth, M. E., The origin and mode of occurrence of the Lake Superior copper deposits: Trans. Am. Inst. Min. Eng., vol. 27, 1898, pp. 694–696. See also Müller, Albert, Verhandl. Naturf. Gesell. Basel, 1857, pp. 411–438; Bauermann, Hilary, Quart. Jour. Geol. Soc., vol. 22, 1866, pp. 448–463; Wadsworth, M. E., Notes on the iron and copper districts of Lake Superior: Bull. Mus. Comp. Zool. Harvard Coll., Geol. ser., vol. 1, 1880, p. 126.

[d] Pumpelly, Raphael, The paragenesis and derivation of copper and its associates on Lake Superior: Am. Jour. Sci., 3d ser., vol. 2, 1871, pp. 188–198; 243–258; 347–355.

[e] Smyth, H. L., Theory of origin of the copper ores of the Lake Superior district: Science, new ser., vol. 3, 1896, p. 251.

[f] Irving, R. D., op. cit., pp. 419–426.

[g] Pumpelly, Raphael, op. cit., pp. 353–355.

Wadsworth,[a] Lane,[b] and others have been inclined more or less strongly to the theory of concentration under the direct downward movement of meteoric waters. Pumpelly has also implied that concentration may have occurred when sediments were still below sea level. Lane [c] has suggested that the waters were salt waters of the type now found in the deep copper mines, and that they represent fossil sea waters or fossil desert waters, which in the tilting of the series have migrated downward. Van Hise [d] has argued that while meteoric waters have done the work, it has been during their upward escape after a long underground course. Smyth [e] assigned the first concentration of the ores to ascending solutions from a deep-seated source not specified.

OUTLINE OF HYPOTHESIS OF ORIGIN OF COPPER ORES PRESENTED IN THE FOLLOWING PAGES.

The copper ores are characteristically associated with basic igneous rocks. The source of the copper-bearing solutions lies in these igneous rocks. The original copper-bearing solutions were hot. These solutions may be partly direct contributions of juvenile water from the magma, partly the result of the action of meteoric waters on crystallized hot rocks.

ASSOCIATION OF ORES AND IGNEOUS ROCKS.

From 60 to 70 per cent of the copper produced in this region comes from the amygdaloids. The veins of mass copper also are all in igneous rocks and these veins are richest where they lie parallel to or intersect amygdaloidal beds. The ore-bearing rocks are characteristically near thick rather than thin flows. Barren conglomerates are interbedded with productive flows. The only productive conglomerates, the Calumet and Hecla and the Allouez, are associated with thick flows. Especially is the overlying flow thick.

Not only is the association of the ores and the igneous rocks conspicuous in the producing district, but throughout the Keweenawan area of Lake Superior traces of copper are widely distributed in the igneous rocks.

Copper is associated principally with basic igneous flows, but it is now reported in drilling in felsite, supposedly intrusive, at the Indiana mine. Copper sulphide is also reported by Wright [f] in association with intrusive gabbros and ophites of Mount Bohemia.

ORE DEPOSITION LIMITED MAINLY TO MIDDLE KEWEENAWAN TIME.

It is believed that the original deposition of the copper was limited mainly to middle Keweenawan time, or, if not, at least to the cooling period of the igneous rocks of that time. As shown below, the wall-rock alterations associated with the ores seem to be characteristic of hot water. Some of the gangue minerals are hot-water deposits. Bowlders of some barren conglomerate beds show mineralization which was developed before they were broken from the parent underlying ledge. The deposition of the copper was an episode in the work of cementation of both sedimentary and igneous rocks, which certainly began as soon as the beds were deposited but which continued to the end of the volcanic period of the middle Keweenawan and even longer. Pumpelly's work, mentioned below, shows that the copper was relatively late among the minerals introduced. The same thing is shown in some places by the absence of deformation effects upon the copper. The late introduction of the copper is argued by Smyth [g] from the contrast of minerals first deposited in the copper-bearing series with those coming later and carrying the copper, the first, according to him, being developed under conditions of weathering before the series was folded, and the second being developed after the series was folded.

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[a] Wadsworth, M. E., The origin and mode of occurrence of the Lake Superior copper deposits: Trans. Am. Inst. Min. Eng., vol. 27, 1898, p. 695.
[b] Lane, A. C., The theory of copper deposition: Am. Geologist, vol. 34, 1904, pp. 297-309.
[c] Lane, A. C., The chemical evolution of the ocean: Jour. Geology, vol. 14, 1906, pp. 221-225.
[d] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 1136.
[e] Op. cit., p. 251.
[f] Wright, F. E., The intrusive rocks of Mount Bohemia, Michigan: Ann. Rept. Michigan Geol. Survey for 1908, 1909, pp. 361-397.
[g] Smyth, H. L., Theory of the origin of the copper ores of the Lake Superior district: Science, new ser., vol. 3, 1896, p. 251.

Wadsworth[a] cites the extension of copper in a continuous mass from one flow to another as evidence of introduction "after the copper-bearing series was complete."

Wright[b] finds veins of iron and copper sulphides developed in the intrusives of Mount Bohemia, but is uncertain whether they are closely related in time with the consolidation of the intrusives.

It may well be that the introduction of the copper, begun relatively early in the middle Keweenawan, was to a considerable extent the work of hot solutions after the entire middle Keweenawan was piled up, when relatively quiescent conditions had been reached; for the lavas, the slowly cooling, deep-seated intrusives, and the underlying reservoir would be sources of heat and hot solutions for a long time after active volcanism had ceased.

On the whole, the evidence seems to indicate clearly that part of the copper was deposited soon after the extrusion of the associated igneous rocks, but late in the cycle of mineral deposition in which copper was formed, and that much of the deposition of the copper followed the folding and deformation of the Keweenawan rocks. As this deformation undoubtedly accompanied and immediately followed the deposition of the Keweenawan series, the fact that copper deposition followed deformation does not necessarily remove it much in time from the formation of the adjacent rocks. But, on the other hand, there is no evidence which fixes the close of this period of deposition.

DEPOSITION OF THE COPPER ACCOMPLISHED BY HOT SOLUTIONS.

That the copper was deposited by hot solutions seems to be established by the facts stated below.

NATURE OF GANGUE MINERALS.

Prehnite, epidote, chlorite, laumontite, and other gangue materials of the copper are aluminum silicates. Alumina is not ordinarily transported by cold pluvial waters, and, specifically, it is not transported by the fresh mine waters near the surface at the present time in any but the most minute quantity. (See analyses, p. 579.) In the deeper, warmer, heavily concentrated chloride waters (see analyses) alumina and ferric oxide are in larger though still small amounts. The analyses report the alumina and ferric oxide together, and the proportion which is alumina is not known.

Other characteristic associates of the copper are datolite, containing boron, and apophyllite, a fluorine mineral—both substances which are not ordinarily ascribed to solution, transportation, and deposition by cold solutions. Mine waters working on the gangue materials, which may be said to contain a concentration of boron and fluorine, even now contain only traces of the boron and fluorine minerals, not enough to afford materials for their precipitation.

NATURE OF WALL-ROCK ALTERATIONS.

The wall rocks are obviously altered by the same solutions that have deposited the copper. The bleaching of the wall rock is so characteristic of copper veins that it is regarded as a favorable sign in exploration. This bleaching alteration, when measured quantitatively, is found to vary in several important respects from alterations which would be typical of surface waters carrying the agencies of the atmosphere. Below is a table containing two pairs of analyses of the fresh and altered wall rocks, selected carefully to eliminate, so far as possible, variations in original composition; a group of analyses made under the direction of Pumpelly, which indicate the general trend of chemical change in the trappean beds; an analysis of an altered Calumet and Hecla conglomerate bowlder described by Lane; a group of analyses by Lindgren illustrating the changes in chemical composition of basic igneous rocks altered by hot solutions; and two analyses of fresh and weathered basic igneous rocks given by Merrill.

[a] Wadsworth, M. E., The origin and mode of occurrence of the Lake Superior copper deposits: Trans. Am. Inst. Min. Eng., vol. 27, 1898, p. 695.
[b] Wright, F. E., op. cit., p. 392.

Analyses of fresh and altered wall rocks compared with other rock alterations.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
SiO_2	45.83	49.40	46.78	46.66	47.74	42.71	42.83	46.32	49.20
Al_2O_3	18.92	16.12	17.04	16.97	16.75	14.93	16.58	15.95	16.00
Fe_2O_3	6.02	11.51	7.95	9.52	2.55	7.45	4.42	2.86	3.03
FeO	6.24	2.13	6.31	4.16	6.31	3.48	3.81	8.92	7.10
MgO	8.49	3.52	6.31	5.02	8.32	2.70	6.96	4.08	6.98
CaO	9.28	10.90	6.94	9.37	11.40	22.76	14.11	10.28	3.44
Na_2O	2.10	3.02	3.44	4.08	1.93	.54	1.29	3.56	5.05
K_2O	.32	.58	1.10	.44	.14	.04	1.39	1.23	1.31
H_2O-	.50	.10	.66	.91	{ 2.73	{ 3.56	{ 6.48	{ 3.25	{ 4.51
H_2O+	2.70	2.30	3.62	2.79	......	......	......	......	......
TiO_2	......	......	......	......	1.02	1.29	1.36	2.78	2.26
P_2O_5	......	......	......	......	......	......	......	......	......
CO_2	.10	.59	.08	.02	......	......	......	......	......
S	......	......	......	......	......	......	......	......	......
SO_3	......	......	......	......	......	......	......	......	......
Cu	.01?	.04	......	......	......	......	......	......	......
MnO	......	......	......	......	.52	.22	.87	.89	1.17
FeS_2	......	......	......	......	......	......	......	......	......

	10.	11.	12.	13.	14.	15.	16.	17.	18	19.
SiO_2	52.83	31.42	45.70	46.22	45.56	37.01	51.01	45.74	47.00	42.50
Al_2O_3	16.30	16.83	20.44	10.22	14.15	12.99	11.89	5.29	15.70	21.60
Fe_2O_3	9.60	15.58	9.50	12.88	11.20	.43	1.57	.13	4.78	17.00
FeO	2.48	12.08	8.95	7.45	9.83	3.57	6.08	2.06	9.96	......
MgO	3.98	3.36	2.24	.84	6.76	5.49	8.87	.94	6.36	2.70
CaO	2.98	2.84	7.46	15.56	2.30	9.78	10.36	23.85	8.96	4.20
Na_2O	6.54	1.98	.80	.18	1.57	.13	4.17	.11	2.77	1.50
K_2O	2.49	1.04	.28	1.01	1.18	4.02	.15	1.29	1.23	.70
H_2O-	{ 2.76	{ 14.52	.35	.58	.23	.13	.24	.22	{	{ ......
H_2O+	......	......	2.78	3.91	4.84	1.92	2.09	1.07	3.24	9.80
TiO_2	......	......	1.10	.95	1.11	.85	.98	.36	......	......
P_2O_5	......	......	......	......	.14	.06	.17	.07	......	......
CO_2	......	......	......	......	3.04	15.04	......	18.91	......	......
S	......	......	......	......	......	......	......	......	......	......
SO_3	......	......	......	......	.03	.04	......	......	......	......
Cu	......	......	Trace.	Trace.	......	......	......	......	......	......
MnO	......	......	......	......	.25	.24	......	......	......	......
FeS_2	......	......	......	......	7.86	7.99	1.73	.49	......	......

1. Specimen 47500B, country rock 70 feet from the lode, seventh level of Winona mine, Keweenaw Point, Mich. Analysis by R. D. Hall, University of Wisconsin, 1909.
2. Specimen 47499, center of lode, same locality. Analysis by R. D. Hall, University of Wisconsin, 1909.
3. Specimen 47506, 12 feet from footwall of sixty-third level of Quincy mine, Keweenaw Point, Mich. Analysis by R. D. Hall, University of Wisconsin, 1909.
4. Specimen 47505, footwall near lode, same locality. Analysis by R. D. Hall, University of Wisconsin, 1909.
5. Melaphyre, lower zone of bed 64, Eagle River section, Mich. Pumpelly, Raphael, Metasomatic development of the copper-bearing rocks of Lake Superior: Proc. Am. Acad. Arts and Sci., vol. 13, 1878, p. 293.
6. Prehnitized upper zone of bed 64, same locality. Idem.
7. Pseudo-amygdaloid, middle zone of bed 64, same locality. Idem.
8. Bottom of bed 87, same locality. Idem., p. 285.
9. Middle of bed 87, same locality. Idem.
10. Diabase porphyrite, regarded by Lane as the original of the altered conglomerate. Lane, A. C., The decomposition of a bowlder in the Calumet and Hecla conglomerate: Econ. Geology, vol. 4, 1909, p. 161.
11. Altered conglomerate. Idem.
12. Fresh basaltic rock from center of flow, 15 feet from lode, Dingle Creek mine, Douglas County, Wis. Analysis by W. G. Wilcox, University of Wisconsin, 1910.
13. Superjacent amygdaloidal lode, same flow. Analysis by W. G. Wilcox, University of Wisconsin, 1910.
14. Amphibolite schist, Mina Rica vein, Ophir, Placer County, Cal. Fairly fresh, but contains some calcite and pyrite. Lindgren, Waldemar, Metasomatic processes in fissure veins: Trans. Am. Inst. Min. Eng., vol. 30, 1901, p. 666.
15. Completely altered amphibolite schist, Conrad vein, Ophir, Placer County, Cal. Idem.
16. Fresh diabase, Grass Valley, Cal. Idem.
17. Altered diabase, North Star mine, Grass Valley, Cal. Idem.
18 and 19. Average of five fresh (16) and weathered (17) basic igneous rocks—diabase from Spanish Guiana, diabase from Medford, Mass., basalt from Bohemia, basalt from Crouzet, France, and diorite from Albemarle County, Va. Calculated from analyses given by G. P. Merrill in Rocks, rock weathering, and soils.

In the following table the first two pairs of analyses given above are calculated as closely as possible into the minerals actually observed in the rocks:

Mineral compositions of fresh and altered wall rocks calculated from first two pairs of analyses given above.

Minerals.	47500B.	47499.	47506.	47505.
Orthoclase	1.67	2.78	6.67	2.22
Albite molecule	17.82	25.15	28.82	33.54
Anorthite molecule	25.02	20.29	22.24	25.02
Olivine	9.30	......	2.00	......
Augite	27.09	......	30.74	1.88
Chlorite	13.60	13.41	12.90	20.58
Water	.50	......	.66	.91
Copper	.01?	.04	......	......
Hematite	5.00	5.28	4.64	2.88
Prehnite	......	15.22	......	......
Epidote	......	7.66	......	13.05
Calcite	......	1.40	.20	.05
Quartz	......	9.30	......	......
	100.01	100.73	100.87	100.13

Analyses representing ordinary weathering alterations indicate a uniformity of results which may serve as a basis for comparison with alterations of unknown cause. Comparing the alterations of the wall rocks of the copper deposits of unknown origin with the known results of weathering of similar types of basic rocks and the results of the alteration of similar basic igneous rocks by thermal solutions, the following conclusions seem justified:

1. The changes in the chemical composition of the Lake Superior copper rocks lack uniformity.

The changes in the composition of basic igneous rocks by thermal solutions lack uniformity.

The weathering of basic igneous rocks, as well as the weathering of all other rocks, causes certain changes in the chemical composition, which are almost rigidly uniform.

2. The changes effected in the silica content of the Lake Superior copper rocks adjacent to the deposits are not governed by silicate ratios in the original rock.

The changes effected in the silica content of basic igneous rocks elsewhere by their alteration by thermal solutions are not controlled by silicate ratios in the original rocks.

The changes effected in the silica content of basic igneous rocks by weathering, as well as those effected by the weathering of all other silicate rocks, are governed by the silicate ratios in the original rocks.

3. The changes in the chemical composition of the Lake Superior copper rocks show local concentration of lime or alkalies, depending on the stage of mineral paragenesis represented by the analysis. There has been an increase in the ferric iron and water content throughout; FeO appears to have been consistently removed or rather oxidized in place. There is evidence of both the removal and the introduction of Al_2O_3.

The changes in the chemical composition of the rocks altered by thermal solutions elsewhere show a consistent increase in K_2O and a consistent decrease in Na_2O, Fe_2O_3, and MgO. Al_2O_3 has suffered considerable decrease in some rocks. In others the evidence for the decrease, increase, or stability of Al_2O_3 is not very clear.

The changes in the chemical composition of basic rocks by weathering consist in a uniform decrease in CaO, MgO, Na_2O, K_2O, and SiO_2; Al_2O_3 remains nearly constant and water is introduced.

It follows from the facts presented that the changes in the chemical composition of the Lake Superior copper rocks effected by their alteration adjacent to the copper deposits are fundamentally different from those which are known to have been caused by the action of weathering solutions. On the other hand, these changes present similarities to the changes effected by thermal solutions.

4. Coincident with the changes in the chemical composition of the Lake Superior copper rocks, the tendency of their mineralogical alteration is not in accord with the change produced by weathering, but it is in harmony with the mineralogical alterations effected by thermal solutions.

The weathering of basic igneous rocks results in the development of kaolin, quartz, carbonates, and other simple compounds and the decomposition of all minerals not in the list of secondary minerals. The development of kaolin in the absence of the development of other secondary silicates is one of the best-established criteria of the decomposition of rocks under the influence of meteoric solutions.

The mineralogical changes caused by the alteration of the Lake Superior copper rocks adjacent to the deposits can be generalized as a progressive development of chlorite, prehnite, epidote, quartz, and the alkaline silicates in succession, with more or less overlap, in place of the original mineral constituents of these rocks—plagioclase feldspars, augite, some magnetite, olivine, and other accessory minerals.

The mineralogical changes of the basic igneous rocks altered elsewhere by hot solutions consist in the development of sericite and calcite from augite, hornblende, epidote, biotite, and feldspars. The ferromagnesian minerals alter also to chlorite, which in turn changes to muscovite. Magnetite alters to siderite, and ilmenite to rutile. The final product is essentially sericite, carbonates, quartz, and sulphides.

The results of the alteration of the copper-bearing rocks by the solutions which deposited the copper and gangue minerals have been found to contrast with the effects of weathering in a manner similar to the results of the alteration of certain basic igneous rocks by thermal solutions elsewhere. A fuller discussion of these contrasts will be found in a paper by Steidtmann.[a]

PARAGENESIS OF COPPER AND GANGUE MINERALS.

A study of the paragenesis of copper and gangue materials, according to Pumpelly,[b] discloses the following order of deposition of the minerals: (1) Chlorite and some laumontite; (2) laumontite; (3) laumontite, prehnite, epidote; (4) quartz and a green earth mineral; (5) calcite; (6) copper and calcite; (7) calcite, alkaline minerals, orthoclase, analcite, apophyllite, datolite. The members of this order overlap one another. Copper was largely deposited after the development of ferrous iron-bearing minerals, chlorite, and epidote and is more intimately associated with these iron-bearing minerals than with non iron-bearing minerals, except prehnite.

The phenomenon of mineral paragenesis in deposits derived from solutions indicates that the parent solutions have experienced certain definite physical and chemical changes. Depositional cycles are as certainly related to changes in concentration of the solutions, changes in temperature or pressure, changes in chemical composition, etc., as cycles of sedimentary deposition are related to certain definite changes in physiographic conditions. It is difficult to see how present pluvial waters could develop such a depositional cycle.

Smyth[c] argues that, of the above-named series of minerals, the first deposits, principally chlorite with other nonalkaline, hydrous silicates, were developed by ordinary weathering immediately after the igneous rocks were extruded at the surface; that the copper and later associated minerals were introduced later, after the folding of the Keweenawan series; that therefore the succession of minerals does not, as Pumpelly[d] supposed, represent a continuous march of alteration. The minerals of the second period are sharply separated from the alteration products of the first period, which they often replace, by their richness of alkalies and by the presence of fluorine and boron. Smyth's[e] argument is essentially that copper was introduced in solutions contrasting with ordinary meteoric solutions and of later origin. Still further, Smyth[e] cites the occurrence of copper under impervious layers of greenstone as evidence of arrest of solutions coming from below.

CONTRAST WITH PRESENT WORK OF METEORIC SOLUTIONS.

In general, the kind of work done by the waters which deposited the copper contrasts with that being accomplished to-day by meteoric waters. It is true that the minute quantities of sulphides in the basic igneous rocks are oxidized to the sulphates of copper, transported, and redeposited by coming into contact with ferrous solutions in the presence of alkaline carbonates. Evidence of solution at the surface is to be seen at many places in the stains of carbonates of copper, and yet there is no evidence that ground or surface waters are at present segregating copper deposits from the country rocks. Pluvial solutions now active in the copper ores are not known to carry copper. The concentrated solutions of the deep mines, which can not, under any hypothesis of deposition from meteoric solutions, be regarded as the normal meteoric solutions from which the copper was derived, are known to deposit small amounts of copper on mine tools, but analyses of these waters show only a very small percentage of copper. It seems evident that if pluvial solutions are so inefficient in carrying copper from the concentrated materials at the present time, their inefficiency in leaching the sparsely disseminated primary

[a] Steidtmann, Edward, A graphic comparison of the alteration of rocks by weathering with their alteration by hot solutions: Econ. Geology, vol. 3, 1908, pp. 381–409.

[b] Pumpelly, Raphael, Paragenesis and derivation of copper and its associates on Lake Superior: Am. Jour. Sci., 3d ser., vol. 2, 1871, p. 350.

[c] Smyth, H. L., Theory of origin of the copper ores of the Lake Superior district: Science, new ser., vol. 3, 1896, p. 251.

[d] Pumpelly, Raphael, op. cit.

[e] Op. cit., p. 251.

copper of the igneous rocks of the series would be a thousandfold greater. Waters away from the mines, even where they are running through the basic igneous rocks, are found to be nearly if not quite lacking in copper.

SOURCE OF THERMAL SOLUTIONS.

THREE HYPOTHESES.

Three hypotheses as to the source of the thermal solutions suggest themselves—that they were juvenile solutions, aqueous or gaseous, given off by the igneous rocks on cooling; that they were meteoric waters heated by contact with igneous rocks; that they were some combination of the two. That both juvenile and meteoric sources contributed to the thermal solutions would be expected from the general conditions of sedimentation of the Keweenawan series. Lava beds were piled one above another at comparatively short intervals, separated by the deposition of coarse fragmental sediments, probably developed subaerially. Simultaneously, or later, intrusives penetrated the interbedded igneous and sedimentary rocks, both parallel to and across the bedding. The waning of igneous activity allowed sediments to accumulate in thicker beds and finally, in the upper Keweenawan, without interruption. The igneous rocks may be supposed to have carried with them the usual complement of magmatic waters and vapors. They were fluid and became amygdaloidal. Such solutions would be speedily mixed with surface meteoric waters. The rapid piling up of beds would imprison both juvenile and meteoric waters under conditions that would cause them to lose their heat only slowly. The maximum bleaching and cementation of both igneous rocks and sediments and the simultaneous deposition of copper may be supposed to have occurred at this time. Tilting of the beds, with accompanying fractures and faults, began early in Keweenawan time and continued throughout the period. The tilting may be supposed to have slowly moved the contained solutions, and when erosion had beveled the beds, access for more meteoric waters was given. At this time, when the elevations were certainly mountainous and the openings in the rocks not cemented, as at present, meteoric solutions would have a vigorous and deep circulation. These general facts lay the burden of proof heavily on anyone attempting to show that the thermal solutions were juvenile or meteoric alone. They seem to show that the meteoric solutions were in the greater abundance. They do not show whether the distinctive work of copper deposition accomplished by these solutions was due to the juvenile or the meteoric contributions, or both.

This leads us to the question whether the copper was contributed directly in hot juvenile solutions escaping from the igneous rock, or whether it was leached from crystalline wall rocks by hot solutions of both juvenile and meteoric nature. In the nature of the case, quantitative evidence with which to answer this question is difficult to obtain.

The view that at least some of the ore-bearing solutions were magmatic is favored by the evidence cited on foregoing pages that the ores are associated in place and time with igneous extrusions, that the ore-depositing solutions were hot, that they carried fluorine and boron, and that the ores were deposited in mineral cycles showing rapidly changing conditions.

Of similar import is the apparent scarcity in the crystallized wall rocks of copper which could be leached and concentrated in sufficient amounts to explain the present deposits. Copper has been found most sparingly as a primary constituent in the fresh igneous rocks. It has not been reported from microscopic examination of the fine-grained surface rocks, and in only a few cases, in minute quantities, have sulphides of copper been found in the coarser igneous rocks. No evidence has been thus far adduced that such minutely disseminated copper is more abundant in the igneous rocks in the copper-bearing areas than in igneous rocks outside the copper-bearing areas. The few copper determinations which have been made in the analyses of fresh igneous rocks show either no copper or but little more than a trace. On the other hand, analyses are few, and the final word as to the original copper content of the fresh igneous rocks can not be said until more analyses are available.

There is no reason to believe from present known facts that the unleached wall rocks are any richer in copper in the vicinity of productive lodes than they are in other parts of the Keweenawan series throughout the Lake Superior region. In northern Minnesota and other known nonproductive areas there seems to be fully as much copper in the igneous rocks as in those of Keweenaw Point. If it is assumed that the copper deposits have been concentrated entirely by the action of meteoric waters on the basic igneous rocks, it is difficult to account for the absence of deposits throughout much of the Keweenawan and also in certain porous strata within the producing district. The extreme localization of the deposits in time and place seems to be something more characteristic of highly concentrated magmatic solutions than of a universally acting agent like meteoric waters working down from the surface.

But granting that the fresh igneous rocks contain minute quantities of copper, which may have been picked up and concentrated by meteoric solutions later, is not their presence in these wall rocks evidence that during the cooling of these lavas concentrated copper-bearing solutions were present, some of which may have escaped from the parent rock during crystallization? The inherent probability of such an origin of the solutions is increased by consideration of the evidence derived from certain western copper deposits, where a fairly good case has been made out for the direct contribution of copper salts in juvenile solutions, as, for instance, in the Clifton district of Arizona by Lindgren.

None of the evidence above cited for the direct contribution of copper salts in juvenile solutions entirely excludes the hypothesis that meteoric waters, aided by the heat of the lavas, may have accomplished the result by leaching of wall rocks. From the known conditions of extrusion of the lavas and the association of the sediments it is practically certain that meteoric waters were present, that they were hot, and that therefore they were able to accomplish some alterations. To what extent they may have concentrated copper we have no apparent means of knowing. They were probably effective in rearranging the copper to give the present variation in grade with depth. This change in depth is the one fact which seems to be more closely related to the activity of meteoric solutions than to the deposition from juvenile solutions.

On the whole the evidence is taken to point to a probable original concentration of copper by hot solutions largely of juvenile contribution, but more or less mixed, necessarily, with meteoric waters and a later working over of the deposits by waters dominantly of meteoric source. In any case there is a high degree of probability that the associated basic igneous rocks are the source of the copper deposits. The doubt arises only as to the manner of their derivation from these wall rocks—whether they are due to the escape of solutions of a juvenile nature before or during the crystallization of the lavas, or whether on the breaking up of the crystallized rocks by katamorphic alterations the minute portions of copper they contained were concentrated in the deposits.

WERE THE THERMAL SOLUTIONS DERIVED FROM EXTRUSIVE OR FROM INTRUSIVE ROCKS?

The attempt to ascertain the particular igneous rocks from which the copper ores were contributed and the conditions favoring the release of the copper solutions leads first to a scrutiny of the conditions under which the igneous rocks associated with the copper ores cooled. Most of the igneous rocks containing the copper deposits or associated with them are clearly surface flows, with typical surface textures, interbedded with other flows and with sediments. So clear is this origin and so uniform the bedded succession that it has been commonly assumed that most of the igneous rocks associated with the ores are flows, yet some undoubted intrusive rocks are known and some of the bedded traps lack specific evidence of extrusive character and may possibly be sills or laccolithic intrusives, such as are known to be present in other parts of the Keweenawan of the Lake Superior region. Certain irregularities in the strikes, dips, and thickness of the igneous beds may be thus explained.

Was the copper brought in by the extrusive rocks which are interbedded with the sediments, or was it subsequently introduced by intrusives? The evidence available is not conclusive.

There are perhaps fewer parallels elsewhere of the deposition of metallic ores in quantity from surface extrusive rocks than from intrusives, though it has been shown definitely that some ores have been derived from extrusives.

At the base of certain barren conglomerates occur copper-bearing amygdaloidal pebbles that are apparently identical in character with an underlying amygdaloidal flow, from which they seem to have been derived. In such cases mineralization has evidently taken place before the development of the conglomerate, which points to the effusive rock as the source of the copper-bearing solutions, for the conglomerates closely followed the lavas in deposition.

Copper-bearing amygdaloidal traps have been found in Alaska[a] in which a similar line of evidence points to the trap as the direct source of the copper.

SIGNIFICANCE OF SULPHIDES OF COPPER IN THE INTRUSIVES AND LOWER EFFUSIVES.

The intrusive rocks carrying sulphides are possibly the deep-seated equivalents of the lavas which carry metallic copper. Wright so regards the intrusives of Mount Bohemia. The absence or subordination of native copper in the intrusives may be due to the temperature conditions of the rocks when copper deposition took place. If hot cuprous sulphates were delivered from the intrusive rocks, they may have been deposited as sulphide in the highly heated intrusive, and partly as native copper in the equivalent traps, where there was more rapid cooling and where a lower temperature prevailed. (See p. 589.) Another speculation is that the extraordinary differential concentration of native copper in the upper lavas may have been due to a process of magmatic differentiation. The intimate relation of the ores with basic igneous rocks and their general absence from the felsites is further suggestive of this.

CONCLUSION AS TO SOURCE OF COPPER-BEARING SOLUTIONS.

It is concluded, therefore, that the copper-bearing solutions were hot, that they were both juvenile and meteoric, that the copper probably was in part contributed directly in juvenile waters and in part by leaching of wall rocks by the hot solutions, the evidence developed being as yet insufficient to enable quantitative statements as to the relative importance of the two.

It is known that magmas expel on consolidating all constituents which can not assume stable mineral form under the existing chemical and physical conditions. Water, copper, and numerous other substances belong to this class. Such a source for ore-bearing solutions has been repeatedly appealed to in the search for the origin of western copper and other ores. Positive evidence for such contribution is in the nature of the case extremely elusive. As a rule the best that can be done is to present evidence eliminating the hypothesis that meteoric waters are accomplishing the work, and to show that direct igneous contribution is a possible alternative source. For the Lake Superior copper this explanation of source meets the objections which have been cited against the deposition of the copper by meteoric solutions and best explains the transportation of abundant alumina silicates, fluorine, and boron, the remarkable concentration of copper as compared with other constituents, the cycles of mineral deposition, the peculiar alterations of the wall rocks, the facts that the period of ore deposition was largely limited to middle Keweenawan time and that ore deposition at the present time is almost nil, and finally the extreme localization of the copper lodes, a localization which seems to be characteristic of the association of ores of all kinds with igneous rocks. The conclusion that the ore-depositing solutions have been contributed hot by the igneous rocks does not exclude the cooperation of hot and cold meteoric waters, either in the primary deposition of the ore or in further segregation and modification of it.

It is suggested later that the present deep mine waters represent the residuum or brine of these solutions, possibly more or less mixed with pluvial waters. We are unable to follow Lane[b] in his conclusion that the waters represent fossil or connate waters either of the Keweenawan sea or of the arid conditions under which the Keweenawan may have been deposited.

[a] Knopf, Adolph, The copper-bearing amygdaloids of the White River region, Alaska: Econ. Geology, vol. 5, 1910, p. 251.

[b] Lane, A. C., The chemical evolution of the ocean: Jour. Geology, vol. 14, 1906, pp. 221-225.

CHEMISTRY OF DEPOSITION OF COPPER ORES.

The uncertainty of the conditions of deposition of the copper of course requires that any discussion of the chemistry of the deposition of these ores be tentative and that a wide range of processes be taken into consideration. A hypothesis of the chemical processes of copper deposition may be based on the postulates that the hot solutions which deposited the copper derived part of their constituents, notably boron, fluorine, and perhaps copper, directly from the igneous rocks as magmatic emanations; that they may have partly derived the alkalies, alkaline earths, alumina, silica, and perhaps some copper, from the decomposition of the wall rocks, affected by the thermal solutions, and that these solutions probably carried the copper as the chloride and possibly as the sulphate. The sparseness of sulphides in the deposits seems to imply that the primary solutions were either lean in sulphates or else the conditions were unfavorable to the deposition of sulphides. The abundance of chlorides in deep-mine waters of possibly residual origin suggests that the copper was carried as chloride.

The deposition of metallic copper from such solutions has been accomplished experimentally in these ways and perhaps others. First, Fernekes succeeded in precipitating metallic copper from a cupric chloride solution with ferrous chloride at a temperature of 200° to 250° C., in the presence of prehnite and other silicates, which neutralized the hydrochloric acid resulting from the reaction.[a] Second, Stokes obtained metallic copper by the cooling of a hot solution of cuprous and cupric sulphate; by the action of ferrous sulphate on cupric sulphate at 200° C.; and by the action of hornblende and siderite on cupric sulphate at 200° C.[b] Third, Biddle succeeded in throwing down copper from a solution of ferrous and cupric chlorides in the presence of an excess of alkaline carbonate at ordinary temperature.[c] Fourth, Sullivan[d] finds that various silicates—feldspar, biotite, shale, prehnite, augite, amphibole, etc.—will throw out copper from copper sulphate solutions by an act of double decomposition. The bases of the silicates pass into solution in very nearly the same proportion as copper is taken out. The mineral form of the copper deposited in this manner is unknown, but the process may bear some relation to the problem in hand.

Lane[e] suggests that electrochemical action between the copper solutions and the wall rock may have caused the precipitation of copper. Pumpelly[f] regards the intimate association of copper with protoxide silicates, in which the replacement of alumina by ferric oxide is especially favored, as indicative of a close genetic relation between the ferric condition of the iron oxide in the associated silicates and the metallic state of the copper, and believes that the higher oxidation of the iron was effected through the reduction of the oxide of copper at the expense of the oxygen of the latter. Van Hise[g] believes that the reducing agents which precipitated native copper were ferrous solutions derived from the iron-bearing silicates and ferrous compounds in the solid form, magnetite and silicate. This view is in accord with the findings of Sullivan.

The geologic relations of the copper which are especially applicable to the problem are these: First, copper is intimately associated with and preceded by ferrous silicate minerals; second, it was deposited with calcite, it is known to replace quartz, and its deposition was usually followed by the development of alkaline silicates.

A tentative hypothesis of the chemistry of the deposition of the ore may be built on the preceding postulates as follows:

Hot solutions containing copper chlorides, boron, and fluorine compounds, CO_2, and possibly other magmatic emanations entered the porous parts of the formations, where they began

[a] Econ. Geology, vol. 2, 1907, p. 580.
[b] Stokes, H. N., Experiments on the solution, transportation, and deposition of copper, silver, and gold: Econ. Geology, vol. 1, 1906, pp. 644–650.
[c] Biddle, H. C., The deposition of copper by solutions of ferrous salts: Jour. Geology, vol. 9, 1901, pp. 430–436.
[d] Sullivan, E. C., The interaction between minerals and water solutions: Bull. U. S. Geol. Survey No. 312, 1907, p. 64.
[e] Ann. Rept. Michigan Geol. Survey for 1903, 1905, p. 249; Econ. Geology, vol. 4, 1909, p. 170.
[f] Pumpelly, Raphael, The paragenesis and derivation of copper and its associates on Lake Superior: Am. Jour. Sci., 3d ser., vol. 2, 1871, pp. 353–354.
[g] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 1136.

the work of deposition and the solution and replacement of the wall rock. Hot solutions, in general, remove lime and soda with great rapidity. Pressure and CO_2 alone could cause the solution of alumina.[a] In general, there would be a tendency for the decomposition of all minerals in the wall rocks, and a consequent enrichment of the solutions in the constituents taken out of the wall rocks. However, as Lane[b] suggests, the calcium silicate and sodium silicate in the solution would tend to keep magnesium out of solution. These processes would tend to develop chlorite by replacement and to keep magnesia permanently out of solution. In general, chlorite is the most stable mineral form which magnesia assumes in the presence of hot solutions.[c] This first step in the cycle of deposition thus accounted for left the solution rich in lime, iron, and aluminum silicates. Changing conditions, perhaps, of concentration, heat, and pressure brought about the saturation of these constituents, and a generation of laumontite, prehnite, and epidote followed the development of chlorite. Silica became insoluble in this solution after the deposition of the lime-aluminum silicates, which resulted in the precipitation of quartz. The individualization of quartz was followed by the deposition of copper. It is suggested that the solutions were relatively rich in alkalies, probably the carbonates and chloride both, when the period of copper deposition began, for the deposition of copper accompanied the solution of quartz and was followed by the deposition of alkaline silicates. Under these conditions copper-bearing solutions reacting with the ferrous silicates of the wall rock and perhaps with ferrous salts in solution in presence of alkaline carbonates caused the precipitation of copper. It is furthermore suggested that the deposition of calcite, coeval with the deposition of copper, was due to the interaction of alkaline carbonate and calcium chloride, As calcium chloride is a solvent of copper, its precipitation as a carbonate would give additional impetus to the precipitation of copper.

It is quite possible that the progress of the cycle of deposition of the copper outlined on page 585 was accompanied by a gradual loss of heat and pressure and that this loss was greatest where the solutions were nearest the surface. According to Soret's principle[d] when two parts of a solution have different temperatures, there will be a concentration of the dissolved parts in the cooler portion. This concentration tends to bring about deposition of some of the dissolved parts. This is shown also by the work of Stokes[e] on the interaction of cuprous and cupric sulphates. Consequently, deposition of copper may have begun in the upper zones of the solution and gradually extended downward. Diffusion and convection currents would tend to keep the composition of the solutions uniform. However, when the deposition of copper began at the lower horizons the richness of the solutions was diminished. It is possible that such a process caused the gradual diminution of the richness of the ore deposits with increase in depth.

Throughout this process there was a continual concentration of the alkalies in the solutions. After the deposition of copper these alkalies became partly insoluble in the solution under the existing physical and chemical conditions and were thrown out as analcite, orthoclase, fluorine-bearing apophyllite, and other alkaline zeolites. The boron silicate, datolite, was thrown out at the same time. It is also possible that the major precipitation of the datolite and apophyllite took place in the upper zones, as appears to have been the case with copper, for Lane and other observers are inclined to believe that certain alkaline silicates are more abundant in the upper levels of the mines.

This closes the cycle of deposition of the copper and gangue minerals. The general results of the process suggest that the present deep mine waters represent the more or less modified residuum or brine of the solutions that accomplished the deposition of the copper.

[a] Gawalowski, A., Chem. Centralbl., pt. 1, 1906, p. 640.
[b] Lane, A. C., Econ. Geology, vol. 4, 1909, p. 166.
[c] Steidtmann, Edward, A graphic comparison of the alterations of rocks by weathering with their alterations by hot solutions: Econ. Geology, vol. 3, 1908, p. 398.
[d] Soret, Charles, Annales chim. phys., 5th ser., vol. 22, 1881, p. 293.
[e] Stokes, H. N., Econ. Geology, vol. 2, 1907, p. 580.

CAUSE OF DIMINUTION OF RICHNESS WITH INCREASING DEPTH.

There is little in the Lake Superior copper deposits in the nature of the oxide or weathered zone so characteristic of sulphide deposits. Possibly glaciation has removed marked evidences of surficial change. In a few places the upper few hundred feet of the lodes is less rich than the parts below, suggesting a leaching from the upper part of the lode. Below this the ores very gradually and uniformly diminish in richness with increase in depth, a diminution which is caused mainly be slight changes in proportions of minerals rather than by differences in kinds of minerals in the ores.

The relation of the richer portions of the lode to the erosion surface suggests at once a downward concentration by meteoric waters such as has been demonstrated to explain this relation in so many mining districts. But this explanation presents many difficulties. The present underground waters near the surface do not carry copper in abundance, nor can we suggest any probable chemical reaction which would explain the solution of metallic copper. The ore diminishes in value far below the depth of the present meteoric circulation. There is no sharply discriminated oxide zone. The kinds of minerals are essentially the same from the top down, and the changes in proportions and values are much more gradual than the changes ordinarily ascribed to secondary concentration from the surface. The diminution of value with increase in depth has been demonstrated so generally to be the result of concentration from downward-moving meteoric waters that one hesitates to offer any other explanation except on most decisive proof. Such decisive proof is here lacking. But nevertheless another hypothesis seems to us reasonable—that the richness of the ore near the surface was due to a precipitation of copper from primary solutions near the surface, where they were cooled under less pressure and became mingled with oxidizing waters. It would be necessary to assume that convection and diffusion would tend to equalize the concentration of the copper solutions, thus causing some migration of copper salts toward the zone of precipitation and thus diminishing the amounts of salts precipitated from solutions lower down. The oxidation of cuprous salts in solution, effected by the mingling of meteoric waters, would develop cupric salts which in moving down and by reacting with the cupric salts would deposit metallic copper, as noted on page 589.

This hypothesis avoids the difficulty of getting the copper into solution from the metallic form, which would have to be assumed on the hypothesis of a downward concentration by meteoric waters.

In this hypothesis of deposition of richer copper ores by primary solutions near the surface, there is no emphasis on the direction of movement of the solutions. It is conceivable that they may have been upward-moving waters, that at the time of deposition the waters may have been moving little or none at all, or possibly that the waters had begun to take a downward movement as a result of the cooling and contraction of the lavas. Lane [a] has estimated such downward movement as amounting to possibly a mile down the dip in the vicinity of the present erosion surface. So far as the currents were downward moving, there may have been upward artesian flow through fissures in impervious beds overlying pervious beds. Wadsworth [b] cites as evidence of downward-moving waters the occurrence of spikes of copper and calcite which extend from one bed down into others, with the small end downward, like an icicle.

RELATION OF COPPER ORES TO OTHER ORES OF THE KEWEENAWAN.

It is an interesting and significant fact that rocks of probable Keweenawan age are closely associated with a considerable variety of ores on the north and east sides of Lake Superior. On Silver Islet, on the northwest side of the lake, and thence westward on the main shore are igneous dikes of probable Keweenawan age cutting the slates of the Animikie group and carrying native silver and other minerals. (See pp. 593–594.) On the north shore of Lake Huron basic igneous bosses and dikes of probable Keweenawan age are associated with quartz veins carrying chal-

[a] Lane, A. C., Econ. Geology, vol. 4, 1909, p. 164.

[b] Wadsworth, M. E., The origin and mode of occurrence of the Lake Superior copper deposits: Trans. Am. Inst. Min. Eng., vol. 27, 1898, p. 695.

copyrite, which is the source of the copper ores of the Bruce mines and many small prospects in this district. In the Sudbury district, to the northeast, basic igneous rocks of probable Keweenawan age are closely associated with the nickel deposits; and still farther to the northeast basic igneous rocks, probably of Keweenawan age, are associated with cobalt-silver deposits. The main structural lines in all these districts trend north of east and south of west, corresponding to the axial line of the Lake Superior syncline. All these districts have certain ore-bearing minerals in common. The difference is primarily a difference in proportion. For instance, the Lake Superior copper deposits are associated with metallic silver and a minute amount of cobalt and nickel. The silver deposits of Silver Islet carry small amounts of copper, cobalt, and nickel. The Sudbury nickel deposits carry considerable copper and a small amount of cobalt and native silver. In the Cobalt district the native silver and cobalt ores carry considerable amounts of nickel and copper. In the discussion of general geology (Chapter XX) it will be shown that this general region was probably a geosyncline of deposition during pre-Cambrian time, affected by repeated foldings along axes parallel to the shore, and a locus for igneous activity. The distribution and character of the ores through this general zone further suggest the generalization that here is a metallographic province along which igneous rocks have brought up quite different but still related ores, these ores taking a considerable variety of structural, mineralogical, and chemical characteristics, partly because of original differences in the composition of the ore-bearing solutions in these different districts and partly because of the different conditions under which they approached the surface, those in Canada remaining as intrusive beneath the surface and those at Keweenaw Point coming largely to the surface.

Still further, in pre-Keweenawan time this same general region was a shore line of deposition with repeated outbursts of volcanism. The attempt has been made to connect the iron-ore deposits of the Lake Superior region with this volcanism. Thus along this great geosyncline earlier volcanism was associated with extrusion of iron salts and later volcanism with a variety of cobalt and silver, copper, and nickel salts.

CHAPTER XIX. THE SILVER AND GOLD ORES OF THE LAKE SUPERIOR REGION.

SILVER ORES.

PRODUCTION.

Mention has already been made of the mining of silver with the Keweenaw Point copper ores. The total value of silver thus mined from 1887 to the end of 1909 is $1,805,308.50.

In addition to this, veins in the slates of the Animikie group on the northwest side of Lake Superior have yielded silver ores, principally from Silver Islet, as follows:

Silver produced from veins on northwest side of Lake Superior.[a]

Produced by Silver Islet, from commencement to close of mining	$3,250,000
Produced by the mainland group to 1903, including the Shuniah, Rabbit Mountain, and Silver Mountain groups of mines	1,885,681
	5,135,681

SILVER ISLET.

The following account of Silver Islet is largely quoted from Ingall.[b] Silver Islet is a small island of nearly flat-lying Animikie slates about a mile out in Lake Superior off Thunder Cape.

The silver-bearing vein cuts the Animikie slates and a diorite dike, but its principal value is found within the diorite dike. This dike dips from 60° to 75° SE. The dikes in the Animikie of this part of the Lake Superior region are connected with the Logan sills, of Keweenawan age. The vein strikes N. 35° W. and dips 70° to 80° SE.; its thickness averages about 8 to 10 feet, but in some places it has shown from 20 to 30 feet of solid vein stuff. Two bonanzas were found in the vein; the first, yielding over $2,000,000, was shaped like an irregular pear with its large end down; the second bonanza, found considerably later, was shaped like an inverted cone. The gangue of the vein consists of calcite, quartz, and dolomite, the dolomite varying in color from cream to pink according to the varying amounts of manganese it carries. The relative quantity of calcareous and siliceous matter varies, however, in different parts of the vein, and in places streaks of quartz have preponderated to such an extent as to make some of the ore highly siliceous. The metallic minerals are native silver, argentite, galena, blende, copper, and iron pyrites, with marcasite. Macfarlane also mentions tetrahedrite, domeykite, niccolite, and cobalt bloom, the two latter probably oxidation products of a peculiar mineral called macfarlanite, containing arsenic, cobalt, nickel, and silver. Two new minerals are also said to have been found in the ore by Wurtz, called by him huntelite and animikite. The three minerals last named, according to Lowe, "are now [October, 1881] the principal producing silver ores of the mine." Besides the above, Courtis found in the ore shipped to the Wyandotte smelting works rhodochrosite, annabergite, antimonial silver, and cerargyrite, the last "where the rock has been decomposed." The native silver is generally disseminated through the ore in more or less dendritic masses, the points of native silver forming nuclei for the deposit of niccolite and sulphurets. Graphite also occurs in considerable quantity and seems to be connected in some way with the occurrence of the silver. Silver does not occur without graphite, but graphite may be present without silver. Out of the whole series of twenty-one

[a] Eighteenth Ann. Rept. Ontario Bur. Mines, pt. 1, 1909, p. 12.

[b] Ingall, E. D., Report on mines and mining on Lake Superior: Ann. Rept. Geol. and Nat. Hist. Survey of Canada for 1887-88, vol. 3, new ser., pt. 2, 1888, pp. 27H-40H.

dikes cut by the vein the Silver Islet, carrying the ore, is the only one impregnated strongly with graphite and pyrite.

A curious feature of the vein is the combustible gas which has been encountered in large quantities in the workings. This gas is accompanied by water containing calcium chloride in solution. The gas and water are confined principally in large vugs or cavities in the vein, under great pressure in the deepest workings. Above the eighth level all water infiltrating into the mine is pure lake water. An analysis of the water is as follows:

Analysis of water from Silver Islet mine.[a]

Chloride of potassium	0.4582
Chloride of sodium	16.8098
Chloride of calcium	17.0867
Chloride of magnesium	1.2937
Sulphate of lime	.0672
Carbonate of lime	.2936
Silica	.0540

GENERAL ACCOUNT OF SILVER IN THE ANIMIKIE GROUP.

Passing over Ingall's detailed description of mines and prospects, his summary of the occurrence of silver in the Animikie group northwest of Lake Superior is partly as follows:

The veins, as regards their strike directions, resolve themselves into three series—a northwest series, a northeast series, and an east-west series. The northwest direction of strike characterizes the Coast group of mines, of which the famous Silver Islet vein is the most striking example. The vein of the Beaver mine also has this trend.

All the veins of the Rabbit Mountain group of mines, with the exception of the Beaver, may be classed as northeast; the vein in the Thunder Bay mine also belongs to this series.

The veins of the third series do not run in general due east and west, but a little north of east and south of west. To this series belong nearly all the chief veins of the Port Arthur mines, with the exception of the Thunder Bay, just mentioned, and nearly all the Silver Mountain group of mines.

The vein-filling minerals consist in general of quartz, barite, calcite, and fluorite constituting the basis of the gangue, in which occur the different metallic minerals—blende, galena, pyrites of several species, and here and there some sulphurets of copper; the silver in the orey parts occurs as argentite and in the native state, the former being the more common. At some places the veins carry a dark-green, probably chloritic material which on some surfaces has a bright, waxy luster. Locally a soft, greasy talcose material, probably saponite, accompanies the ore, notably at the Beaver mine and to a lesser extent at one or two other places. Carbon in various forms has also been found here and there. In some of the vugs in the veins, which have been found near the surface, stiff clay and ocherous material have sometimes been obtained, along with nuggets of argentite, the former, however, having evidently been washed in from the surface and having thus embedded the silver minerals already existing in the vugs.

The Silver Islet vein was somewhat exceptional in carrying, besides the minerals above noted, various arsenical and antimonial ores of silver, with compounds of nickel and cobalt and other metallic minerals which have, so far, not been found in the rest of the veins. Other salient features of this vein were the pink and cream-colored dolomite spar which formed a characteristic and prominent constituent of much of the gangue of the rich ore and the predominance of native silver in the rich parts, whereas in the rest of the veins, though native silver occurs in considerable quantity at some places, yet argentite seems to be the form in which it is generally found.

It is interesting to note that both the mineral waters and the inflammable gas that were found in opening the Silver Islet mine have also been encountered at other points in the district. Inflammable gas comes up at several points in and around Thunder Bay, causing considerable ebullition in the water and keeping it open all winter. At one of these points has been

[a] Ingall, E. D., op. cit., p. 29H.

placed a small tank connected with an inverted funnel anchored on the bottom, and it affords sufficient gas to keep a good-sized light burning. At the Rabbit Mountain mine, in one of the lower levels, water running over the breast of the drift gave off a faint odor of sulphureted hydrogen and was depositing a white flocculent material, and both here and at the Beaver mine it was reported that small quantities of inflammable gas had been struck.

ORIGIN OF SILVER ORES IN THE ANIMIKIE GROUP.

The origin of the silver ores in the Animikie group has not been studied by the writers. The ores have been regarded by some observers as brought up by thermal waters accompanying the trap intrusions. All the ore bodies found so far occur near or within a moderate distance of trap in some form, either in dikes, as in the Coast group of mines, or in sheets, as in the other groups. Many similarities to the Sudbury and Cobalt ores further suggest this origin. Ingall argues,[a] on the other hand, that as the fissures intersect and dislocate the trap sheets and dikes equally with the other rocks the traps must have been formed and solidified long before the fissures. He suggests that the silver may be derived from the traps through decomposition of some of their mineral constituents carrying minute quantities of silver by waters infiltrating downward through all their joints and pores, and that these waters, passing onward and soaking into the permeable parts and minerals in the gangue of the veins, have there deposited their silver contents, the various forms of carbon present in the sedimentary rocks having had some influence in effecting this precipitation. The presence of the soft talcose and the various chloritic materials in this connection he regards as favorable to this assumption.

GOLD ORES.

Low-grade, free-milling gold-quartz ores have a widespread distribution in the Lake Superior region. The best known of them are the Rainy Lake deposits, the Ropes gold mine in the Marquette district of Michigan, and many gold prospects on the northeast shore of Lake Superior, including the Grace mine near Michipicoten. The gold-bearing quartz veins of Ontario are principally in the Laurentian and to a less extent in the Keewatin series. Coleman[b] classifies them as follows (his "Huronian" includes Keewatin):

1. True fissure veins.
    a. In granite and gneiss.
    b. In Huronian massive or schistose rocks.
2. Bedded, lenticular, or segregated veins.
    a. In gneissoid rocks.
    b. In Huronian schists.
3. Contact deposits between granite or gneiss and Huronian rocks.
4. Fahlbands in Huronian schists.
5. Dikes of porphyry or felsite with associated quartz, mainly in Huronian rocks.
6. Eruptive masses.
7. Placer deposits of Pleistocene age.

The Rainy Lake and Michipicoten gold ores are mainly in rocks of the Laurentian series. Though containing rich shoots, the ores are as a whole of low grade, yielding less than $12 a ton, and their mass is not large enough for profitable mining of ores of this grade. A large number of mines and plants have been equipped at much expense for the mining and extraction of these ores, but thus far none have apparently been put on a reasonably profitable basis. Mining began in 1891 and reached its maximum in 1899, since which it has waned and is now almost abandoned.

Gold mining on the northeast side of Lake Superior is yet in the exploratory state, no considerable shipments having been made.

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[a] Op. cit., p. 113H.
[b] Coleman, A. P., Third report on the west Ontario gold region: Sixth Rept. Ontario Bur. Mines, for 1896, 1897, p. 115.

The total production of gold in Ontario since 1891 has been $2,281,292.[a]

Like the gold ores of the north shore of Lake Superior, the ores at the Ropes mine consist of metallic gold in quartz veins in peridotite in the Laurentian rocks. Their grade is low and it is doubtful whether there has been a profit on the ore taken out. Mining was conducted intermittently at the Ropes mine from 1882 to 1897. During this period of activity the mine produced gold (with some silver) to the value of about $650,000. Since that time some gold has been taken out of the tailings.

A small amount of gold has been taken out of similar quartz veins in the peridotites at the Michigan mine, about 3 miles west of the Ropes.

[a] Report on the mining and metallurgical industries of Canada, 1907-8, Dept. of Mines, 1908, p. 307.

CHAPTER XX. GENERAL GEOLOGY.

INTRODUCTION.

In the early chapters of this volume the general geography and physiography of the Lake Superior region have been treated, and a history of the development of knowledge concerning the region, as well as the views of various authors, has been given. In the chapters on the individual districts have been considered the geologic succession, topography, deformation, and the lithology, metamorphism, relations, and thickness of each of the formations. Also the formations have been classified by groups and series, and the relations of these groups and series have been discussed. Finally, a résumé of the geologic history of each district has been given. In short, each chapter treating of a district is substantially independent, giving briefly a complete discussion of the geology.

It therefore remains for this closing chapter to consider the broader features of the Lake Superior geology, and especially the comparative features. The fundamental thought of this chapter will be the comparison of the different districts with one another from several points of view. This comparison will be essentially confined to the principal ore-producing districts which have been studied in detail by the United States Geological Survey. Several outlying areas, including north-central Wisconsin and the Baraboo and Minnesota River districts, are so isolated that attempts at correlation are largely speculative in the present state of knowledge. These districts, therefore, will be referred to only incidentally in the following discussion, and the reader is referred to Chapters IX and XIV for the available information concerning them.

In Bulletin 360 of the United States Geological Survey the reasons are fully given which lead to the major division of the pre-Cambrian rocks into Archean and Algonkian. The discussion leading to this conclusion will not be here repeated. Those who are interested in it may refer to that volume.[a] The general succession of series of the Lake Superior region proposed by the United States geologists has been agreed to by an international committee of geologists. (See p. 84.) This succession has been established in the Lake Superior region since 1904. It has now been found to apply to parts of Canada, and has been recently applied by Adams[b] to the entire Canadian shield. But Canadian geologists have not grouped the series into the major systems of Archean and Algonkian, as has been done for the Lake Superior region.

It remains to distribute the formations that occur in each of the districts of the Lake Superior region between the broader divisions of Archean and Algonkian, and to correlate the series and, so far as possible, the formations which occur in one district with those found in another. Our classification and correlation of the Lake Superior pre-Cambrian rocks are given in the accompanying table.

PRINCIPLES OF CORRELATION.

The lowest rocks found in the region are those of the Archean system or basement complex, consisting of the Keewatin and Laurentian series, with their characteristic features and relations. This system gives us a horizon from which to work upward. At the top of the pre-Cambrian is the Keweenawan series, which occurs mainly in a great continuous area, and which gives us a horizon from which to work downward. Between the Archean and the Keweenawan

[a] Van Hise, C. R., and Leith, C. K., The pre-Cambrian geology of North America: Bull. U. S. Geol. Survey No. 360, 1909, pp. 19–25.
[b] Adams, F. D., Jour. Geology, vol. 17, 1909, pp. 1–18.

is the Huronian series. The Keweenawan and Huronian series together make up the Algonkian system. In certain districts the Huronian is separable into three divisions, marked by unconformities; in other districts it is separable into two divisions, and in still other districts it is not yet divisible. The most serious questions therefore arise in the correlation of the Huronian formations of the several districts.

In correlating the Huronian rocks the following principles are used:

1. Relations to series or groups of known age; that is, to recognized horizons. In using this criterion the relations of the Huronian to the Archean and to the Keweenawan are especially helpful, for these rocks are readily recognizable and afford datum planes from which to work up and down. The upper Huronian (Animikie group) adjacent to Lake Superior, being continuous through so much of this region, is also very helpful as a recognizable datum plane.

2. Unconformities. The unconformities between the divisions of the Huronian are of great assistance in correlation. Where all of the Huronian is present, separated by two unconformities, there is naturally no difficulty in separating it into lower, middle, and upper. Where, however, the Huronian has only one unconformity or where in a disconnected district only one division of the Huronian is present, the unconformities fail to be a determining factor.

3. Lithologic likeness of the formations. This criterion is of assistance, but it clearly has severe limitations, because again and again the geologic conditions have been the same, producing like formations at different times. This is illustrated by the remarkable similarity of the iron-bearing formations of the upper Huronian, middle Huronian, and Archean. The natural belief that they were of the same age long acted as a bar to progress.

4. Like sequence of formations. Similar sets of formations in the same order are of much greater importance as a criterion for correlation than the likeness of single formations. But conditions producing similar sets of formations have frequently recurred during geologic time. For instance, when a sea transgresses over a land area, there are normally formed in order a psephite, a psammite, a pelite, and a nonclastic formation.

5. Subaerial or subaqueous origin. Closely connected with the third and fourth criteria is the question whether the deposits were formed under air or under water. It is clear that the conditions of the formation of these two classes of deposits are so different, and therefore the nature of the formations which may be contemporaneous so variable, that there is difficulty in correlating the two. Also it is plain that the difficulties in correlating disconnected continental deposits are scarcely less great. On the other hand, the correlating of subaqueous deposits with one another is relatively easy.

6. Relations with intrusive rocks. The older the series the more intricately it is likely to be cut by intrusive rocks, and this relation is of assistance in connection with the other criteria. However, as there have been igneous intrusives, both acidic and basic, in great quantities up to middle Keweenawan time, this criterion has relatively small utility in the correlation of the Lake Superior Huronian.

7. Deformation. The amount and nature of deformation are of assistance in correlation. On the whole the older the series the greater and more intricate the deformation. Thus in this respect the Archean rocks exceed all later series. The Keweenawan is much less deformed than the other pre-Cambrian series. But the differences in deformation of the Huronian divisions may not be so marked in a single district as to give important assistance in the discrimination of these divisions from one another. Also a particular division of the Huronian may be much deformed in one district and not in another.

8. Degree of metamorphism. The degree of metamorphism is of some assistance in correlation. On the whole the older rocks are more metamorphosed than the younger rocks, but this criterion has limitations, since within comparatively short distances the closeness of folding and the quantity of igneous intrusions may greatly vary, and these are very important factors in producing metamorphism.

The criterion relied on more than all others in the correlation of the Cambrian and post-Cambrian formations—that of fossils, showing similarity of the life on the earth at the time the equated formations were laid down—is not available for the pre-Cambrian rocks of the

Correlation of pre-Cambrian rocks of the Lake Superior region

System.	Series and group.	Marquette district.	Crystal Falls district.	Sturgeon district	Felch Mountain district	Calumet district	Menominee district.	Florence district.
Algonkian — Keweenawan series	Upper							
Algonkian — Keweenawan series	Middle.	Not identified, but probably represented by part of intrusives in upper Huronian.	Not identified	Doubtfully present	Doubtfully present	Absent	Granite (?).	Granite and gneiss (Keweenawan?) (?).
Algonkian — Keweenawan series	Lower.							
					Unconformity			
Algonkian — Huronian series	Upper Huronian (Animikie group).	Greenstone intrusives and extrusives Michigamme slate. To the south partly replaced by the volcanic upper-middle Huronian Clarksburg formation. Bijiki schist (iron bearing) Goodrich quartzite	Greenstone intrusives and extrusives Michigamme slate, with its Vulcan iron-bearing member		Vulcan formation (iron bearing) Felch schist.	Michigamme slate Vulcan formation (iron bearing) Felch schist	Quinnesec and other schists, greenstone intrusives and extrusives. Michigamme ("Hanbury") slate Vulcan formation, subdivided into the Curry iron-bearing member, Brier slate member and Traders iron-bearing member	Quinnesec schist, greenstone intrusives and extrusives. Michigamme slate, including quartzites of doubtful age, and Vulcan iron-bearing member.
		Unconformity	Unconformity ?				Unconformity	
Algonkian — Huronian series	Middle Huronian	Negaunee formation (chief productive iron-bearing formation) Siamo slate Ajibik quartzite	Negaunee (?) formation (iron bearing) Ajibik quartzite Hemlock formation (volcanic), with iron-bearing slate member near top	Iron-bearing beds (Negaunee?)	Absent	Absent	Quartzite, in most of district not separated from upper part of Randville dolomite.	Not identified
		Unconformity	Unconformity ?	Unconformity ?	Unconformity ?	Unconformity ?	Unconformity	
Algonkian — Huronian series	Lower Huronian	Wewe slate Kona dolomite Mesnard quartzite	Randville dolomite Sturgeon quartzite	Randville dolomite Sturgeon quartzite	Randville dolomite Sturgeon quartzite	Randville dolomite. Sturgeon quartzite	Randville dolomite Sturgeon quartzite	Not identified
		Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	Unconformity	
Archean	Laurentian series (intrusive into Keewatin)	Granite, syenite, peridotite Palmer gneiss	Granites and gneisses	Granites and gneisses	Granites and gneisses	Granites and gneisses	Granites and gneisses cut by granite and diabase dikes	
Archean	Keewatin series	Kitchi schist and Mona schist, the latter banded and in a few places containing narrow bands of nonproductive iron-bearing formation					Green schists	

Series and group.	Iron River district	Penokee-Gogebic district.	North-central Wisconsin (after Weidman)	Barron, Rusk, and Sawyer counties, Wis.	Lakewood, Wis., and vicinity	Necedah, North Bluff, and Black River areas.	Baraboo district	Waterloo area, Wisconsin
Keweenawan Upper		Absent.		Absent				
Keweenawan Middle.		Gabbros, diabases, etc.		Absent				
Keweenawan Lower.		Conglomerates.						
		Unconformity						
Upper Huronian (Animikie group).	Greenstone intrusives and extrusives Michigamme slate, including Vulcan iron-bearing member	Greenstone intrusives and extrusives Tyler slate Ironwood formation (iron bearing) Palms formation.	North Mound conglomerate and quartzite. Arpin conglomerate and quartzite Mosinee conglomerate. Marshall Hill conglomerate Marathon conglomerate				Quartzite (upper Huronian?)	
			Unconformity				Unconformity	
Middle Huronian	Not identified	Absent.	Igneous Granite and nepheline syenite series Gabbro-diorite series Rhyolite series Intrusive relations Sedimentary Rib Hill quartzite Powers Bluff quartzite Hamburg slate Wausau graywacke.	Huronian quartzites. Possibly including Keweenawan quartzites. Huronian possibly subdivided into two groups	Huronian quartzites	Huronian quartzites and iron-bearing beds.	Granite, intrusive into lower formations. Freedom dolomite, mainly dolomite, including iron-bearing member in its lower horizon Seeley slate Baraboo quartzite	Waterloo quartzite, possibly middle Huronian
	Unconformity ?	Unconformity	Unconformity					
Lower Huronian	Saunders formation (interbedded dolomite and quartzite, believed to be the equivalent of the Randville dolomite and Sturgeon quartzite)	Bad River limestone (cherty limestone) Sunday quartzite					Absent	
	Unconformity ?	Unconformity	Unconformity				Unconformity	
Laurentian series (intrusive into Keewatin)		Granite and granitoid gneiss		Granite and gneiss			Granite, rhyolite, tuff, etc. (Laurentian?)	
Keewatin series	Greenstone, green schists, and tuffs	Greenstones and green schists	Gneiss and schists					

Series and group.	Fox River valley	Mesabi district	Gunflint Lake district	Pigeon Point.	Animikie or Loon Lake district	Cuyuna district	Vermilion district	Lake of the Woods and Rainy Lake district.	Michipicoten district	North shore of Lake Huron
Keweenawan Upper		Absent.	Absent	Absent.	Absent.	Absent	Absent.			
Keweenawan Middle.		Embarrass granite (intrusive) Diabase Duluth gabbro.	Conglomerate, sandstone, marl, diabase sills (Logan sills), and gabbro (Duluth).	Gabbro and "red rock"	Conglomerate, sandstone, marl, and diabase sills (Logan sills).	Basic and acidic intrusive and extrusive rocks (Keweenawan?).	Duluth gabbro and diabase sills (Logan sills)			
Keweenawan Lower.										
		Unconformity	Unconformity		Unconformity		Unconformity			
Upper Huronian (Animikie group).		Acidic and basic intrusive rocks. Virginia slate Biwabik formation (iron bearing and productive). Pokegama quartzite	Rove slate Gunflint formation (iron bearing)	Interbedded quartzites and slates	Black slate Iron-bearing formation	Virginia ("St. Louis") slate, including Deerwood iron bearing member	Rove slate Gunflint formation (iron bearing but nonproductive)	Absent.	Absent	Sediments near Sudbury
		Unconformity	Unconformity		Unconformity		Unconformity			
Middle Huronian		Giants Range granite, intrusive into rocks below Sediments (slate, graywacke and conglomerate), which are the equivalent of the Knife Lake slate and Ogishke conglomerate of the Vermilion district.	Greenstone and granite intrusive Graywacke		Granite and greenstone, intrusive into rocks below Slate, graywacke, and conglomerate		Granites, granite porphyries, dolerites, lamprophyres, intrusive into rocks below Knife Lake slate Agawa formation (iron bearing, but nonproductive) Ogishke conglomerate	Sediments, mainly slates and mica schists, with intrusive and extrusive rocks. (Previously mapped in part as "Coutchiching" series.)	Lower-middle Huronian ("Upper Huronian" of Coleman and Willmott) Granite and greenstone, intrusive into rocks below Doré conglomerate	Sediments, with intrusive and extrusive rocks
Lower Huronian										Sediments
		Unconformity	Unconformity		Unconformity		Unconformity	Unconformity	Unconformity	Unconformity
Laurentian series (intrusive into Keewatin)	Acidic volcanic rocks, probably Laurentian	Granites and porphyries	Granites and gneisses, intrusive into Keewatin		Granites and gneisses intrusive into Keewatin		Granites and other intrusive rocks	Granites and gneisses.	Granites and gneisses	Granites and gneisses intrusive into Keewatin
Keewatin series		Greenstones, hornblende schists, and porphyries	Green schists, greenstones and mashed porphyries		Green schists, greenstones and mashed porphyries		Soudan formation (iron bearing and productive) Ely greenstone and ellipsoidally parted basic lenses and largely volcanic rock	Green schists and tuffs, with some slate and iron-bearing rocks. (Previously mapped in small part as "Coutchiching".)	("Lower Huronian" of Coleman and Willmott) Eleanor slate Helen formation (iron bearing and productive) Wawa tuff Gros Cap greenstone	Thessalon group greenstones and green schists mapped by Logan and Murray as Huronian slate")

Lake Superior region. Recognizable fossils have not yet been discovered in these rocks, although the carbonaceous slates which extend back to the Archean seem to show that life existed at the time of the earliest pre-Cambrian series.

The correlation of the pre-Cambrian rocks is not as definite as that for fossiliferous rocks—a fact which makes it desirable to retain local names to an extent not warranted were fossil evidence available. The use of local names is desirable in this region also for the reason that the districts in which they are applied are separated by considerable areas that are much less known. The geologist or mining engineer is seldom interested in the general correlation of formations and finds it convenient to have local terms which have areal as well as stratigraphic significance. Local terms have been used in the six preceding reports on this region by the United States Geological Survey, have become permanently entrenched in the literature, and are known and understood by the local mining men. To discard these terms in favor of more general terms would, it is believed, introduce confusion and perhaps vagueness. At some future time, when explorations shall have made the areal connection so definite that there can be no question about correlation, a sweeping change in names might be introduced to advantage. At present, with so many unsolved problems and with possibilities for changes in views of correlation, there can be little advantage in substituting general names, even for formations whose correlation is regarded as reasonably well established.

GENERAL CHARACTER AND CORRELATION OF THE ARCHEAN.

The Archean system comprises the Keewatin series and the Laurentian series.

KEEWATIN SERIES.

The Keewatin series, wherever it is found in a relatively unchanged condition, is remarkably uniform in its general character, and even the portions that have been metamorphosed show features that are consistent with the theory that before metamorphism they had the same general character as the less altered portions. The Keewatin comprises two great formations, a dominant igneous formation and a subordinate sedimentary formation. It is found in its most typical facies in a comparatively unaltered condition in the Vermilion and Lake of the Woods districts. The characterization of the Ely greenstone for the Vermilion district, given on pages 119–122, might be applied to each of the other districts without important changes. The Keewatin is a great volcanic series, composed dominantly of basalts and intermediate rocks. For all of these regions where the rock is lava and is least metamorphosed, a peculiar ellipsoidal or pillow structure is characteristic. It has been pointed out (see pp. 510–512) that this structure and the relations of the Keewatin to the iron-bearing rocks are evidences that the eruptions were at least in part subaqueous. Associated with the lavas are vast quantities of volcanic fragmental rocks. In some districts—for instance, the Marquette and the Menominee—the tuffaceous variety of greenstone appears, but the ellipsoidal structure is not common. However, in these districts the Keewatin is much metamorphosed by dynamic action and by later intrusions, so that the ellipsoidal structure would have been largely destroyed even if it once existed, as it has been where the Keewatin rocks lie close to similar large intrusive masses on the north shore. Barring the changes due to metamorphism, there is a very remarkable likeness of the dominating igneous portion of the Keewatin in the different parts of the Lake Superior region.

Associated with the igneous rocks of the Keewatin are subordinate masses of sediments. These sediments comprise slates, iron-bearing formation, and dolomite. The slates that have been metamorphosed are so similar to the schistose phases of the greenstone itself that they are in places difficult to recognize. They have been found in almost every district. The iron-bearing formation is the prominent sedimentary one in the Vermilion, Atikokan, Kaministikwia, and Michipicoten districts. It occurs very subordinately in the Marquette district. In the Lake of the Woods district the iron-bearing formation has not been found, but small masses of dolomite occur. In all the districts the iron-bearing formation and the dolomite are associated with the slates. It is believed that in areas where these sedimentary formations are of considerable extent and thickness they represent later Keewatin time. The chief reason for this belief appears in the Vermilion district, where the iron-bearing formation is thick and large masses of it occur adjacent to the Huronian, in both the Lake Vermilion and the Ely areas, showing that the main mass of this formation was at the top of the series at the beginning of Huronian sedimentation.

The Keewatin is the oldest series in the Lake Superior region. It is dominantly volcanic. Moreover, the lavas were poured out mainly below the water. Thus for the earliest time of which we have record in this region the surface conditions were those of submarine, regional volcanism. Sedimentation was local and subordinate, and the sediments of the Keewatin are believed to have a close genetic connection with the associated volcanic rocks. (See pp. 126–127.)

The Keewatin locally is schistose and the original textures and structures are discernible with difficulty. Where not schistose the Keewatin may be separated into distinct lava flows and beds of pyroclastic rocks, with interleaved sedimentary beds for which strike and dip are determined. The folding is usually close and the beds stand at steep attitudes. Topographically the Keewatin, though rough in detail, has on the whole less bold relief than the Algonkian sediments. The schistose phases are in general less resistant to weathering and stand lower than the massive phases. The Keewatin occupies a part of the great Archean peneplain.

LAURENTIAN SERIES.

The Laurentian series is dominantly represented by great masses of granite, granitoid gneiss, and syenite—all acidic rocks. Intermediate and basic rocks are subordinate. The Laurentian intrudes the Keewatin series, the intrusive masses ranging from great batholiths many miles in diameter to dikes and minute injections, even to "lit par lit" intrusions. The great batholiths are perhaps best illustrated and have been most accurately described for the region north of Lake Superior, particularly near Lake of the Woods and Rainy Lake, by Lawson.[a] These intrusive rocks, in connection with the concurrent dynamic action, have produced profound metamorphic effects in the older Keewatin rocks, which in consequence have been changed over extensive areas to hornblende schist and hornblende gneiss. In many considerable areas the Keewatin and Laurentian are so intimately mixed that it would be difficult to give an estimate of the relative proportions of the two. In some places there is evidence that the Keewatin has actually been absorbed to some extent and thus modified the composition of the Laurentian intrusives. This, combined with the intricate relations along the contacts of the two formations, gives locally an appearance of gradation from the massive Laurentian granite through the gneiss containing various mixtures of intrusive and intruded rocks to the extremely metamorphosed variety. These facts have led Lawson[b] to his theory of subcrustal fusion, according to which all the acidic material is but the fused Keewatin. From our point of view, however, the evidence for such a conclusion is inadequate, the most fundamental point against its correctness being the very great difference in chemical composition of the Laurentian and Keewatin. Where not influenced by each other, the Laurentian has the chemical composition of ordinary acidic igneous rocks, whereas the Keewatin has the average composition of a basic rock of the basalt type. If, as Daly[c] suggests, the Laurentian is supposed to have invaded the Keewatin by a process of overhead stoping and the stope blocks have sunk, the contrast in composition near contacts is explained. In the nature of the case, evidence for this kind of subcrustal fusion is difficult to obtain, and so far as the Lake Superior region is concerned this hypothesis may be noted merely as an interesting guess.

[a] Lawson, A. C., Report on the geology of the Lake of the Woods region, with special reference to the Keewatin (Huronian) belt of the Archean rocks; Ann. Rept. Geol. and Nat. Hist. Survey Canada for 1885, new ser., vol. 1, 1886, pp. 5–151 cc, with geologic map; Report on the geology of the Rainy Lake region; Idem for 1887–88, new ser., vol. 3, pt. 1, 1888, pp. 1–182 F, with 2 maps.

[b] Op. cit., 1888, p. 131 F.

[c] Daly, R. A., The mechanics of igneous intrusion: Am. Jour. Sci., 4th ser., vol. 26, 1908, p. 30.

The Laurentian of the Lake Superior region as a whole is characterized by both massive and schistose phases. It is perhaps surprising that so large a proportion should be massive. It is topographically rough in detail, the massive parts usually standing somewhat higher than the schistose parts, but altogether it forms a part of the Archean peneplain.

GENERAL STATEMENTS CONCERNING THE ARCHEAN SYSTEM.

Both Laurentian and Keewatin rocks appear in each of the important districts that have been considered in the detailed chapters. Manifestly the wide and irregular distribution of the Archean is a natural consequence of the fact that these rocks constitute the basement complex upon which later formations were laid down. Whether or not they are now at the surface at any particular locality depends on subsequent deposition, folding, and denudation—that is, it depends on whether geologic agencies have brought them to the surface.

If, in the future, erosion should cut the Lake Superior region to a depth of several thousand feet below the present surface, it would probably be seen that much the larger part of the area would be occupied by the Archean, and it is believed that the Archean everywhere underlies all later rocks.

It appears from the foregoing characterization of the Keewatin and Laurentian that the Archean as a whole was a period of regional igneous activity. All succeeding series contain sedimentary rocks in large or dominant proportions; they are treated essentially as sedimentary series and the igneous rocks are considered with reference to the sediments. In the Archean, on the other hand, the igneous rocks, which make up more than 90 per cent and probably more than 95 per cent of the area, are primarily considered, and the subordinate masses of sedimentary rocks are discussed in reference to the igneous rocks.

The igneous activity of Archean time was both plutonic and volcanic on a tremendous scale. Probably at present the plutonic igneous rocks of the Archean occupy a much larger area at the surface than the volcanic rocks, but this is doubtless due in large measure to the very profound erosion which has taken place since Archean time, and which has in considerable measure removed the volcanic rocks and exposed the plutonic rocks.

A very characteristic feature of the Archean of the Lake Superior region is its likeness from one district to another, and this is so whether the lithologic types of rocks or their relations are considered. The foregoing description of the intrusive relations between the Laurentian and Keewatin is applicable with scarcely a change to each of the several districts. If a set of specimens from the Laurentian or Keewatin south of Lake Superior were unlabeled, they could not be discriminated from a set of specimens from the Archean northwest or east of the lake. There are, of course, some exceptional types of rocks which occur only locally, but these are extremely subordinate in their mass. This extraordinary parallelism of phenomena of the Archean of one part of the Lake Superior region with that of another part—and, for that matter, with the Archean of other parts of the world—has led to the phrase that the Archean is "homogeneous in its heterogeneity"—that is, while it is heterogeneous for any one district, it shows the same kind of heterogeneity in each of the other districts.

Topographically also the Archean is a unit. Though rough in detail it is a great peneplain, the irregularities of which do not constitute regular lineaments, and it is thus in contrast to the Algonkian rocks, part of which usually stand above the peneplain surfaces with conspicuous linear features.

Whether or not it is generally accepted that the Archean, as the term is here used, can be safely correlated with similar rocks of other geologic provinces, it can hardly be doubted that the Archean rocks of the different districts of the Lake Superior region form parts of a single great system. This conclusion is supported by substantially all the criteria in reference to correlation given on pages 597–599. The system wherever it occurs is in a basal position. It rests unconformably below all the series with which it comes into contact. The general lithologic likeness of the heterogeneous mass is remarkable. The Keewatin rocks are largely submarine. The complexity of intrusives is greater than that in any other series. The deformation is greater than in other pre-Cambrian series. The metamorphism is profound. Similarity of sequence of formations in different areas of the Keewatin is lacking, but in place of this are the prevalent intrusive relations which exist between the Keewatin and Laurentian.

It is of interest to note that the oldest recognized Archean rocks are basalts, with textures indicating both subaqueous and subaerial extrusion. The basement upon which they rest has not been identified. It is natural to turn to the Laurentian granites and gneisses, but wherever these are found in contact with the Keewatin they are intrusive into it. Whether some parts of the Laurentian represent the original basement or whether the Laurentian as a whole has formed the basement and has been subsequently fused, there is no evidence to show.

GENERAL STATEMENTS CONCERNING THE ALGONKIAN SYSTEM.

CHARACTER AND SUBDIVISIONS.

The Algonkian system on the whole contrasts with the Archean in being dominantly sedimentary rather than dominantly igneous, in being less metamorphosed, in having distinctly recognizable stratigraphic sequence, and in topography. The sediments are largely water assorted and deposited but in part are probably subaerial. The iron-bearing formations are regarded as having an exceptional character, being derived partly from submarine volcanic rocks either in magmatic solutions or by the reaction of hot volcanic material with sea water, or both. (See p. 516.)

The Algonkian system comprises in its fullest development in the Lake Superior region four unconformable divisions—lower Huronian, middle Huronian, upper Huronian, and Keweenawan. The Keweenawan series is essentially a unit geographically and lithologically and is considered as such in the following discussion. The Huronian series, especially the lower and middle Huronian, presents such variation in lithology and succession as to require its consideration under two main geographic subprovinces—(1) the northern subprovince, including the north shore of Lake Superior and westward extension into Minnesota, and (2) the southern subprovince, including the Gogebic and Marquette districts of the south shore of Lake Superior and the continuation of this belt eastward to the north shore of Lake Huron, and the Menominee, Crystal Falls, and Iron River districts of Michigan.

NORTHERN HURONIAN SUBPROVINCE.

LOWER-MIDDLE HURONIAN.

LITHOLOGY AND SUCCESSION.

The Huronian rocks unconformably above the Archean and unconformably below the upper Huronian (Animikie group) of the north shore of Lake Superior are extensive and thick. The unconformities above and below are great. At many places the comparatively flat-lying Animikie group may be seen resting upon the steeply inclined or vertical truncated edges of the middle or lower Huronian. The latter rocks consist mainly of conglomerates, graywackes, slates, and mica schists. In some places it is possible to divide them into two formations, the lower consisting dominantly of conglomerates and the upper dominantly of graywackes and slates and their metamorphosed equivalents.

The most characteristic and widespread of these rocks are the conglomerates of the lower formation. Those which lie near the subjacent rocks from which they are derived are commonly coarse bowlder conglomerates. Their fragments vary in lithology, depending on the underlying formation. They may be dominantly from granite, from greenstone, or from gneiss, or mixtures of these three in various proportions and also with other materials. Many of the conglomerates at higher horizons have a fine-grained matrix. Some of them have a slate matrix through which very numerous isolated pebbles and bowlders are scattered in an irregular manner. These have been called slate conglomerates. In certain localities the slate conglomerates are the only rocks found. Associated with the slate conglomerates in many places are beds of well-laminated slate and schist.

As has been intimated, the upper formation consists commonly of pelites. The most extensive areas of pelite are those of the Vermilion, Rainy Lake, and Hunters Island districts.

At the west end of the Vermilion district, between the conglomerate (there called the Ogishke conglomerate) and the slate (known as the Knife Lake slate) is a thin iron-bearing formation (called the Agawa formation) which appears to grade toward the southwest into a calcareous slate. The latter is the only known representative of a limestone in the lower or middle Huronian of the northern subprovince. At this particular locality the succession is in certain respects similar to that of the middle Huronian of the Marquette district, but by far the greater areas and masses of these rocks in the northern subprovince exhibit no close analogy in succession or lithology with either the lower Huronian or the middle Huronian of the south shore.

IGNEOUS ROCKS.

During the time of the deposition of the rocks under discussion there were very great outbreaks of igneous rocks, basic and acidic, plutonic and volcanic. Contemporaneous volcanic detritus is mingled in varying proportions with ordinary sedimentary material, from a subordinate to a dominant amount, as at Kekekabic Lake. The contributions of volcanic material were so great as to make them quantitatively very important. Some of the larger of the plutonic masses are the intrusive granites in the Mesabi and Vermilion districts. The slates that have been intruded by great masses of granites and have been deformed have become pelite schists (mica schists). This phase is extensively illustrated in the Rainy Lake and Namakan Lake areas. The conglomerates under similar circumstances are metamorphosed to psephite schists or gneisses, as illustrated by the schistose conglomerates adjacent to the Snowbank granite in the Vermilion district.

CONDITIONS OF DEPOSITION.

Coleman[a] holds that the lower Huronian slate conglomerate at one locality in the Cobalt district of Ontario is a glacial till. He points out the likeness of the great masses of the slate conglomerate to modern glacial till and to the Dwyka glacial deposits of South Africa, and concludes that they are all till. However, even if the glacial origin of the conglomerate-bearing striated and grooved bowlders at Cobalt is accepted—geologists are not all agreed as to this—it does not follow that the Huronian conglomerate of the northern subprovince as a whole is of this origin, because, among other reasons, the Cobalt area is a long way east of the Lake Superior region.

Whether or not Coleman's conclusion as to origin applies to the lower-middle Huronian in this subprovince, it is regarded as likely that these rocks are essentially of terrestrial deposition because of their unassorted character, being made up principally of conglomerate and graywacke, lacking quartzite and limestone; because of the recurrence of conglomerates at many horizons through several hundred feet; because the extensive conglomerate beds, like the Ogishke, have a thickness and extent which are more easily explained by terrestrial than by subaqueous sedimentation, which, according to Barrell,[b] is not likely to produce conglomerates over 100 feet thick; and finally because the part of the lower-middle Huronian nearest the granite or greenstone of the Archean is locally a recomposed rock, which has not been sorted

CORRELATION.

The criteria under which the formations under discussion are classed as middle or lower Huronian are the following: They rest upon the Archean and are below the Animikie group, or upper Huronian; they are separated from these rocks by unconformities; they are extensively cut by both basic and acidic igneous rocks; they are similar in their deformation and

[a] Coleman, A. P., The lower Huronian ice age: Jour. Geology, vol. 16, 1908, p. 154.

[b] Barrell, Joseph, Relative geological importance of continental, littoral, and marine sedimentation: Jour. Geology, vol. 14, 1906, pp. 433-446; also personal communication.

degree of metamorphism. It thus appears that the assignment of the rocks under discussion to the general place of lower Huronian and middle Huronian is unquestioned. But as large portions of these rocks may be land formations, they can not be exactly correlated with the aqueous deposits of the middle and lower Huronian to the south. The deposition of land sediments may well have begun earlier than that of the aqueous deposits or it may have continued later. On earlier maps published by the United States Geological Survey the rocks here named lower-middle Huronian appear as lower Huronian. As earlier continental deposits are likely to be removed by later erosion, however, it is probable that part, probably the larger part, of these rocks are of middle-Huronian age. It has already been noted that in northeastern Minnesota there is a similarity in succession to the middle Huronian of the Marquette district.

UPPER HURONIAN (ANIMIKIE GROUP).

LITHOLOGY AND SUCCESSION.

The upper Huronian of the northern subprovince extends from a point some distance east of Nipigon Bay, on the north shore of Lake Superior, westward through Thunder Bay to the Mesabi district of Minnesota, thence southwest and south to the Cuyuna, Little Falls, Carlton, Cloquet, and St. Louis River districts of Minnesota. The belt extending from Nipigon Bay to the Mesabi district consists from the base up of the following rocks:

1. Conglomerate, quartz slate, and quartzite. These reach a thickness of 200 feet on the Mesabi range. Farther east, in the vicinity of Gunflint Lake and Thunder Bay, the thickness becomes only a few inches or a few feet.
2. Iron-bearing formation, 700 to 1,000 feet thick in the Mesabi district and thinning somewhat toward the east and west.
3. Slate, best exposed in the Thunder Bay district. Thickness unknown, but large.

Throughout the northern part of this belt the sediments are gently inclined to the south at angles ranging from 5° to 20° and locally even up to 45°, with pitches of gentle minor folds in the same direction. In general the upper Huronian is not schistose but has suffered contact metamorphism where it is in contact with the Keweenawan gabbro and granite and other large intrusive masses. It rests unconformably against the older rocks to the north, the unconformity being marked by areal relations, differences in steepness of dip, amount of schistosity, kinds of metamorphism, relations to intrusive rocks, basal conglomerates, and topography. The unconformity is one of the most conspicuous in the Lake Superior region. The line of contact is easily recognized by casual field observation. That the essential continuity of the upper Huronian is obvious is indicated by the early use of the term Animikie not only for the upper Huronian rocks on Thunder Bay, but for those in the Mesabi district.

In the area southwest of the Mesabi district, in the St. Louis River and Cuyuna districts and the country to the west, the upper Huronian consists principally of slate, carrying lenses of iron-bearing formation, with many intrusive and possibly extrusive rocks and certain rare quartzites, the horizon of which is not satisfactorily determined but which are probably basal to the division. The upper Huronian in this area contrasts markedly with that along the Mesabi range and farther east in being closely folded, in the abundance of its intrusive rocks, and in possession of cleavage, as well as in the differences in lithologic character just noted. It is suggested (pp. 214, 528, 611) that the structural differences may be related in some way to proximity to the axis of the Lake Superior syncline, or that the Mesabi and eastward belt of the upper Huronian may represent a shore phase of deposition, while the upper Huronian of the Cuyuna area to the south may be an offshore phase.

IGNEOUS ROCKS.

Intrusive into the upper Huronian are the great Duluth gabbro of northern Minnesota, the basic sills of the Gunflint and Animikie Bay districts (Logan sills), a few basic dikes and possibly sills in the Mesabi district, a granite mass on the east end of the Mesabi range, and more abundant basic and intrusive masses in the Cuyuna district. Most of the intrusives are of Keweenawan age. Contemporaneous volcanic rocks have not been recognized.

Extrusive rocks rest on the Animikie in the Cuyuna district. It has been shown that many of the capping diabases of the Nipigon area may be extrusive. These are doubtless middle Keweenawan, but some of them may be late Animikie.

CONDITIONS OF DEPOSITION.

The upper Huronian is a unit for the region, hence the conditions of deposition are discussed on pages 612–614, after the southern subprovince has been treated.

CORRELATION.

The correlation of the upper Huronian of the northern subprovince with that of the southern subprovince is discussed on page 610.

SOUTHERN HURONIAN SUBPROVINCE.

LOWER HURONIAN.

LITHOLOGY AND SUCCESSION.

The lower Huronian of the southern subprovince reaches its fullest development in the Marquette district, where it consists, from the base up, of the Mesnard quartzite, Kona dolomite, and Wewe slate. In the Gogebic district the lower Huronian includes similar quartzite and dolomite named respectively the Sunday quartzite and the Bad River limestone, but the slate overlying the limestone is absent.

Although the north shore of Lake Huron does not fall within the area covered by this report, it is desirable to consider the position of the series there because that is the district to which the term Huronian was first applied. The lower Huronian of the north shore of Lake Huron includes a great clastic formation above which is a limestone. In most places the clastic formation comprises a conglomerate at the base, above this a quartzite, and above this a slate. In other places the conglomerate is almost immediately overlain by the limestone. The succession is very similar in its essential features to that of the lower Huronian of the Marquette district.

The lower Huronian is represented in the Menominee, Iron River, and adjacent districts of Michigan and Wisconsin. It consists of a quartzite (the Sturgeon quartzite) followed by a dolomite (the Randville dolomite); but in the Iron River district the quartzite and dolomite are interbedded and for them the new name Saunders formation has been introduced.

The lower Huronian partakes of the major structure described for each of the districts. As a whole the folding is not as intense as in the Archean. Cleavage is usually lacking, jointing is abundant, and bedding is easily discerned.

The quartzite of the lower Huronian of this subprovince represents a cleanly assorted sand, now strongly indurated, more or less iron stained, and locally showing fracturing and rock flowage, but retaining its original bedding structure as a conspicuous feature. It therefore contrasts in many respects with the lower Huronian of the northern subprovince. The dolomite overlying the quartzite is very cherty and shows more evidence of deformation than the quartzite. The weathering of this dolomite emphasizes the folded and brecciated chert layers and serves to make the formation easily identifiable.

IGNEOUS ROCKS.

In the areas which are certainly known to be lower Huronian, contemporaneous igneous activity was not important. This applies to all the districts south of Lake Superior, as well as to the area north of Lake Huron. In this respect the lower Huronian contrasts with the middle and upper Huronian and to a more marked degree with the Archean. The contrasts between the Archean and the lower Huronian in this respect are contributory evidence of the unconformity between the two. (See pp. 617–618.) The volcanic activity of Archean time apparently had died out completely in this Huronian subprovince before the deposition of the rocks unquestionably belonging to the lower Huronian.

Later intrusive rocks cut the lower Huronian in small dikes. The post-Huronian or Keweenawan granites of the Florence district of Wisconsin doubtless also cut the lower Huronian, but exposed contacts are only those of the granite and upper Huronian.

CONDITIONS OF DEPOSITION.

It has appeared that the lower Huronian south of Lake Superior and on the north shore of Lake Huron comprises first a great clastic formation consisting from the base up of conglomerate, quartzite, and slate. Over this is a largely nonclastic formation now represented by a dolomite, and localy above this in the Marquette district is another clastic slate formation.

The essential subaqueous origin of the lower Huronian is believed to be shown by the cleanly assorted nature of the sediments, the ripple marks of a shore rather than a stream type, and extensive beds of limestone. It remains to be proved that such thick and continuous limestone formations may be produced as terrestrial formations. Finally the conglomerate at the base of the group contrasts strongly with the arkose and thick conglomerate masses at the base of the middle-lower Huronian of the north shore, and is believed to be more characteristic of aqueous sedimentation.

It therefore appears that at the beginning of lower Huronian time the conditions in the southern subprovince had become those of normal sedimentation in which the material destroyed by the epigene agents was sorted and laid down in beds one upon another, the lithologic character varying from time to time. This is evidence that the erosive forces of air and water were working as at present. Moreover, as emphasized by Chamberlin and Salisbury,[a] it is evidence that the weathering processes possessed their full efficiency, and this would favor abundant vegetation.[b] With the beginning of Huronian time at the latest commences the part of the history of the world to which Lyell's principles of uniformity[c] are applicable. These ancient Huronian rocks have no lithologic peculiarity which can discriminate them from the rocks of much later age; indeed, there is nothing to indicate that when they were laid down the conditions were in any respect different from those which prevail to-day, with the sole negative point that fossils have not been found.

CORRELATION.

The Gogebic, Marquette, and original Huronian districts are approximately in an east-west line and the prevailing strikes of the lower Huronian in all but the Crystal Falls and Iron River districts are in the same general direction, favoring the correlation of the rocks of the different districts.

In each district the lower Huronian rests with profound unconformity upon the underlying Archean or basement complex, the unconformity being marked where exposed by differences in lithology, by metamorphism, and by the presence of a basal conglomerate, and being shown also by the areal relations and relations to intrusive rocks.

The lower Huronian is overlain unconformably by the upper Huronian (Animikie group) in all the districts, and by the middle and upper Huronian in the Marquette, Crystal Falls, original Huronian, and Menominee districts.

The lower Huronian of the southern subprovince has no counterpart in the northern subprovince, though it occupies the same general position in the succession as the lower-middle Huronian of the northern subprovince.

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[a] Chamberlin, T. C., and Salisbury, R. D., Geology, vol. 2, 1906, pp. 162–163.
[b] Van Hise, C. R., A treatise on metamorphism: Mon. U. S. Geol. Survey, vol. 47, 1904, p. 477.
[c] Lyell, Charles, Principles of geology, vol. 1, 10th ed., 1867, pp. 305–326.

MIDDLE HURONIAN.

LITHOLOGY AND SUCCESSION.

The middle Huronian is represented in the Marquette, original Huronian, Crystal Falls, and Menominee districts. In the Marquette district, where it was first discriminated and is best developed, it consists from the base up of the Ajibik quartzite, Siamo slate, and iron-bearing Negaunee formation (nonclastic). On the north shore of Lake Huron the broader features of the middle Huronian are analogous with those of the Marquette district—that is to say, the rocks comprise a clastic formation below, consisting of a conglomerate at the base and over this a quartzite, both so thick and extensive that they have been mapped separately, and above these clastic formations a cherty limestone.

In the Crystal Falls district the middle Huronian is represented principally by the volcanic Hemlock formation, containing iron-bearing slate near the top. The iron-bearing Negaunee formation is doubtfully present; the Ajibik quartzite is present near the northeast corner of the district, near the Marquette district. Volcanism seems to have intervened between the deposition of the lower Huronian and the upper Huronian, making lithologic correlation difficult. It is to be noted, however, that the Clarksburg volcanic rocks of the Marquette district began to be extruded in middle Huronian time, and these are therefore to be partly correlated with the Hemlock volcanic rocks of Crystal Falls.

In the Menominee district the middle Huronian is taken to be represented by cherty quartzite, heretofore not separated from the Randville dolomite of the lower Huronian. There is evidence also in the jasper and iron pebbles in the conglomerate at the base of the upper Huronian that an iron-bearing formation corresponding in position and character to the Negaunee was present in the district before upper Huronian time, but no remnants of this are now known.

IGNEOUS ROCKS.

In the Marquette district the middle Huronian is associated with part of the Clarksburg formation of basic intrusive and extrusive rocks. In the original Huronian district igneous rocks are lacking in the middle Huronian. The presence of igneous rocks in the middle Huronian of the Marquette district and their absence in the middle Huronian of the original Huronian district may perhaps be correlated with the presence in the former, and the absence in the latter, of an iron-bearing formation. (See pp. 506–507.)

Hemlock volcanic rocks form the principal part of the middle Huronian in the Crystal Falls district. In the Menominee district volcanic rocks are absent from the division. The Keweenawan (?) granites of Florence County doubtless also cut the middle Huronian, though they nowhere come into contact with it at the surface.

CONDITIONS OF DEPOSITION.

The extensive formations of cleanly assorted, well-rounded, ripple-marked sands, now quartzites, of the middle Huronian, both south of Lake Superior and north of Lake Huron, point toward subaqueous deposition. The pure nonclastic iron-bearing formation south of Lake Superior and the cherty limestone formation north of Lake Superior point in the same direction. Still further is this shown by the association of these rocks with partly subaqueous volcanic rocks of the Clarksburg formation. The iron-bearing formation and possibly some of the associated slates have a close genetic connection with some of the associated volcanic rocks.

In the Crystal Falls district the middle Huronian was principally a time of extrusive volcanism, partly subaqueous. The volcanic rocks are interbedded with the slates and iron-bearing rocks, subaqueously deposited. In the Menominee district the middle Huronian is represented only by shreds of quartzite and perhaps by the iron-bearing Negaunee formation.

The quartzite is very cherty, as if derived from decomposition of the Randville dolomite, against which it rests. It is well bedded and well assorted. At one locality there seems to be a conglomerate with well-rounded bowlders near its base.

On the whole the evidence favors subaqueous deposition of the middle Huronian.

CORRELATION.

The middle Huronian rocks in the Marquette and original Huronian districts are correlated on the basis of similar succession of clastic and nonclastic rocks, similar relations to the lower Huronian, similar east-west trend, similar metamorphism, and the fact that they are subaqueous in both districts. They differ in that the nonclastic formation of the Marquette district is an iron-bearing formation and that of the original Huronian district a limestone, that associated igneous rocks are present in the Marquette district and not in the original Huronian district, and that in the Marquette district the overlying rocks are upper Huronian and in the original Huronian district no upper Huronian is present, although to the northeast in the Sudbury basin rocks probably to be correlated with the middle Huronian are overlain unconformably by rocks with upper Huronian characteristics.

The middle Huronian of the Crystal Falls district, being largely volcanic, may be correlated lithologically with the lower part of the Clarksburg formation of the Marquette district. So far as the Ajibik and Negaunee formations are present in this district they are correlated directly with formations of the same names in the Marquette district. They occur, however, in the northeast corner of the Crystal Falls district, the area nearest to the Marquette district, and the correlation is of little aid in correlating the middle Huronian as a whole. The middle Huronian of the Crystal Falls district is principally a great assemblage of volcanic rocks lying between the lower Huronian and upper Huronian and differing from the dominantly sedimentary middle Huronian of other districts. Its correlation is therefore based principally on its position in the geologic column.

The middle Huronian of the Menominee district is correlated with the middle Huronian of other areas almost entirely on the basis of its stratigraphic position, unconformably above the lower Huronian and unconformably below the upper Huronian. As it consists only of a remnant of quartzite, lithologic comparison with the middle Huronian of other districts is of no value.

The equivalents of the middle Huronian have not been identified in the other districts of the Lake Superior region, though it is possible that future work may result in its identification in the Florence and Iron River districts.

UPPER HURONIAN (ANIMIKIE GROUP).

LITHOLOGY AND SUCCESSION.

The upper Huronian of the southern subprovince consist mainly of a thick slate formation carrying two or more iron-bearing beds or lenses near its base and possibly others higher in the group.

In the Gogebic district it consists from the base up of the Palms formation, the iron-bearing Ironwood formation, and the Tyler slate.

In the Marquette district it consists from the base up of the Goodrich quartzite, the iron-bearing Bijiki schist, and the Michigamme slate.

In the Menominee district the lower iron-bearing part of the upper Huronian is called the Vulcan formation and the upper slate the Michigamme ("Hanbury") slate. The Vulcan formation is subdivided, from the base up, into the Traders iron-bearing member, the Brier slate member, and the Curry iron-bearing member.

In the Crystal Falls district a similar subdivision into Vulcan and Michigamme is made, but there not only are the members of the Vulcan formation not discriminated, but the formatiou is interbedded near the base of the slate and is treated as a member of the Michigamme and not as a distinct formation, although it is mapped separately. On former maps of the Crystal Falls district[a] the iron-bearing rocks were not given a separate name, but were mapped with the slate as upper Huronian. In this report they are correlated with the Vulcan formation and called the Vulcan iron-bearing member.

In the Calumet district the upper Huronian is divided into the Michigamme slate, the Vulcan formation, and a third formation at the base, the Felch schist. The Vulcan formation is subdivided into three iron-bearing beds and two slate beds.

In the Felch Mountain district the slate is absent except where the district opens out to the west; the Vulcan formation is not subdivided and the Felch schist forms the base of the upper Huronian. The Vulcan and Felch formations of this district correspond respectively with the "Groveland" and "Mansfield" formations of the earlier mapping of the district. The reasons for the change of names are given on pages 303-305.

In the Iron River district the upper Huronian is represented by the Michigamme slate, interbedded near the base of which is an iron-bearing member that has been correlated with the Vulcan formation, although the evidence is not conclusive that certain iron-formation bands classed as Vulcan may not belong stratigraphically higher than the Vulcan formation as typically developed in the Menominee district. The same remarks may be made concerning the Florence district in Wisconsin.

Throughout the southern subprovince the Michigamme slate is closely folded and in much of the area, especially in the vicinity of the intrusive rocks it has a strongly developed cleavage. Bedding is usually to be observed except in places where there has been exceptionally good development of cleavage. The iron-bearing formations and quartzites also have been closely folded, but lack cleavage.

IGNEOUS ROCKS.

Basic intrusive and extrusive rocks in the upper Huronian are represented in this subprovince by the Clarksburg formation of the Marquette district; by the Presque Isle area of the Penokee-Gogebic district, where volcanic rocks, lavas, and tuffs were built up during the larger part of upper Huronian time, and by basaltic schists of the Menominee, Crystal Falls, Iron River, and Florence districts. In individual occurrences it has not been found possible to determine whether these basic igneous rocks are intrusive or extrusive or even to exclude the possibility of the rocks being pre-Huronian. Some of the intrusive rocks are probably of Keweenawan age. Granites of probable Keweenawan age intrude the upper Huronian and associated basaltic extrusives in the Florence district.

CONDITIONS OF DEPOSITION.

The conditions of deposition of the upper Huronian in this subprovince are discussed on pages 612-614.

CORRELATION.

There can be little doubt about the correlation of the upper Huronian in the several districts of the southern subprovince. The rocks as a whole are easily eroded and heavily drift covered and therefore have few outcrops, with the result that areal connections have not been everywhere traced, although they probably exist. The upper Huronian of the Marquette district opens on the west and southwest into a great slate area, which, so far as known, is the same slate area as that surrounding the Crystal Falls district, and thence extends south and southwest into the Menominee and Iron River districts. Throughout the subprovince the greater part of the upper Huronian is slate and the iron-bearing formation is characteristically near the base of the group. In metamorphism, folding, amount of intrusive rocks, and relations to intrusive rocks the upper Huronian within the province is a unit.

[a] Mon. U. S. Geol. Survey, vol. 36, 1899.

From a study of the structural facts alone it may not be affirmed that the unconformity at the base of the upper Huronian of the southern subprovince represents a considerable time interval. However, when this unconformity is considered in connection with the deep erosion and local absence of the middle Huronian between two divisions, which are identified on satisfactory evidence, as upper Huronian and lower Huronian, it is evident that the time break represented may be a large one. Great time intervals are known to be represented in other parts of the geologic column, as, for instance, between the Paleozoic and Mesozoic in parts of the West, where structural evidence is slight.

The correlation of the upper Huronian of the southern and northern subprovinces is scarcely less clear. In each subprovince the basal member is quartzite and slate, followed by an iron-bearing formation and then by thick slate. The differential metamorphism is similar in the two subprovinces. In both the upper Huronian rests with strong unconformity upon Archean or middle or lower Huronian. In both it is unconformably beneath the Keweenawan. On the north shore it dips gently to the south under the Lake Superior syncline; in the northern part of the southern subprovince the upper Huronian of the Gogebic district dips steeply to the north under the same syncline. The identity in the succession of formations in these two subprovinces, their position immediately below the Keweenawan, and their general structural alliances with that series give such strong evidence of equivalence that no one can seriously doubt that the upper Huronian of the two regions is essentially contemporaneous.

If one saw the flat-lying, little-altered upper Huronian at one locality and the most folded and metamorphosed phases at another far distant and had not proved their continuity, he might think that the rocks of the different localities belonged to different divisions, but in many places the various metamorphosed and unmetamorphosed phases have been found to connect.

GENERAL REMARKS CONCERNING THE UPPER HURONIAN (ANIMIKIE GROUP) OF THE LAKE SUPERIOR REGION.

CHARACTER.

The Animikie is the only group that is continuous throughout the Huronian subprovinces. It is the principal iron-bearing group. Although it has been described in connection with each of the subprovinces, a further general description is here presented to emphasize its unity over the Lake Superior region.

The upper Huronian was deposited on a remarkably uniform peneplain. Remnants of this peneplain appear from beneath the upper Huronian in the Mesabi, Animikie, and Gogebic districts. The post-Animikie and post-Keweenawan folding have resulted in the tilting of this plain to various angles and it is truncated by later peneplains. In each of the districts in which a full succession is found there is a clastic formation at the bottom, a middle iron-bearing formation, and an upper slate formation. The bottom clastic formation consists of a conglomerate at the base, which in the northern subprovince and the northern part of the southern subprovince passes up into a shale or slate and in most places finally into a quartzite. In the different districts, and in the same district, the relative proportions of conglomerate, quartzite, and slate vary, as does also the particular phase which is adjacent to the iron-bearing formation. For instance, in the Marquette district conglomerate and quartzite are dominant in the Goodrich quartzite and there is comparatively little slate. In the Penokee-Gogebic district conglomerate and slate are dominant in the Palms formation and the quartzite is a thin formation at the top. In the Mesabi district the Pokegama quartzite is somewhat similar. In the Animikie, Menominee, and Crystal Falls districts the clastic formation is very thin indeed.

Over the clastic formation is the iron-bearing formation, which in the Marquette district is known as the Bijiki schist, in the Menominee district as the Vulcan formation, in the Crystal Falls, Iron River, and Florence districts as the Vulcan iron-bearing member, in the Gogebic district as the Ironwood formation, in the Mesabi district as the Biwabik formation, and in the Cuyuna district as the Deerwood iron-bearing member. This iron-bearing formation is by far the most persistent and important of those of the Lake Superior region. In it are probably 95 per cent of the known ore reserves. It is not a pure nonclastic formation, but has interstratified slaty layers of variable thickness. A number of these layers have been recognized in the Mesabi and Gogebic districts. In the Menominee district one of them is of sufficient thickness to constitute a distinct member of the formation and is known as the Brier slate member; it separates the two ore-bearing members of the Vulcan, the Curry and Traders. The maximum thickness of the iron-bearing formation forthe region is 1,000 feet.

In parts of the region the iron-bearing formation does not lie at a definite horizon between the coarse clastic sediments at the base and the shales above, but appears as more or less isolated and overlapping lenses entirely within the slate which forms the upper part of the upper Huronian. This is the characteristic occurrence of the iron-bearing formation of the upper Huronian in the great area extending south and west from the Mesabi and St. Louis River districts, including the new Cuyuna range, and of the triangular area of Michigan between the Marquette, Menominee, and Gogebic districts, including the Florence, Iron River, and Crystal Falls districts. The iron-bearing formation in this relation to the slate appears also in the western part of the Marquette district. Iron-bearing lenses of this kind seem on the whole to be more numerous near the base of the slate than elsewhere, but in many places it is not known what their stratigraphic position really is, the rocks both above and below them being slate. It will be noted that the sharply delimited, extensive iron-bearing formations, occurring at a definite horizon above the lower clastic formations of the upper Huronian, border the older formations on the northwest and southeast sides of the Lake Superior syncline, and that the discontinuous lens-shaped parts of the formations in the slate are located far from the contacts with the older formations. The suggestion is made that this difference may be due to original difference of conditions of deposition near the old shore against which the upper Huronian sea washed, as compared with the conditions off shore.

Above or associated with the iron-bearing formation is the upper slate formation known as the Michigamme slate in the Marquette, Crystal Falls, Calumet, Menominee, Iron River, and Florence districts, the Tyler slate in the Penokee-Gogebic district, the Virginia slate in the Mesabi, Cuyuna, and adjacent districts, and the Rove slate in the Vermilion district. It occupies a large area in Michigan south of Lake Superior, an immense area west of Lake Superior extending far into central Minnesota, and a very large area about Thunder Bay and vicinity. It probably extends westward beyond the western boundary of Minnesota and widens out in this direction. It is entirely possible that this formation will ultimately be found to connect beneath the later formations with the slates of the Black Hills of South Dakota and even with the Belt series of Montana. Indeed, the areal extent of this formation is far greater than that of all the other Huronian sediments of the Lake Superior region.

The formation being for the most part a slate and so soft as to be extensively covered by the drift, exposed sections in which to measure its thickness are rare. Also cleavage in these sections has so obscured bedding that estimates are worth little. In the Penokee-Gogebic district, where such a section is exposed, the possible maximum thickness has been estimated at about 12,000 feet, but this is probably too large. Seaman and Lane [a] suggest 4,000 feet.

The rocks of this formation in the Mesabi and Animikie districts are principally shales. Elsewhere they are principally slates. At Carlton and Cloquet, on St. Louis River, the formation is much folded and has a slaty cleavage, and farther to the southwest, where intruded by masses of granite and diorite, it locally becomes so metamorphosed as to pass into a schist. A like change is noted in the character of the upper formation, the Tyler slate, at the west end of the Penokee district, where it is intruded by igneous rocks.

Conspicuous in the slate at many horizons are seams and lenses of pyritiferous and graphitic slates. These are so characteristically associated with some of the discontinuous iron-bearing lenses, originally iron carbonate, as to serve as guides in exploration.

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[a] Lane, A. C., and Seaman, A. E., Notes on the geological section of Michigan: Jour. Geology, vol. 15, 1907, p. 686.

The slate as a whole gives evidence by its composition of being less leached of its bases than average slates or residual clays. The composition also shows that it must have been derived from rocks on an average more basic than granites. In figure 76, prepared by S. H. Davis, the mineralogical composition of the upper Huronian slates, calculated from chemical composition, is compared graphically with that of a variety of other clays and soils.

The upper Huronian slate and iron-bearing formations are interbedded locally with abundant basaltic extrusive rocks, partly subaqueous, and tuffs in the southern subprovince. In the northern subprovince these are yet known definitely only in the Cuyuna district of Minnesota.

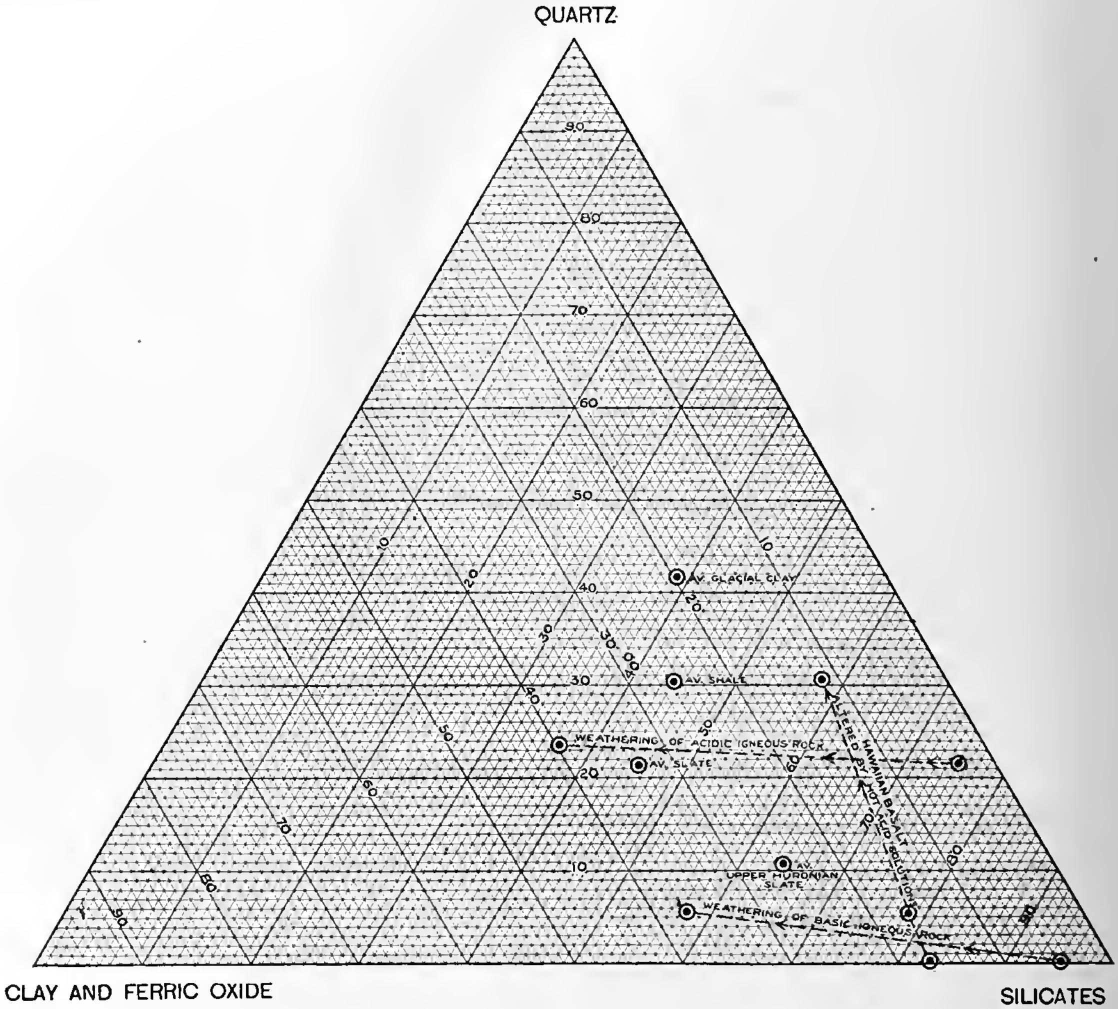


FIGURE 76.—Triangular diagram comparing the amounts of undecomposed silicates, quartz, and residual weathered products, such as clay and ferric oxide, in different kinds of muds, shales, and weathered rocks. For description of method of platting see page 182. The mineral compositions are calculated from chemical analyses. Dotted lines with arrows indicate the progressive change in proportions of constituents between the unaltered and altered rocks. The diagram brings out clearly the fact that the upper Huronian shale represents the little-decomposed débris of a basic igneous rock.

CONDITIONS OF DEPOSITION OF THE UPPER HURONIAN (ANIMIKIE GROUP).

Any hypothesis of the conditions of deposition of the upper Huronian must be built around the following salient facts:

The succession of a thin fragmental base, an iron-bearing formation, and a thick mud deposit, and the thinness, evenness, and wide extent of the basal conglomerate and quartzite.

The fact that the upper Huronian rests upon a flat plane beveling alike hard and soft, resistant and nonresistant rocks, without residual or terrestrial deposits at the base.

The association of discontinuous iron carbonate lenses with graphitic slates at different horizons, pointing strongly to bog or lagoon conditions.

The lack of sorting or decomposition in the slates as shown by analyses.

Contemporaneous volcanism, partly submarine, probably related to the deposition of the ore, so associated with the upper Huronian as to indicate subaqueous origin for at least a part of it.

The hypothesis which seems to fit this group of facts better than others which have suggested themselves to us is this:

1. The first upper Huronian event was the advance of the upper Huronian sea to a shore line somewhere north of the present northern boundary of Lake Superior. In the area of Michigan and Wisconsin it passed over middle and lower Huronian rocks which were nearly flat-lying and perhaps not much eroded. On the north shore it passed over middle and lower Huronian rocks which had been closely folded and deeply eroded. This advance was perhaps accompanied by some planation or scouring of the land area, as suggested by the evenness of this plane and the manner in which it bevels alike soft and hard formations and by the absence of residual or terrestrial deposits beneath the cleanly assorted fragmental base of the upper Huronian. Had the land been base-leveled by terrestrial erosion prior to the advance of the sea, that advance would seem likely to have flooded the river mouths and required them to build up to grade, resulting in the development of terrestrial deposits, including much mud, in advance of the encroaching sea, to be ultimately covered by it, and not removed. It is entirely conceivable that farther to the south the upper Huronian sea may actually have advanced over this zone of terrestrial deposition, but that in the Lake Superior region the sea had encroached upon the upper portions of the rivers and was cutting into the rock. There seems to be an absence of sea cliffs to the north of the present upper Huronian beds, but this may be explained by later erosion.

The advance of the sea over a gently sloping surface was accompanied by deposition of a thin conglomerate and sand formation spread evenly over a large area. Barrell [a] has shown that with the low gradient characteristic of such advance the conglomerate at the base is likely to be very thin, if not altogether lacking, being worn out by littoral abrasion, and in modern instances being observed to disappear a short distance from the shore. Conglomerates of this sort may be thick and coarse only around monadnocks standing above the plane of transgression. The deposit of the upper Huronian sea seems to be similar to the thin fragmental base of the Cambrian, which was laid down by the Paleozoic sea advancing also from the south over a flat surface. The absence of conglomerate in the Cambrian except around monadnocks is well known.

2. Then came the deposition of the iron-bearing material. This is a chemical precipitate requiring either quiet conditions of deposition or extreme rapidity of deposition to account for the lack of interbedded coarse fragmental sediments. It has been argued in another place (pp. 506 et seq.) that the thick iron-bearing formations near the base of the upper Huronian, such as those of the Mesabi, Gogebic, and Menominee districts, find their essential explanation in their genetic relation with basic volcanism, which furnishes sources for unusually abundant deposition of iron salts. The abruptness of the change from quartz sand to iron-bearing formation and the usual lack of any fragmental material in the iron-formation layers seem to imply some unusual change of conditions, probably not related to topographic or climatic changes.

3. The advance of the upper Huronian sea overlapped the Lake Superior region but may not have progressed much farther north. We find no record of it farther north, though allowance must be made for much erosion. The flatness of the plane would require that planation or scouring should be weakened during the northward transgression. The rivers would then be able to hold their own against the sea, and deposition of river alluvium in the form of great deltas may be supposed to have predominated over marine fragmental deposition. Then were

[a] Barrell, Joseph, Relative geological importance of continental, littoral, and marine sedimentation: Jour. Geology, vol. 14, 1906, pp. 433-446; also personal communication.

built up the thick masses of mud deposits characterized by discontinuous, pyritiferous, graphitic seams, and iron-carbonate lenses at different horizons, which seem better explained by delta and lagoon conditions than by any other hypothesis that has been suggested. Association with subaqueous extrusions is thus explained. So far as deltas are terrestrial the upper Huronian muds are terrestrial.

The lack of decomposition of the muds and the graphitic material associated with iron carbonate, indicating the probable existence of peaty material associated with bog deposits, favor the view that the climate may have been continuously cool and wet, for nowhere are the conditions for lack of decomposition, bog formation, and absence of oxidation of carbon so well developed as in a district where a continuous covering of water prevents the access of oxygen. In warmer regions or in those in which a part of the year is hot and dry the organic material is likely to be oxidized, giving an abundance of carbon dioxide for attack of the rocks.

Contemporaneous basic igneous extrusions, so abundant in the upper Huronian, doubtless furnished an unusual source for mud, by their decomposition when hot,[a] through the agencies of acid solutions, through the agencies of the atmosphere acting upon sulphides and thereby freeing sulphuric acid for attack on the adjacent rock, and finally perhaps by reaction of the hot lavas with sea water. In figure 76 (p. 612) is indicated the direction of alteration of basalt by hot sulphuric-acid solutions of the Hawaiian Islands. The most altered phase represents rock which has not been transported. It is to be noted that the direction of alteration is somewhat different from that of weathering. It is entirely possible, if not probable, from the position of upper Huronian slates in the diagram, that they have been derived from the katamorphism of basic igneous rocks, both by ordinary weathering and by the unusual alteration of hot acid solutions associated with the igneous rocks themselves.

The upper Huronian sediments are therefore regarded as the combined result of an advancing sea scouring, perhaps cutting the old surface, of a source in which basic volcanic rocks form a distinctive part, and of the final deposition of a great mud delta.

The building up of the upper Huronian, developing terrestrial conditions toward the close, furnishes an appropriate setting for the inauguration of the great Keweenawan period of terrestrial sedimentation which followed after an interval of erosion.

KEWEENAWAN SERIES.

As the Keweenawan is a unit to a greater extent than the Huronian or the Archean, being located along the border of Lake Superior with large inland extensions, and as the general outline of the history of the Keweenawan has been given in Chapter XV, we give here only the briefest summary of the salient features of the series.

LITHOLOGY AND SUCCESSION.

It has been seen that the Keweenawan is separable into three divisions, a lower, middle, and upper. The lower Keweenawan was formed during a period of sedimentation and consists of conglomerates, sandstones, shales, and limestones. This division of the Keweenawan is not very thick, but it is widespread. The maximum measurement is 1,400 feet. The middle Keweenawan represents a time of combined sedimentary and igneous action, containing many alternations of sedimentary and igneous deposits. In general the igneous activity greatly dominated in the early part of middle Keweenawan time, but was less dominant in the later part. Upper Keweenawan time was again a period of normal sedimentation. At the base of the upper Keweenawan are thick conglomerates, which are overlain by shales and these by a very thick sandstone formation.

As contrasted with the Huronian the Keweenawan sediments are dominantly clastic. Nonclastic sediments are found only in one locality, in the Nipigon-Black Bay district. Moreover, the clastic formations are coarse, being dominantly either psephitic or psammitic. Only sub-

[a] Maxwell, Walter, Lavas and soils of the Hawaiian Islands: Bull. A, Exper. Sta. Hawaiian Sugar Planters Assoc., 1905, pp. 8–22.

ordinately are pelites present, the single important representative being the shale of the upper Keweenawan.

Another feature in which the Keweenawan sediments contrast with the Huronian is that they are largely derived from the igneous rocks of the series itself.

IGNEOUS ROCKS.

The igneous rocks of the middle Keweenawan are both plutonic and volcanic. They include basic, acidic, and intermediate varieties, the basic rocks being dominant. As the detritus of the middle and upper Keweenawan is derived largely from the igneous rocks of the period itself, in arriving at an estimate of the mass of igneous intrusions and extrusions of this time we must consider not only the original igneous rocks, but the sediments which are derived from them. The mass of the Keweenawan volcanic and plutonic facies is enormous.

CONDITIONS OF DEPOSITION.

It is probable that the sediments of the Keweenawan were largely land deposits. (See pp. 416–418.) The principal arguments for this conclusion are their prevailing red color, their little-assorted, feldspathic nature, and their rapid alternation with abundant extrusive rocks having textures that are ordinarily associated with subaerial cooling, in contrast with the textures of subaqueous cooling so common in the volcanic rocks of the lower Huronian and the Keewatin. But it is also probable that a portion of them were deposited under water. In the discussion of orogeny (pp. 622–623) it is shown that the Lake Superior basin was formed largely in Keweenawan time, and it is highly probable that this basin contained water.

CORRELATION.

The correlation of the different areas of the Keweenawan is a simple problem. The great area of Keweenawan, extending from Keweenaw Point through northern Michigan into Wisconsin and Minnesota and thence northeastward to the Thunder Bay district and Lake Nipigon, is almost continuous. Therefore the only problem of correlation so far as the general series is concerned is that of the rocks of Isle Royal, Michipicoten, and the areas on the east coast of Lake Superior. The placing of these rocks in the Keweenawan is based on their position at the top of the pre-Cambrian, the unconformity at their base, and their remarkable likeness in lithology, succession, deformation, and metamorphism to the rocks of the main Keweenawan area. Though all these points bear on the question, it was the likeness of the lavas of these areas to those of the main area and their interstratification with red sandstones and conglomerates which led the earlier geologists who worked in the Lake Superior region to recognize the identity of the separated areas of Keweenawan rocks.

The problem of fixing the exact relations of the Keweenawan and Cambrian is not so simple The evidence as given in Chapter XV is in favor of the Algonkian age of the main part of the Keweenawan.

PALEOZOIC ROCKS.

The Keweenawan is the latest period which this monograph treats in detail. On the general geologic map (Pl. I, in pocket) the Paleozoic and later rocks are shown as covering a large part of the area south of Lake Superior, but they are all represented by one color, for it is not our purpose to consider the post-Algonkian formations separately. The Paleozoic rocks are mentioned only in so far as they are related to the Proterozoic—that is, the Algonkian and Archean.

For the most part the formation which overlies the Proterozoic rocks is a sandstone, which is generally recognized as of Cambrian age. Its basal portion where in contact with iron-bearing formations consists of detrital ferruginous rocks. This formation is everywhere in a substantially horizontal attitude, thus contrasting strongly with the Proterozoic rocks. In general the relations between this sandstone and the Proterozoic rocks are those of most profound unconformity, and this is true whichever of the more ancient series underlies the sandstone. The manner in which the Cambrian sandstone cuts unconformably across the several series of the pre-Cambrian is well illustrated on the east side of the pre-Cambrian area of the Upper Peninsula of Michigan and northern Wisconsin. Here the Cambrian is fossiliferous. The unconformable relation to the Archean is splendidly illustrated along the Lake Superior shore north of Marquette. The discordant relations with the Huronian are shown at many localities in the Menominee district. At some localities in northern Wisconsin the sandstone rests upon the Keweenawan. The discordant relation between the Cambrian sandstone and the Keweenawan is particularly well seen at Taylors Falls, on St. Croix River. Here the sandstone rests upon the tilted edges of the lower Keweenawan. At this locality the sandstone has been found to contain fossils which have been determined by Berkey [a] to combine "to a certain degree characteristics of both the Middle and Upper Cambrian," which "do not as a whole present a primitive faunal aspect." Apparently the earliest Paleozoic rocks here are either those of the upper part of the Middle Cambrian or the lower part of the Upper Cambrian, or both.

Adjacent to Lake Superior is an area of sandstone, about the age and relations of which there is room for difference of opinion. This area of sandstone is south of the west end of Lake Superior, making the shore of Chequamagon Bay, the south shore of the west end of Lake Superior, and the Madaline Islands (Lake Superior sandstone). In this area the Lake Superior sandstone does not carry fossils and is possibly Keweenawan, but it has been regarded by all as probably the equivalent of the fossiliferous Upper Cambrian to the south and is so treated in this monograph. That these sandstones have relations to the Archean and Huronian like those described for the more extensive areas of Cambrian sandstone to the south has been agreed to by all observers from early days. It is also agreed that these sandstones are certainly later than and have unconformable relations with the middle and lower Keweenawan. Following Irving, we have inclined to the view that the same relation exists between these sandstones and the upper division of the Keweenawan. However, Lane and Seaman [b] believe that the Upper Cambrian sandstone of Chequamagon Bay and the Madaline Islands grades down into upper Keweenawan sandstone (which they call Freda). This has been confirmed by recent work of Thwaites, of the Wisconsin Geological Survey (unpublished). The significance of this relation in the correlation of the Keweenawan series is discussed in the chapter on the Keweenawan (pp. 415-416).

The Paleozoic rocks of this region, except in the area above noted, contain marine fossils at several horizons and are therefore in large part submarine deposits. They form a portion of the great series of Paleozoic rocks which has been traced in continuous overlap over a large part of the North American continent. That any of them are of terrestrial origin is not proved, though it is not impossible that part of the sandstone bordering the southwest shore of Lake Superior may be terrestrial. The abundant partly decomposed feldspar in the Cambrian of the Lake Superior region is probably derived largely from the Keweenawan below, which is believed to be in part a terrestrial deposit.

CRETACEOUS ROCKS.

In northern Michigan, Wisconsin, and eastern Minnesota the Paleozoic are the fossiliferous formations that rest upon the pre-Cambrian, but in northern Minnesota there are local patches of Mesozoic (Cretaceous) rocks which have this position. These show that in such areas either Paleozoic rocks were never deposited over the pre-Cambrian, or else, and this is more probable, they were deposited and removed by erosion before Cretaceous time. The Cretaceous carries marine fossils. Its basal portion contains detrital ferruginous sediments.

[a] Berkey, C. P., Geology of the St. Croix Dalles: Am. Geologist, vol. 21, 1898, p. 292.

[b] Lane, A. C., and Seaman, A. E., Notes on the geological section of Michigan; pt. 1, The pre-Ordovician: Jour. Geology, vol. 15, 1907, pp. 680-695.

PLEISTOCENE DEPOSITS.

The Pleistocene deposits of the Lake Superior region are separately treated in Chapter XVI (pp. 427–459) and will not be summarized here.

PRE-CAMBRIAN VOLCANISM.

It is by contrasting the volcanism of the different pre-Cambrian periods that we gain an idea of their relative importance. The volcanism of the Archean is unique, both as to volume and as to extent. If we may presume that the Archean which is buried is of the same character as that which is now at the surface—and this has been shown in some places by drilling—it would follow that the Archean rocks not only once covered the entire Lake Superior region but extended to an indefinite distance in all directions. They are composed dominantly of igneous rocks, volcanic and plutonic. The mass of igneous rocks of this time is immeasurably greater than that of any succeeding pre-Cambrian epoch; indeed, much greater than that of all of them put together. Evidence has also been given (pp. 510–512) in favor of the idea that some of the basic volcanic rocks are submarine.

In the Huronian also there are intrusive and extrusive rocks of both basic and acidic character in vast volume, but far less in amount than the enormous masses of the Archean. The basic extrusive rocks are abundant in the middle and upper Huronian of the southern subprovince and especially in the upper Huronian, but their distribution is local. Like the extrusive rocks of the Keewatin, those of the Huronian are partly submarine. They are represented by the Clarksburg formation of the Marquette district, the Hemlock formation of the Crystal Falls district, the volcanic rocks of Brule River in the Florence district, the volcanic rocks of Presque Isle in the Gogebic district, and many unnamed greenstones in the Crystal Falls and Iron River districts. In the lower Huronian basic extrusive rocks are subordinate. Granites are extensively intruded into the Huronian.

The Keweenawan was a time of volcanism, plutonic and surface, which extended over the entire Lake Superior basin and to varying distances inland—indeed, a time of regional volcanism which can be fairly compared with the outbreaks of Tertiary volcanoes in parts of the western United States. In northern Canada and in the southwestern United States are large areas showing many volcanic rocks which may belong to this same period. The basic extrusive rocks of the Keweenawan contrast with those dominant in the Huronian and Keewatin in exhibiting textures peculiar to subaerial cooling instead of textures characteristic of subaqueous cooling.

PRE-CAMBRIAN LIFE.

No fossils definitely recognizable as such have yet been found in the pre-Cambrian of the Lake Superior region. The greenalite granules of the Mesabi district, first called glauconite and thought possibly to be of organic origin, are now known to be chemical precipitates. The carbon that is so abundant in the shales, a part of it in the form of hydrocarbon, is probably of organic origin. The limestones give no decisive proof one way or the other, but they are evidence of extensive carbonation of the rocks, which is now largely accomplished by the assistance of organisms. The probable existence of life is also indicated by the well-assorted nature of the sediments of some of the series, implying the presence of vegetable life to assist in rock decay.

UNCONFORMITIES.

UNCONFORMITY BETWEEN THE ARCHEAN AND LOWER HURONIAN.

Unconformity may signify discordance of structure and intervening erosion with or without great time lapse, or great time lapse with or without great discordance in structure or erosion, or both. The lapse of time may be measured by the extent of the intervening deformation and erosion or by the absence of beds known to have been deposited elsewhere during the interval, which may or may not have covered the area in question. "Great unconformity" as the term is ordinarily used means structural discordance, deep erosion, long time interval, and lack of deposition of sediments known to be deposited elsewhere, or some combination of these conditions. Of these criteria, the first three are the ones here emphasized. The correlation of the pre-Cambrian between widely separated areas is still so uncertain in the lack of fossils that the last criterion can not be satisfactorily used.

Wherever the lower Huronian is distinctly recognized as such, there is an unconformity at its base. The rocks on the two sides of the unconformity contrast widely. Those on one side of it are dominantly igneous rocks, partly plutonic; those on the other side are dominantly sedimentary. During the time represented by this unconformity what seems, from present evidence, to have been a great world period of volcanism ceased and the conditions became such that normal sedimentary rocks were formed.

Contrast in the character of the rocks on the two sides of the unconformity is correlated with other evidence of the greatness of the break. Before the lowest Huronian was deposited, the Keewatin and in places the Laurentian rocks had taken on a schistosity. The plutonic rocks of Archean time had been brought to the surface by erosion. The basal conglomerate beds of the lower Huronian rest upon the Keewatin schists at various angles. It is not easy to conceive of a physical break more indicative of lapse of time than that, for instance, which is shown with diagrammatical sharpness at the east end of the Gogebic district between the lower Huronian Sunday quartzite and the Keewatin schists. Of course where the folding has been close and the shearing between the Huronian and the Archean very great, the evidence of unconformity may have been partly obliterated and the two series appear to grade into each other—for instance, at certain places near Teal Lake, but even here the unconformity may be recognized.

On the north shore of Lake Superior the unconformity at the base of the Huronian is not conspicuous but is as certainly existent as that south of Lake Superior. In the Vermilion district the Huronian series is a definite succession beginning with conglomerates and passing up into slates. The discrimination between the basal complex and the Huronian is an easy one. The break usually has the aspect of one of the first magnitude. In some Vermilion localities, especially where only the conglomeratic and arkosic facies of the Huronian are found, and these are largely composed of the immediately underlying rock, the break could not be asserted to be of great magnitude. If the suggestion is correct that in lower Huronian time the region north of Lake Superior was in large measure a land rather than an oceanic area, this, combined with the fact that basaltic tuffs and conglomerates occur in the Archean, is sufficient to explain the confusion and the apparent insignificance at some places of the unconformity at the base of the Huronian. It is entirely possible that mistakes have been made in the placing of certain conglomerates in the Huronian. If it is admitted that there may be localities in which the relation is confused, wherever the Huronian is represented by a great series of sediments, as in the Vermilion district, the Michipicoten district, and the Cobalt district, there is no difficulty whatever in discriminating between the Archean and the Huronian as a whole and in proving that a profound unconformity separates the two.

UNCONFORMITY BETWEEN THE LOWER AND MIDDLE HURONIAN.

Evidence of the unconformity between the lower Huronian and the middle Huronian is plain in the Marquette district, where the basal conglomeratic formation of the middle Huronian cuts diagonally across all the formations of the lower Huronian and down to the Archean. This means that after the lower Huronian was deposited and before middle Huronian time the lower Huronian was indurated and brought to the surface, and differential erosion occurred sufficient to cut through the entire division into the Archean. The discordance of strike and dip between the two divisions at any one locality is slight.

In the Crystal Falls district the middle Huronian is composed mainly of volcanic rocks. So far as its structure can be worked out it is nearly accordant with the lower Huronian, but in the nature of the case conformity or unconformity is difficult to prove. In the Menominee district the middle Huronian quartzite rests on the Randville dolomite of the lower Huronian with slight though distinct structural discordance. Conglomerate is found at one locality in this district.

UNCONFORMITY AT THE BASE OF THE UPPER HURONIAN (ANIMIKIE GROUP).

The unconformity at the base of the upper Huronian is easily recognized as extending over the Lake Superior region. The upper Huronian rests at different localities on each of the more ancient divisions of middle Huronian, lower Huronian, and Archean, truncating and deriving detritus from whichever of these divisions it overlies. The erosion preceding upper Huronian time apparently reduced the larger part of the Lake Superior region to a peneplain. The best illustration of this is furnished by the Penokee-Gogebic, Mesabi, and Animikie districts, in each of which the quartzite at the bottom of the upper Huronian does not vary more than 200 feet in thickness for a distance of more than 80 miles and is in contact here with the Keewatin, there with the Laurentian, and in still other places with the lower Huronian. This shows that the maximum elevations of these heterogeneous rocks at the time of the encroachment of the upper Huronian sea did not exceed a few hundred feet. Even after the deformation which the deposition plane has undergone, it is still to be recognized in the Mesabi and Gogebic districts as a remarkably even surface.

In the Crystal Falls district the relations of the upper Huronian (Animikie group) to the underlying rocks are obscured by the fact that the immediately underlying rocks are those of the volcanic Hemlock formation, and lack of exposures makes it extremely difficult to ascertain the relations, but there is some evidence of unconformity. (See p. 300.) The unconformity between the upper Huronian and underlying rocks in the Menominee district is marked by discordance of structure, basal conglomerates, and overlap.

On the south shore of Lake Superior the discordance in strike and dip between the upper Huronian and the middle and lower Huronian is not strong, but nevertheless is distinct. On the north shore of Lake Superior before upper Huronian time the earlier Huronian had been closely folded and a nearly vertical schistosity developed, so that at many places the upper Huronian (Animikie group) rests upon the edges of the metamorphosed Huronian below.

UNCONFORMITY AT THE BASE OF THE KEWEENAWAN.

The upper Huronian and Keweenawan have an approximately similar strike and dip, and it was only slowly recognized that the two series are discordant. The best evidence of this, so far as contacts are concerned, is found on the north shore of Lake Superior, in the Thunder Bay and Nipigon districts, where the basal Keweenawan contains abundant detritus derived from the upper Huronian (Animikie group) and rests upon its eroded edges, showing that the older series was deposited, indurated, and eroded after having been formed before Keweenawan time. However, the depth of erosion between the two is best shown on the south shore of Lake Superior, where, in the Penokee-Gogebic district, the differential erosion of the upper Huronian apparently amounts to several thousand feet within a few miles.

UNCONFORMITY AT THE BASE OF THE CAMBRIAN.

All the pre-Cambrian formations are in a more or less tilted position, the dip varying from a few degrees in the newest parts of the Keweenawan to verticality in parts of the Huronian and Archean. The Cambrian, on the other hand, is horizontal or nearly so. Moreover, the Cambrian is nowhere cut by igneous rocks. These relations give evidence that the orogenic movements and igneous intrusions so characteristic of the pre-Cambrian had ceased, and that the conditions had arrived which marked the great Cambrian transgression. The Cambrian rests upon a remarkably uniform pre-Cambrian peneplain, which is known to extend far to the north and south of the Lake Superior region. The unconformity at the base of the Cambrian is evidently one of the great breaks in the geologic column.

A possible exception to the above general statements may exist in the relations of the Cambrian and upper sandstone beds of the Keweenawan. From the bottom to the top of the Keweenawan there is progressively less tilting. The structural discordance between the Cambrian and the middle and lower Keweenawan is therefore much more conspicuous than that between the Cambrian and upper Keweenawan, which are perhaps conformable. The significance of this local conformity is discussed on pages 415–416.

DEFORMATION AND METAMORPHISM.

GENERAL CONDITIONS.

From the preceding section on unconformities it is evident that during or after the formation of each of the pre-Cambrian series, or both, there was a time of orogenic movement which produced folding, faulting, and metamorphism. Of the several periods of deformation, three stand out conspicuously—that at the close of the Archean throughout the region, that at the close of the lower-middle Huronian, mainly on the north shore, and that at the close of the Keweenawan on the south shore. As a result of these successive deformations the Lake Superior region is essentially an asymmetric synclinorium with nearly east-west axis.

The amount of deformation in each series is partly a function of the age of the series, as after its formation each series was subjected to all the movements which followed. One would expect the complexity of structure to be the greatest in the Archean and least in the Keweenawan, and such are the facts. But it does not follow that each series has a characteristic degree of deformation and metamorphism corresponding to its position in the geologic column. The difference in deformation of different parts of the Huronian series may be nearly as great as the difference between the deformation of the Archean and that of the Keweenawan.

The Lake Superior region exhibits every variety of folding, from the most intricate plication of the Archean and lower Huronian to the broadest open folding of the upper Keweenawan. The major structure of the region is unquestionably controlled by folding rather than by fracture deformation, but the latter is not unimportant. Every district which has been considered in detail shows faults of greater or less magnitude and exhibits innumerable joint fractures. For the most part these faults are comparatively small and do not greatly modify the general distribution of the formations, although many produce considerable displacements which are important in the detailed geology of the districts. Exceptions to the above statement are to be made in reference to the great faults of the Keweenawan, of which one runs through the center of Keweenaw Point and another extends along the northern part of northern Wisconsin and is believed to be continuous between Isle Royal and the mainland of Minnesota. These faults result in the repetition of the Keweenawan rocks and give them a wider present distribution.

The competent strata controlling the deformation of the pre-Cambrian rocks of this region, whether by folding or by faulting, have been the quartzites and the plutonic rocks, especially the granites. These rocks show on the whole more simple folding and faulting than the softer beds associated with them. The slate formations especially have accommodated themselves to this control by close folding and development of cleavage. For instance, in the Marquette district the Archean and the overlying quartzites are folded into a broad composite syncline with considerable faulting. The intervening and overlying slates, on the other hand, appear in close folds, characteristic of incompetent strata. Their deformation has been obviously controlled by the readjustments between them and the quartzites. It may be assumed that, so far as the competent quartzite is concerned, the development of the Marquette syncline has required movement of the upper beds upward and outward from the syncline as compared with the lower beds, as indicated by arrows in figure 35 (p. 253). The major readjustment has resulted in the overthrust or drag folds in the slate. This is the essential explanation of the abnormal fan-shaped folding of the Marquette district. Similar drag folds in the soft layers between the competent strata may be found in almost any part of the Lake Superior region where competent and incompetent layers have been folded together.

In connection with the folding, faulting, and intrusions there have developed slaty, schistose, and part of the gneissose structures. All these structures are common in the Archean and are widespread in the lower and middle Huronian. In the upper Huronian slatiness occurs rather extensively and schistosity is common where the rocks have been intruded by granite, as in northern Minnesota and Florence County, Wis. The Keweenawan does not exhibit any of these secondary structures.

These structures are all characteristic of the zone of flowage, in which the alterations are anamorphic. During their formation all the phenomena of granulation and crystallization of the individual mineral constituents are exhibited in very diverse rocks and in widely varying degrees, from moderate changes to complete recrystallization. Where the rocks have been under deep-seated conditions and these secondary structures are not found the changes may be moderate, but on the other hand they may be extreme.

In connection with the faults, joints, and other fractures all the alterations of the zone of katamorphism have taken place. These are perhaps best illustrated in the Keweenawan series.

In general in the zone of observation more or less extensive katamorphic changes are superimposed upon the anamorphic changes above mentioned, for the once deep-seated rocks, now near the surface, have long been in the zone of fracture, where the changes are katamorphic. It thus appears that various combinations of the alterations of the zones of anamorphism and katamorphism are exhibited by the same rocks.

PRINCIPAL ELEMENTS OF STRUCTURE.

The major axes of the orogenic movements in this region have been in general parallel to Lake Superior, producing a synclinorium. But the eastern and western parts of Lake Superior show a difference in trend, the dividing north-south line being at about 88° longitude, which cuts Keweenaw Point a few miles west of its end. West of this line the trend of the axis of the lake is about 30° north of east. East of it the trend of the axis is south of east. To these trends the strike of the rocks corresponds almost exactly for the west half of Lake Superior and approximately for the east half. The average strike for the region is nearly east and west. This prevailing structure is represented in the Lake Superior trough itself, in the Mesabi and Animikie monocline, in the repeated folds of the Cuyuna, Iron River, Crystal Falls, and Florence districts, in the Gogebic monocline, and in the Marquette, Menominee, Felch Mountain, Calumet, and Sturgeon synclinoria.

The strikes of the Lake Superior rocks are in accord with those in the greater part of the pre-Cambrian shield to the northwest, north, and northeast, even as far north as the Hudson Bay region.

Locally the strikes vary greatly from the general directions indicated, and they may be even north and south, as is conspicuously illustrated in the Republic trough and the Archean oval of the Fence River area in the Crystal Falls district. The local variations in strike and dip are partly explained by original configuration of the basement rocks. They are more largely explained by the cross folding of the region. The axis of one great cross fold runs north and south through Keweenaw Point and the eastern part of the Crystal Falls district. Another crosses the Marquette district in a north-south direction in the vicinity of Ishpeming. Others cross the Mesabi district from northeast to southwest.

The intrusive rocks are also important factors in producing the variations of the strike of the folds from the major Lake Superior structure. Very commonly the strikes of the strata about massive laccoliths, bosses, or batholiths are much influenced by the igneous rocks, there being a marked tendency for the strikes to be peripheral or tangential to the intrusives. This relation is illustrated in all the districts in which the intrusive rocks occur in large masses, but is best exemplified in the region northwest of Lake Superior. Here the intrusive masses are so large as to be the most important factor in the control of the local strikes and dips, although even here there is an unquestioned tendency for the general east-west strike of the region to maintain itself.

The cross sections A–A and B–B on the general map (Pl. I, in pocket) give the best conception of the dips of the formations. It will be noted that the Archean, lower Huronian, and middle Huronian beds have steep dips in northerly or southerly directions, that the upper Huronian beds are as a whole less steeply inclined and have in part a definite relation to the synclinal structure of the Lake Superior region, and that the Keweenawan beds are still less steeply inclined and are entirely in accord with the synclinal structure of the basin. All this deformation was complete before Cambrian time except the faulting. There is no evidence that the faulting was not much later than the Cambrian—possibly post-Cretaceous.

THE LAKE SUPERIOR BASIN.

The structure of the Lake Superior basin is well shown by the cross sections on the general map (Pl. I, in pocket). The basin is essentially an east-west asymmetric synclinorium with steeper dips on the south than on the north side, shown principally in the Keweenawan and upper Huronian rocks bordering the lake.

The upper Huronian of the Penokee district dips north, toward Lake Superior, at a steep angle, varying considerably but for the most part between 55° and 80°. The upper Huronian of the north shore in the Mesabi and the Animikie districts dips south, toward Lake Superior, at comparatively flat angles, ranging from substantial horizontality up to 45°, the more common dips being between 8° and 20°.

The folding of the Keweenawan has a very close relation to the Lake Superior trough. On the south shore of Lake Superior the Keeweenawan rocks dip northwest, toward the lake, at angles varying from as high as 80° in the lower part of the series to extremely flat angles in the upper part of the series. On the north shore of Lake Superior and on Isle Royal they dip at moderate angles to the southeast, toward Lake Superior. Thus the Keweenawan at Keweenaw Point and its extension to the southwest and the Keweenawan of the north shore constitute a clearly marked synclinal trough which extends inland in Michigan, Wisconsin, and Minnesota. The axis of this syncline lies about halfway between Isle Royal and Keweenaw Point. It does not run to the head of the lake, but to the head of Chequamegon Bay and thence far inland to the southwest. Here it carries minor folds.

To the southeast of the synclinorium in Michigan there is one great fault, and probably two. To the northwest of it in Wisconsin there is another great fault, and this fault, or another, is supposed to continue between Isle Royal and Thunder Bay. The Keweenawan rocks nearest the axis of the syncline are on the upthrow sides, and the "eastern" and "western" sandstones southeast and northwest of the synclinorium, respectively, are on the downthrow sides of the faults. Consequently the Keweenawan of northern Wisconsin and Isle Royal is probably repeated, at least in part, on the Minnesota coast, and below the rocks thus repeated the Minnesota Keweenawan extends down to the base of the series. Similarly a part of the Keweenawan rocks of Keweenaw Point are probably repeated in the "South Range."

At Michipicoten the dips are to the south. On the east shore of Lake Superior the Keweenawan dips westward toward the lake. Some thrusting and buckling have accompanied the faulting along the north side of the synclinorial axis in Wisconsin.

Wherever there is a thick succession of Keweenawan rocks the dips are steeper at the base and grow flatter at the top. This is best illustrated by Keweenaw Point, Isle Royal, and Michipicoten. Elsewhere the changes of dip are not so great. This general lessening of the dip of the Keweenawan in passing from lower to higher horizons is regarded as evidence that the folding of the series which caused the Lake Superior basin took place largely during Keweenawan time.

The development of the Lake Superior basin in Keweenawan time has tended to give parallelism of strike to all the rocks of the region but is not regarded as sufficient to explain the remarkable parallelism actually observed in older rocks. The trend of the axial lines of the

Lake Superior syncline is in accord with that of the folds through a large part of the pre-Cambrian shield of Canada. It is doubtful if the Keweenawan folding ever affected a large part of this shield. Much of the folding is unquestionably earlier. Therefore it is reasonable to assume that the dominant trend in the Lake Superior folds, as well as in the pre-Cambrian of Canada, was probably established before Keweenawan time.

Bordering the main Lake Superior basin are minor synclinal folds of the Marquette, Felch Mountain, Calumet, Menominee, and Mesabi-Cuyuna districts, with axes nearly parallel to the longer axis of the Lake Superior basin. These districts present evidence that they were folded to their present attitude in considerable part at the same time as the main Lake Superior basin; that is, in Keweenawan time. Another fact seems to relate them even more closely to the Lake Superior basin of Keweenawan age. The minor synclinoria are asymmetric and tend to have their steeper sides toward the lake. This may be observed in the Marquette, Felch Mountain, and Calumet districts, principally in the upper Huronian rocks. The upper Huronian of the north shore has a gentle southward dip along the Mesabi, Gunflint, and Animikie ranges, which changes to steeper dips near the axis of the basin in the Cuyuna district. The Vermilion district shows evidence of a similar structure in the Keewatin schists. The normal development of a great syncline of the Lake Superior type would be accompanied by a differential slipping between the competent layers, whereby the upper layers would move up and away from the syncline as compared with the lower layers, just as has been already described for the Marquette district. So far as there is failure of the beds taking part in this movement, it is likely to be influenced by this differential movement and to result in minor folds with steeper sides toward the axis. It is believed that the accordance of structure of the districts mentioned with the requirements of this general principle is more likely to be a natural and necessary sequence than a coincidence. It may be noted that the displacement of the beds in this type of folding has nearly the same direction as the displacement along the main fault lines already mentioned.

The departures from this control of minor folds by the Keweenawan fold of the Lake Superior basin are due to original configuration of basement, to plutonic intrusive rocks, or to cross folding.

The asymmetric character of the Lake Superior basin itself may have interesting significance as to the general orogeny of the region. If, as suggested in the following pages, the Lake Superior basin has been essentially the locus of a shore zone against the continental area to the north, then the gentle southward slope of the north limb of the Lake Superior syncline is away from the old shore line and the steeper dip of the south limb of the syncline faces the shore, as if there had been a thrust from the south toward the continental area to the north.

The extrusions of the volcanic rocks along the borders of the lake on an extensive scale of themselves gave opportunity for subsidence elsewhere. It may be that the depression of the center of the Lake Superior basin was a correlative of the outflows of lava along the border, the two together and the inciting or attendant epeirogenic and orogenic movements lowering the center of gravity of the Lake Superior masses. This movement of subsidence for the basin would be assisted by the deposition of lava beds and of sediments within the basin, although these are regarded as accessory rather than as prime factors in the development of the basin.

RÉSUMÉ OF HISTORY.

This monograph may close with a brief résumé of the great events of the pre-Cambrian period in the Lake Superior region. Early in the history of the earth, when the Lake Superior region was at least in part below the sea, there were great outbreaks of volcanic rocks, which continued for an indefinite time and as a result of which the Keewatin was mainly built up. Subordinate masses of sediment—conglomerate, slate, and iron-bearing rocks—were laid down, especially late in Archean time. The beginning of the Keewatin period we can not even dimly see, for we do not recognize the basement on which the Keewatin rests. Later, or contemporaneously at least with the later stages of the vast regional extrusions, which, as has been explained, were of a magnitude never subsequently approached, was the intrusion of enormous masses of acidic rocks, including great batholiths, bosses, stocks, and dikes. These rocks constitute the Laurentian series. For some unknown reason the extrusive rocks of the Keewatin were dominantly of the basic and intermediate types, and the Laurentian intrusive rocks dominantly of the acidic type, although all these types occur both as extrusives and intrusives.

In Archean time the Keewatin rocks were greatly deformed and extensively metamorphosed, largely under the influence of the Laurentian intrusions. It is extremely probable that during Archean time at many places the land was raised above the sea by the upbuilding of the lavas, the intrusion of the batholiths, and the folding. But the Keewatin rocks now observable are largely submarine, and contemporaneous sediments known to result from erosion are rare or lacking.

Finally there came a time when a general epeirogenic movement, perhaps in connection with the orogenic movements and intrusions, raised the entire Lake Superior region above the sea. This gave the conditions for deep denudation which removed a great but unknown thickness of the Archean rocks, exposing the schistose Keewatin rocks and the coarse, massive textures of the Laurentian batholiths.

The lower Huronian sea then advanced over the region from the south, extending at least as far north as the present south shore of Lake Superior. Under the water of the advancing sea the lower Huronian sediments were laid down. These are of a normal subaqueous type, consisting, first, of a psephite, followed by a psammite, next a pelite, in places carbonaceous, and finally a limestone. The character of these sediments proves beyond question that at the time of their deposition the conditions had become similar to those which prevail to-day, both as to the agents concerned in erosion and as to those concerned in deposition.

The deposition of the lower Huronian was followed by an uplift and recession of the sea. The area of the southern Huronian subprovince and perhaps also that of the northern subprovince were gently folded. Erosion locally cut through the lower Huronian of the Marquette district, but in most of the southern subprovince it has not gone through the Randville dolomite. The next period of deposition was that of the middle Huronian, evidence of which is found only in the southern Huronian subprovince. The middle Huronian here consisted of subaqueous sediments—psephites, psammites pelites, and a nonclastic iron-bearing formation—indicating that the sea had again advanced.

It is believed that during lower and middle Huronian time the sea did not advance over the area north of the present Lake Superior, that this was a land area, and that the great rivers flowed to the south into the Huronian sea. On this northern highland were deposited an extensive and peculiar slate conglomerate and little-assorted graywackes, slates, and conglomerate, which in their general characteristics and associations are taken to be subaerial and delta deposits.

After middle Huronian time the northern and southern Huronian subprovinces were raised above the sea, folded, and eroded. The northern subprovince was much more affected at this time than the southern subprovince. The advance of the upper Huronian sea from the south across the area brought about the deposition of upper Huronian sediments upon a remarkably plane surface, with elevated areas that were perhaps not covered in several places in northern Wisconsin and south of the Marquette district of Michigan. To what extent this surface was one of previous base-leveling by subaerial erosion and to what extent by marine planation is not known. The fresh surface of contact, the manner in which the plane truncates hard and soft rocks, the lack of residual soils or sediments, and the thinness, evenness, and wide area of the fragmental base of the upper Huronian seem to favor the view that the surface may have been finally cleared by marine scouring, whatever the extent of earlier erosion. In the southern Huronian subprovince the rocks had not been previously folded as much as in the northern subprovince, in consequence of which erosion and planation accomplished less conspicuous, or less easily identified results, though erosion seems to have removed nearly all of the middle Huronian in the Menominee district. The upper Huronian was thus laid down, with conspicuous unconformity in the northern part of the region, because of the folding of earlier rocks, and with far less discordance in the southern part of the southern Huronian subprovince, where the earlier rocks had not been so much folded.

The shore deposits of the advancing upper Huronian sea were thin psephites, which were followed by psammites or pelites, and these very extensively by an iron-bearing formation, locally alternating with pelites. This is the formation containing the great deposits of Lake Superior ores, in the Mesabi, Penokee, Menominee, Cuyuna, and other districts. The deposition of the iron-bearing rocks to a thickness of nearly a thousand feet, with so little fragmental sediment, is not duplicated elsewhere in the geologic record and seems to require some unusual condition. The explanation is believed to lie in the great basic extrusions both preceding and accompanying the upper Huronian deposition, furnishing an unusual source of materials for the iron-bearing formation. (See pp. 513 et seq.)

The alternations of iron-bearing formation and pelite were followed by a very thick pelite, the greatest of the Huronian formations. The conditions allowing this unusual accumulation of mud may have been those of delta deposition. The sea seems not to have advanced much farther north than the Lake Superior region, and it is conjectured that when the advance stopped, the rivers were able to make headway against the sea and build up great delta and mud deposits over the previously deposited iron-formation sediments. The character of these deposits is perhaps related to volcanism. The existence of abundant discontinuous pyritiferous and graphitic lenses in the slate, associated with lenses of iron carbonate, seems to be evidence of lagoon conditions accompanying delta deposition. As in most deltas, a considerable part of the deposits may be regarded as terrestrial.

At the close of upper Huronian time the land was raised or built above the surface by delta deposition and the upper Huronian beds were very gently folded and deeply eroded, the differential erosion amounting apparently to thousands of feet. Then followed the events of Keweenawan time, which were first those of terrestrial deposition, associated with enormous extrusions of igneous rock, merging later into conditions of subaqueous deposition in the Lake Superior syncline.

During the time the Keweenawan series was being built up the Lake Superior basin was formed, resulting in marked diminution of dip in passing from lower to upper Keweenawan. The folding of the lower Keweenawan and middle Keweenawan rocks which produced this basin deformed also the adjacent rocks, especially the upper Huronian of the west half of the basin, so that they share in the synclinorial structure. The antecedent movements were probably along axes parallel to that of the Lake Superior syncline, but the present marked parallelism of axes of folds in all of the pre-Cambrian is probably due largely to Keweenawan folding.

At the end of the Keweenawan period the land was raised for the fourth time above the sea and the long-continued denudation preceding the Cambrian period took place, developing a peneplain that is even yet largely preserved. The Cambrian transgression began far to the south and finally overrode the entire Lake Superior region. The floor for the Cambrian deposition was composed of tilted rocks with the exception of the upper Keweenawan sandstone. The structural and lithologic accordance of the Cambrian with the upper Keweenawan beds raises the question whether the deposition of the upper Keweenawan sediments in the Lake Superior basin did not continue until the Cambrian sea reached them and gradually merged into Cambrian deposition. The Cambrian was succeeded by the later Paleozoic deposits.

After Paleozoic time the region was again raised above the sea and eroded. Since then there have been many episodes of uplift, subsidence, and warping. At one time the Cretaceous sea covered the western part of the region. Erosion has removed all but small patches of the Cambrian from the uplands, and reexhumed and modified the pre-Cambrian topography. Faults developed in post-Cambrian and perhaps in post-Cretaceous time.

It thus appears that in the Lake Superior region, from the earliest time to the Cambrian, there were five great periods of rock formation separated and followed by periods of epeirogenic movement, orogenic movement, and erosion, each of these intervals being marked by an unconformity. The first of these unconformities, that at the top of the Archean, is the most conspicuous, represents a strong lithologic contrast, and has been by all geologists taken as an essential datum plane in mapping and working out the geologic history. The unconformities separating the divisions of the Huronian and the Huronian from the Keweenawan are of differing value, but all represent important structural and time breaks. The unconformity at the base of the Cambrian is one of the first magnitude and is coextensive with the great unconformity at this horizon outside of the Lake Superior region.

Of the five periods of deformation, three stand out conspicuously—that at the close of the Archean throughout the region, that at the close of the lower-middle Huronian principally on the north shore, and that at the close of the Keweenawan principally along the axis of the Lake Superior basin and on the south shore. These areas of folding had been shore zones of heavy Huronian and Keweenawan deposition. As is common, the shore zone was a place of recurrent upheaval and subsidence, marked orogenic movement, igneous activity, and sedimentation. To these many causes combined is due the complexity of the geology of the region.

These shore conditions may bear some relation to the fact that part of the Lake Superior region south of the international boundary is one of the great iron-producing areas of the world. It has been a source of surprise to many that the adjacent Canadian region, in which the geology seems to be in a general way similar, has not been found to bear iron ore in anything like the abundance of the States to the south. But by far the larger part of the iron-ore deposits in the States occur in the middle Huronian and dominantly in the upper Huronian formations. The middle Huronian is known in a general belt fringing the main pre-Cambrian area of Canada along the north shore of Lake Superior and extending northeastward through Lake Timiskaming. It may exist also farther north in the interior of the Canadian pre-Cambrian, but, to judge principally from the facts observed on the north shore of Lake Superior, the interior pre-Cambrian region of Canada was probably above the sea during middle and upper Huronian and Keweenawan time and only continental deposits were formed in it. The upper Huronian, the principal iron producer, is but scantily represented along the southern margin of the Canadian pre-Cambrian. The only iron-bearing formation which has an extensive occurrence in the great pre-Cambrian shield of Canada is that of the Keewatin series. The Keewatin iron-bearing formation has not been largely productive. If the apparent scarcity of middle and upper Huronian rocks over this area is a real one, which is not yet finally proved, it can not be expected that in the central highlands of Canada will be found iron-bearing formations that are to be paralleled with those of the middle and upper Huronian south of Lake Superior.

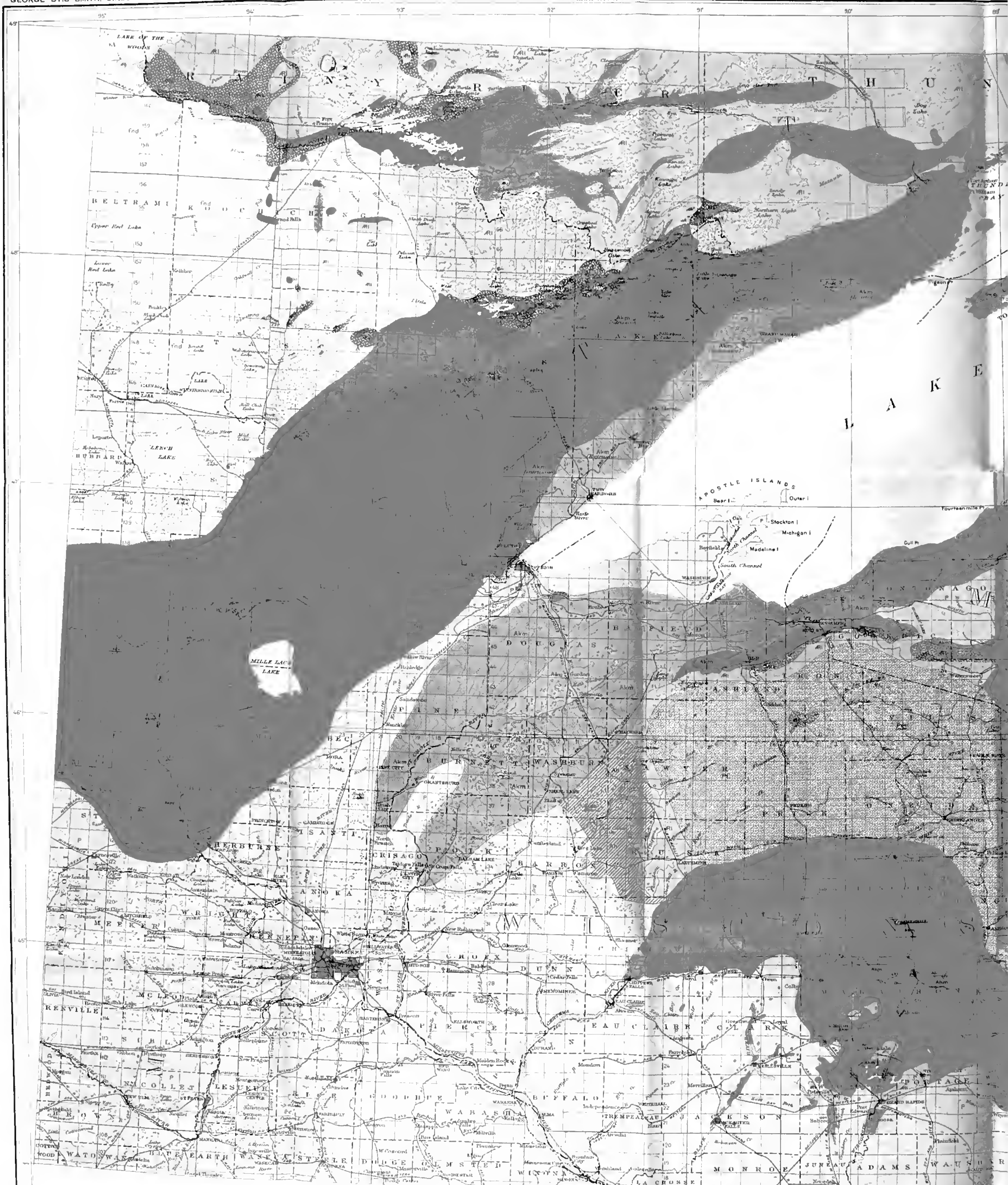
But it may be that in Huronian time the central highland area had a shore zone to the north as well as to the south. The occurrence of probable late Algonkian sediments on the east coast of Hudson Bay and in the Copper Mine region, on the west side of the bay, give color to this suggestion. The Hudson Bay region seems, from available facts, to be another geosyncline of sedimentation and folding corresponding somewhat to that of the Lake Superior and Lake Huron regions. An iron-bearing formation, remarkably similar to the Animikie, is here known.[a] If this hypothesis proves to be true, this northern region warrants careful exploration for mineral wealth.

Attention has been called on pages 591–592 to the possible genetic association of the Lake Superior copper ores with the Georgian Bay copper ores, Silver Islet silver ores, Sudbury nickel ores, and Cobalt silver-cobalt ores. This suggests an hypothesis as a reasonable basis for further geologic work. Huronian and Keweenawan rocks seem to be more abundantly present in the Lake Superior, Georgian Bay, and Timiskaming areas than farther to the north. They have been folded along parallel axes in all of these districts. Volcanism has been an important accompaniment of this deformation. Earlier volcanism has been associated with the deposition of unique iron-bearing formations owing their wide distribution to the agency of sedimentation intervening between their contribution by igneous masses and their final deposition. Later volcanism developed copper, nickel, cobalt, and silver ores, showing some evidence of genetic relationship. The Lake Superior region, then, may be regarded broadly as a part of a great metallographic province containing a variety of ores associated with volcanism, which may be related with folding along an old shore zone.

[a] Leith, C. K., An Algonkian basin in Hudson Bay—a comparison with the Lake Superior basin: Econ. Geology, vol. 5, 1910, pp. 227-246.

INDEX.

U. S. GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

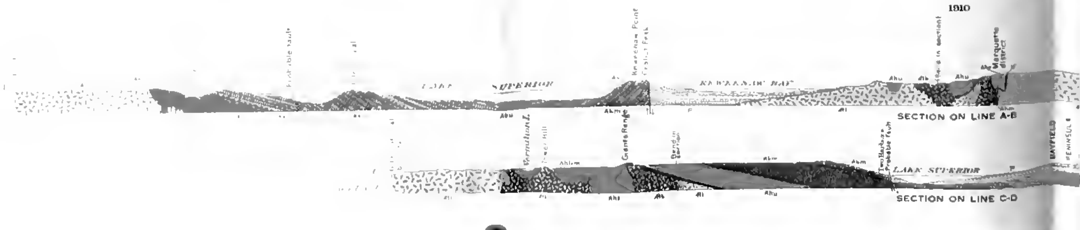


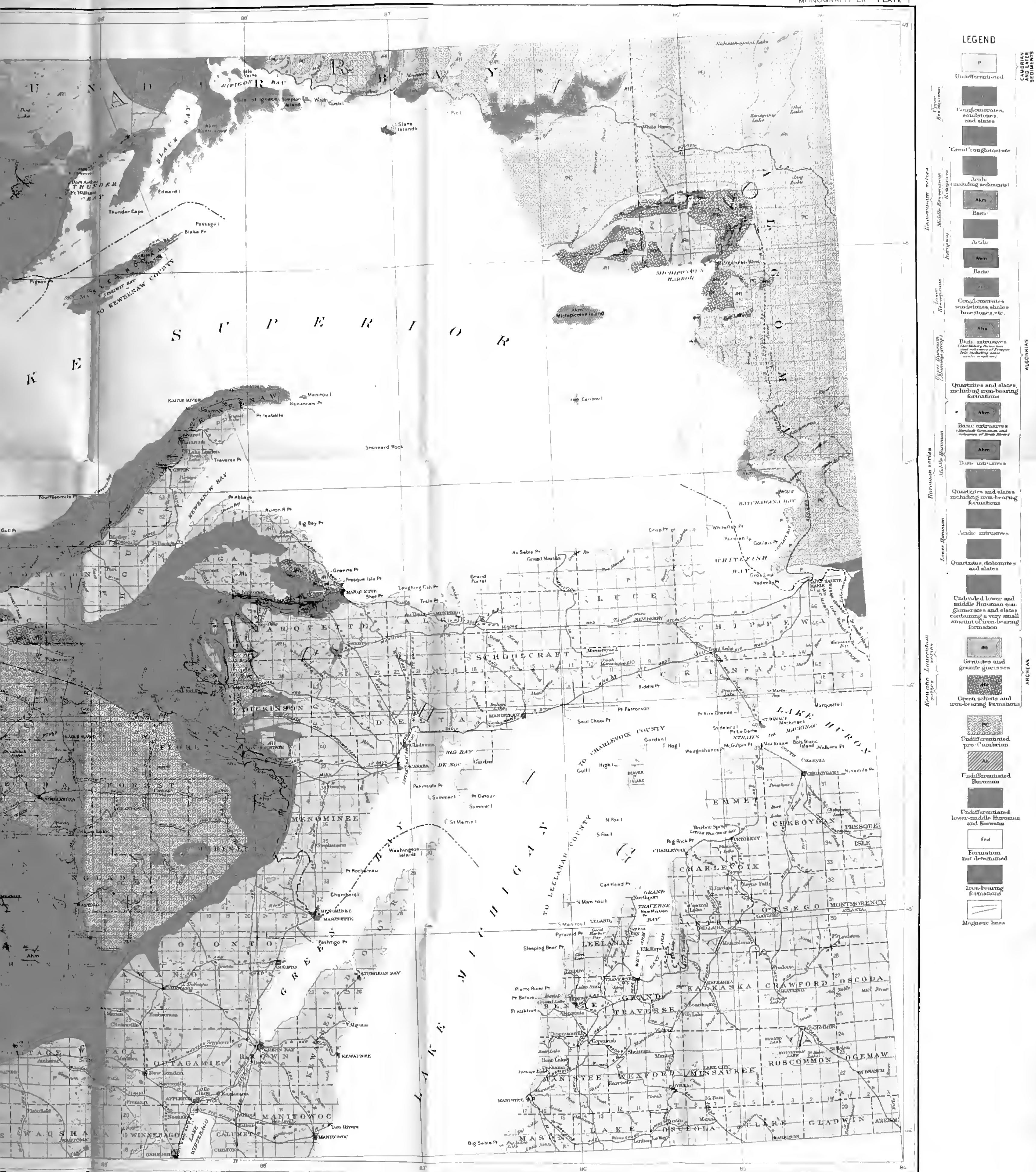
Base compiled by the U. S. Geological Survey from U. S. Geological Survey atlas sheets, Land Office records, compilations by State Geological Surveys, official maps of Canada and other data

GEOLOGIC MAP OF THE LAKE SUPERIOR

Scale 1:000,000

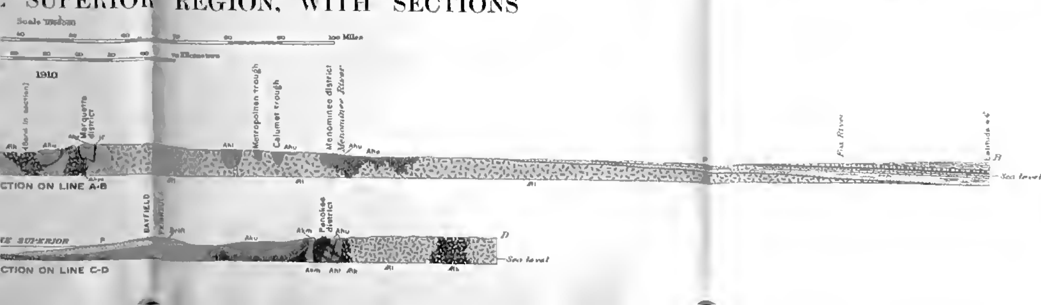
1910



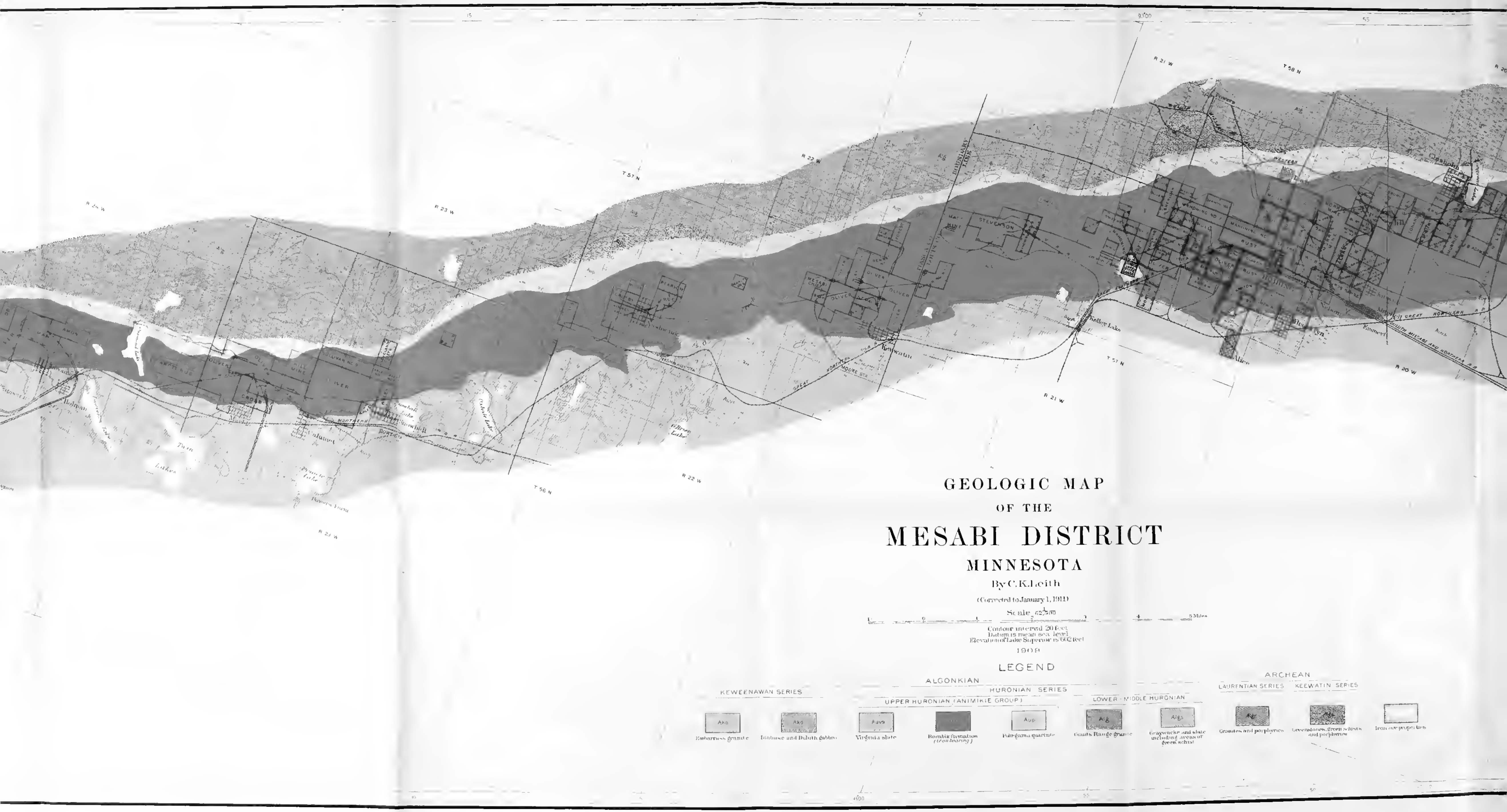


SUPERIOR REGION, WITH SECTIONS

Geology compiled by C. R. Van Hise and C. K. Leith



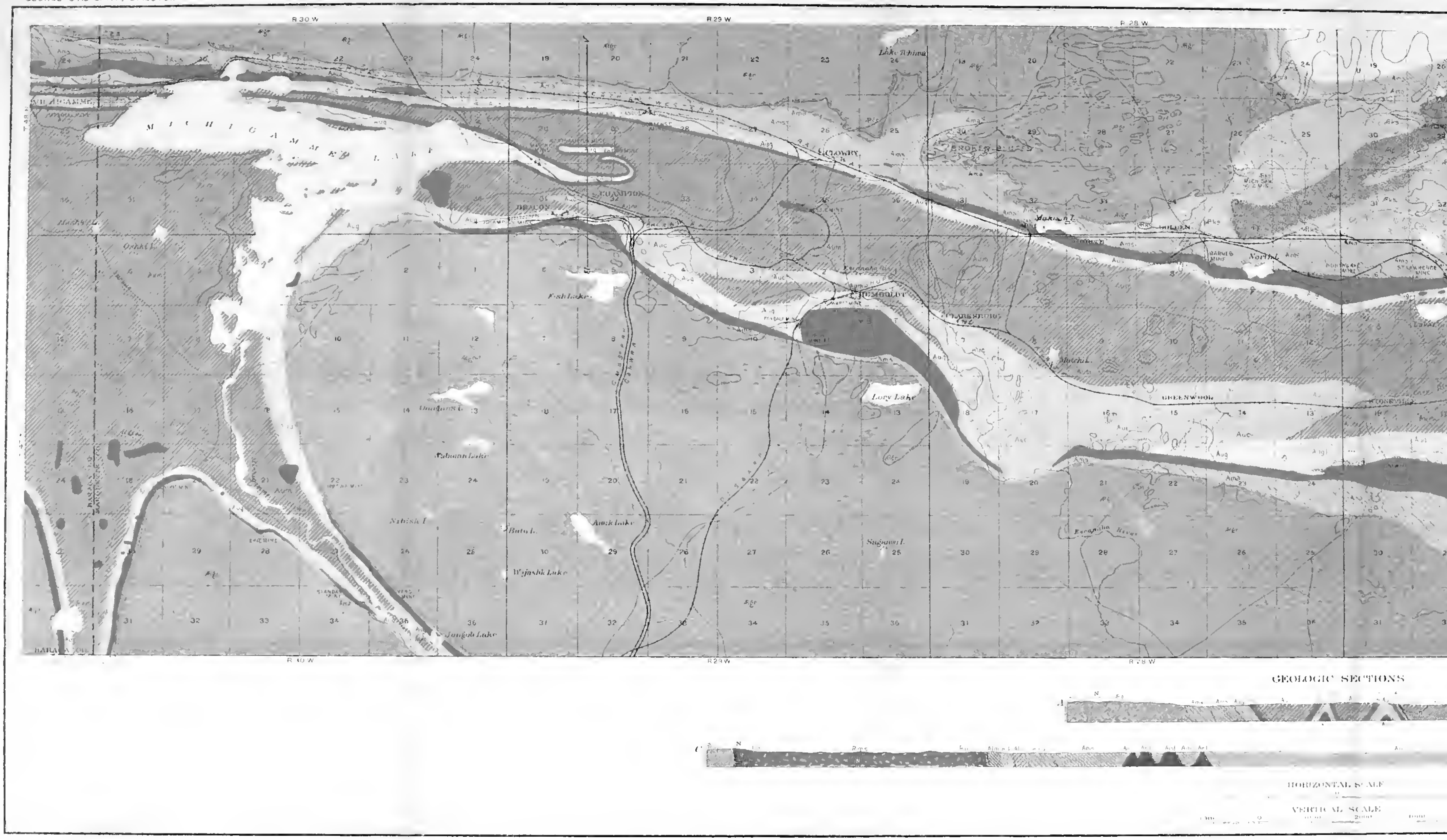
MISSISSIPPI RIVER
POKEGAMA LAKE
Snell Lake
Long Lake
Loon Lake
Rice Lake
Prairie Lake
Trout Lake
Coleraine
Bovey
Bender Pt
Allen Landing
T 56 N
T 55 N
T 54 N
R 27 W
R 26 W
R 25 W
R 24 W


GEOLOGIC MAP
OF THE
MESABI DISTRICT
MINNESOTA
By C.K.Leith
(Corrected to January 1, 1911)
Scale 1/62500
5 Miles
Contour interval 20 feet
Datum is mean sea level
Elevation of Lake Superior is 602 feet
1909
LEGEND
ALGONKIAN
HURONIAN SERIES
KEWEENAWAN SERIES
UPPER HURONIAN (ANIMIKIE GROUP)
LOWER - MIDDLE HURONIAN
ARCHEAN
LAURENTIAN SERIES
KEEWATIN SERIES
Ake
Embarrass granite
Akd
Diabase and Duluth gabbro
Auvs
Virginia slate
Biwabik formation (iron bearing)
Aup
Pokegama quartzite
Alg
Giants Range granite
Algs
Graywacke and slate including areas of green schist
Granites and porphyries
Greenstones, green schists and porphyries
Iron ore properties

Note – Names of mines are as given by mining companies or by the Minnesota Tax Commission. Where the mine has not been specifically named, it appears under the name of the owning company, as for instance, ... It has been the aim to cover the principal ore bearing areas by names and shading, but it was difficult to do this exactly. Probably some ore bearing forties are left out and in some case non-ore bearing forties are included under the shaded area where the block together has been specifically named as a mine.
VIRGINIA
EVELETH
McKINLEY
IRON JCT.
Ely Lake
Saint Mary Lake
Embarrass Lake
Mashkenode Lake
Silver Lake
Wolf
Spina
Kinney
T 59 N
R 17 W
R 18 W
R 16 W
R 20 W
DULUTH MISSABE AND NORTHERN
GREAT NORTHERN


BIRCH LAKE
Iron Lake
T 60 N
R 13 W
R 14 W
T 60 N
R 12 W
R 13 W
T 59 N
R 15 W
R 14 W
92°00'
55
50'
GEOLOGIC SECTIONS
SECTION I
SECTION III
SECTION II
Vertical and horizontal scale
5 Miles

U. S. GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR



GEOLOGIC MAP AND SECTIONS OF THE MARQUETTE IRON-R

Originally prepared by C. R. Van Hise and W. S. Bayley, 1896. Revised to 1910 in
of Cleveland Cliffs Iron Company, Oliver Iron Mining Company, and geologic

1910

LEGEND

QUATERNARY
PLEISTOCENE

Undivided

CAMBRIAN

Upper Cambrian sandstone

Diabase and diorite

ALGONKIAN
HURONIAN SERIES

UPPER HURONIAN (ANIMIKIE GROUP)

Clarksburg formation

Michigamme slate

Bijiki schist

Goodrich quartzite

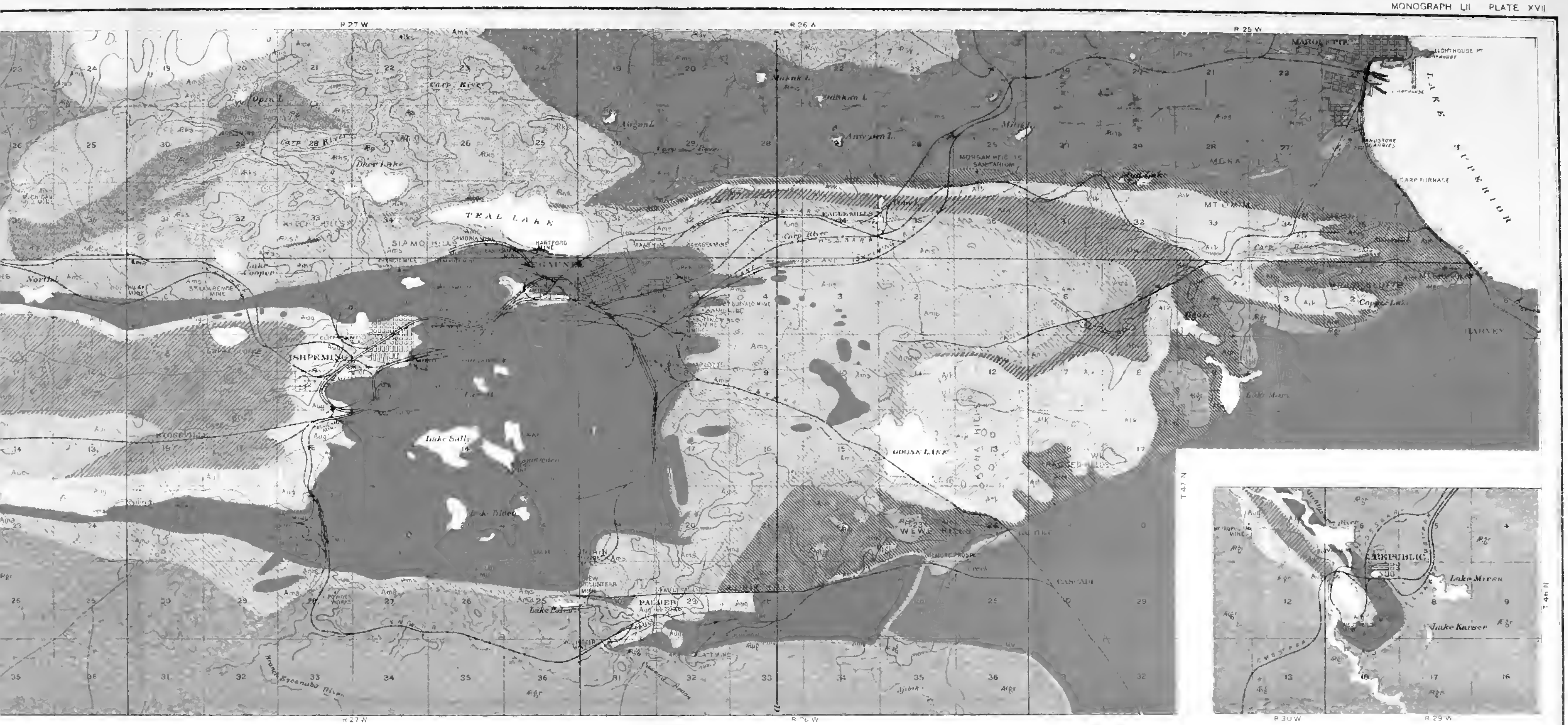
Negaunee formation

MIDDLE HURONIAN

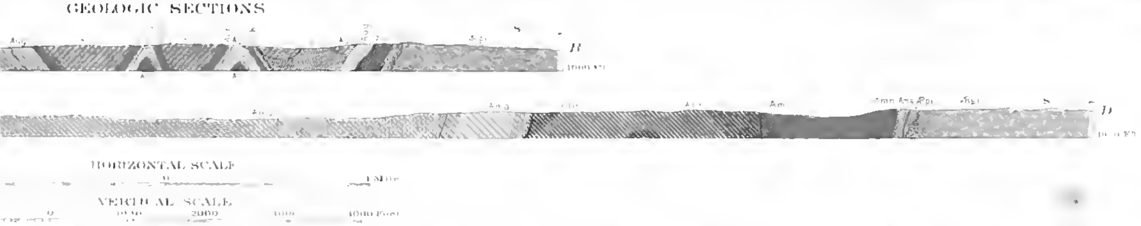
Siamo slate

Ajibik quartzite

Wewe slate



GEOLOGIC SECTIONS



… OF THE MARQUETTE IRON-BEARING DISTRICT, MICHIGAN

…e and W. S. Bayley, 1896. Revised to December 1, 1910 to include explorations … Oliver Iron Mining Company, and geological work of A. E. Seaman and others

Scale $\frac{1}{63360}$

Contour interval 50 feet

1910

LEGEND

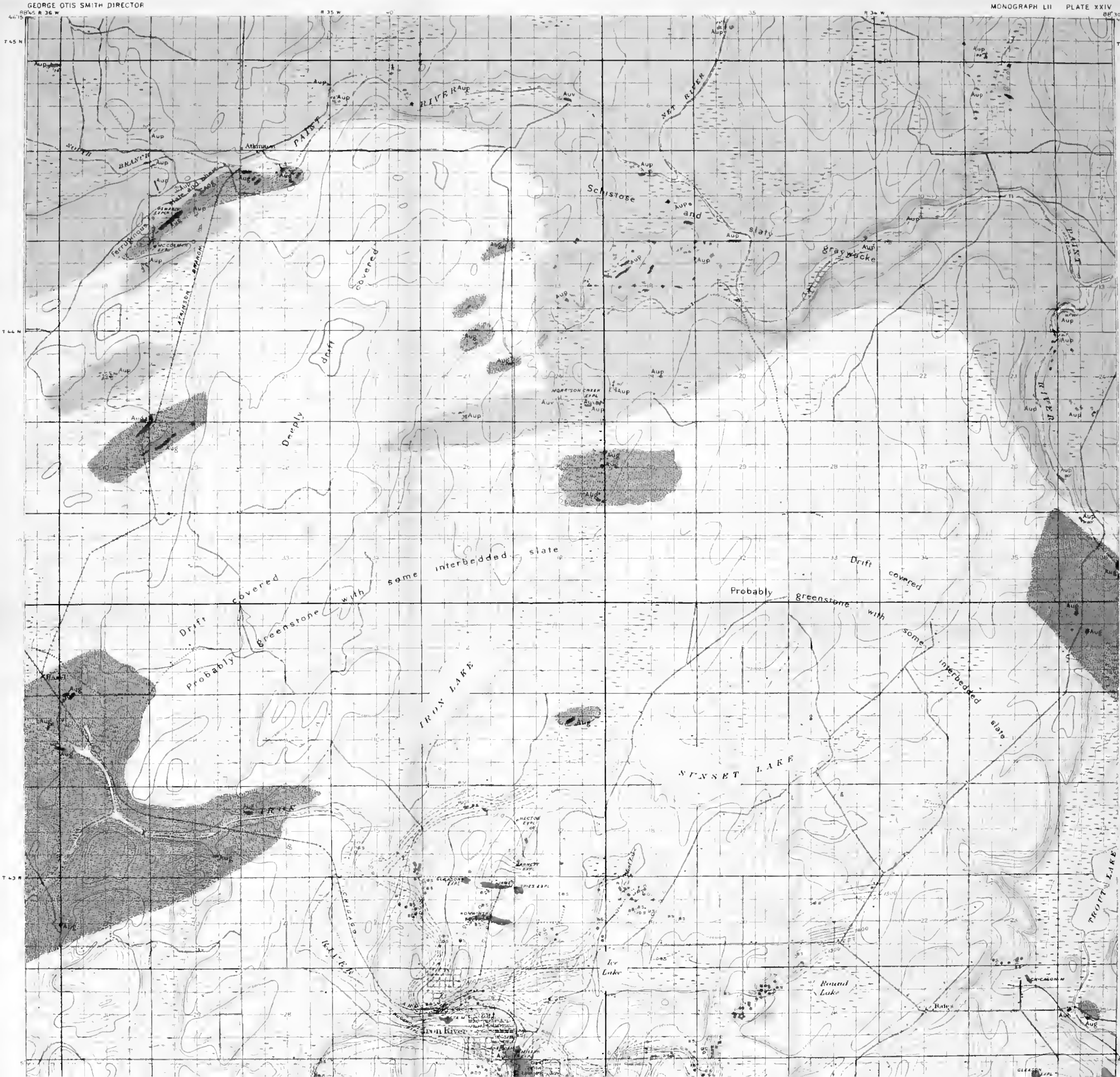
ARCHEAN

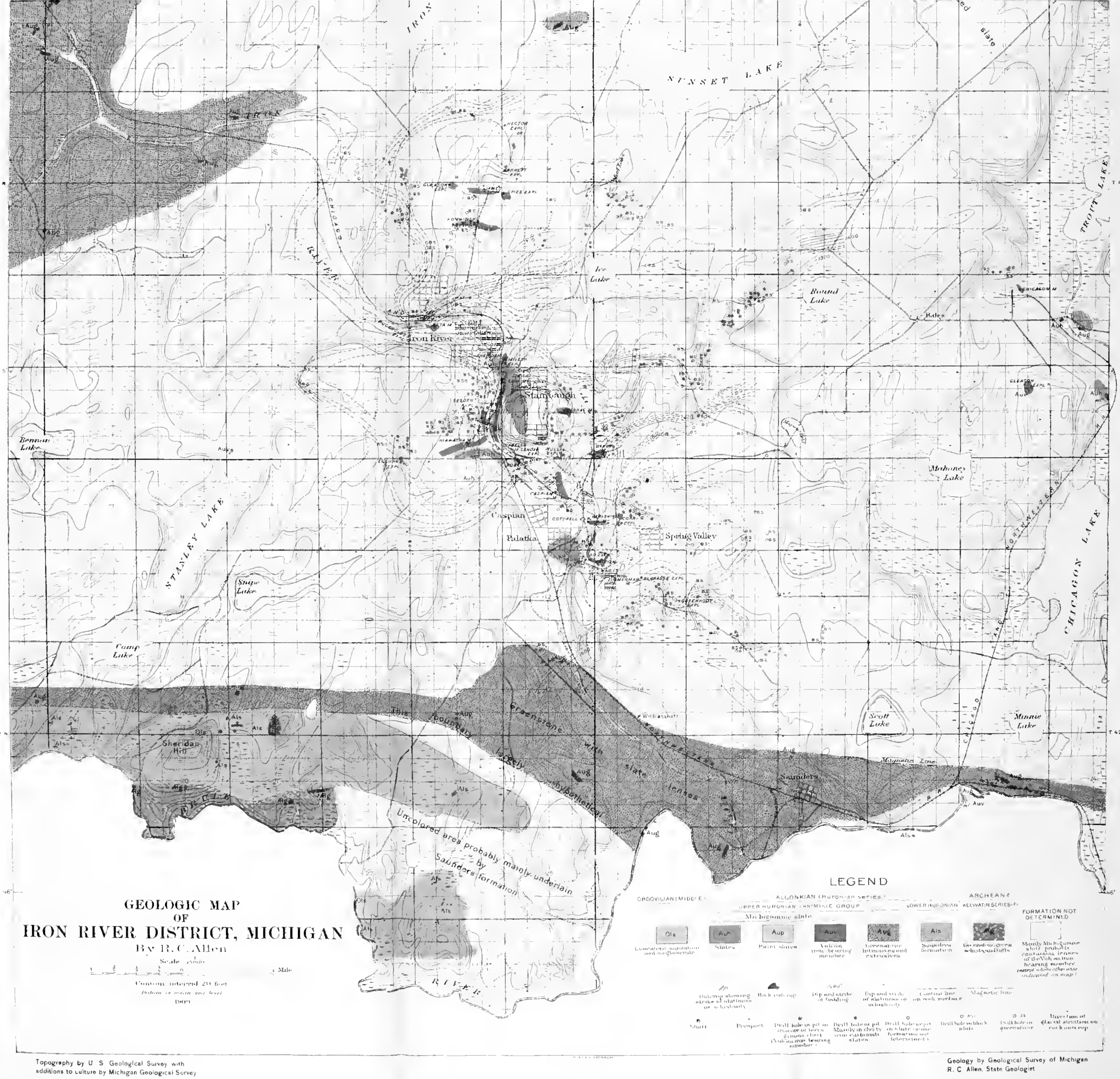
LOWER HURONIAN: Ajibik quartzite; Wewe slate; Kona dolomite; Mesnard quartzite

LAURENTIAN SERIES: Granite; Syenite; Palmer gneiss; Peridotite

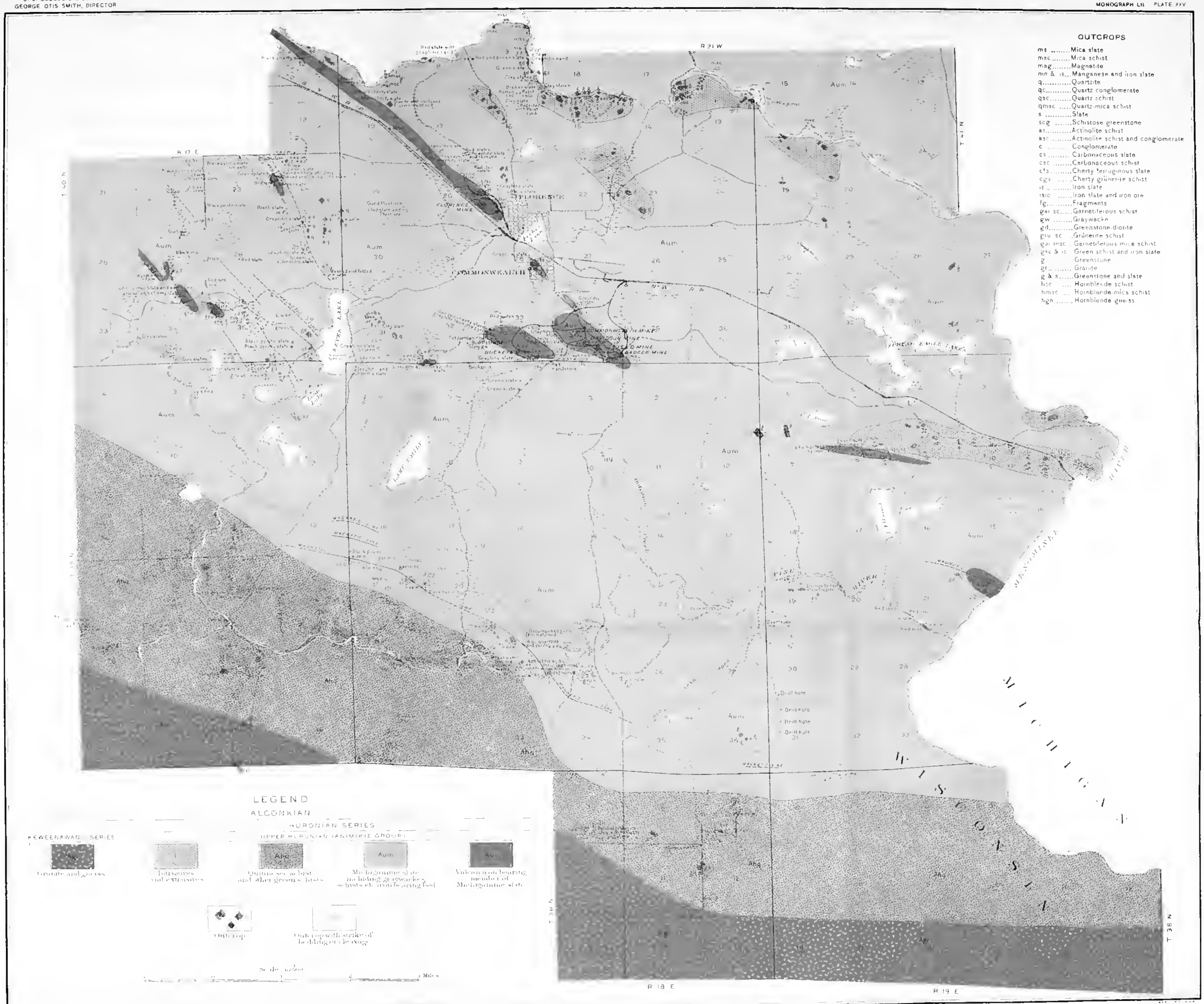
KEEWATIN SERIES: Kitchi schist; Mona schist

UNCLASSIFIED


R 36 W
R 35 W
R 34 W
T 45 N
T 44 N
T 43 N
SOUTH BRANCH
PAINT RIVER
NET RIVER
Atkinson
ATKINSON BRANCH
Ferruginous
Schistose and slaty graywacke
Drift covered
Deeply drift covered
Probably greenstone with some interbedded slate
NORRISON CREEK EXPL
IRON LAKE
SUNSET LAKE
TROUT LAKE
Ice Lake
Round Lake
Bates
Iron River
CHICAGO
IRON RIVER
Aup
Aug
Auv



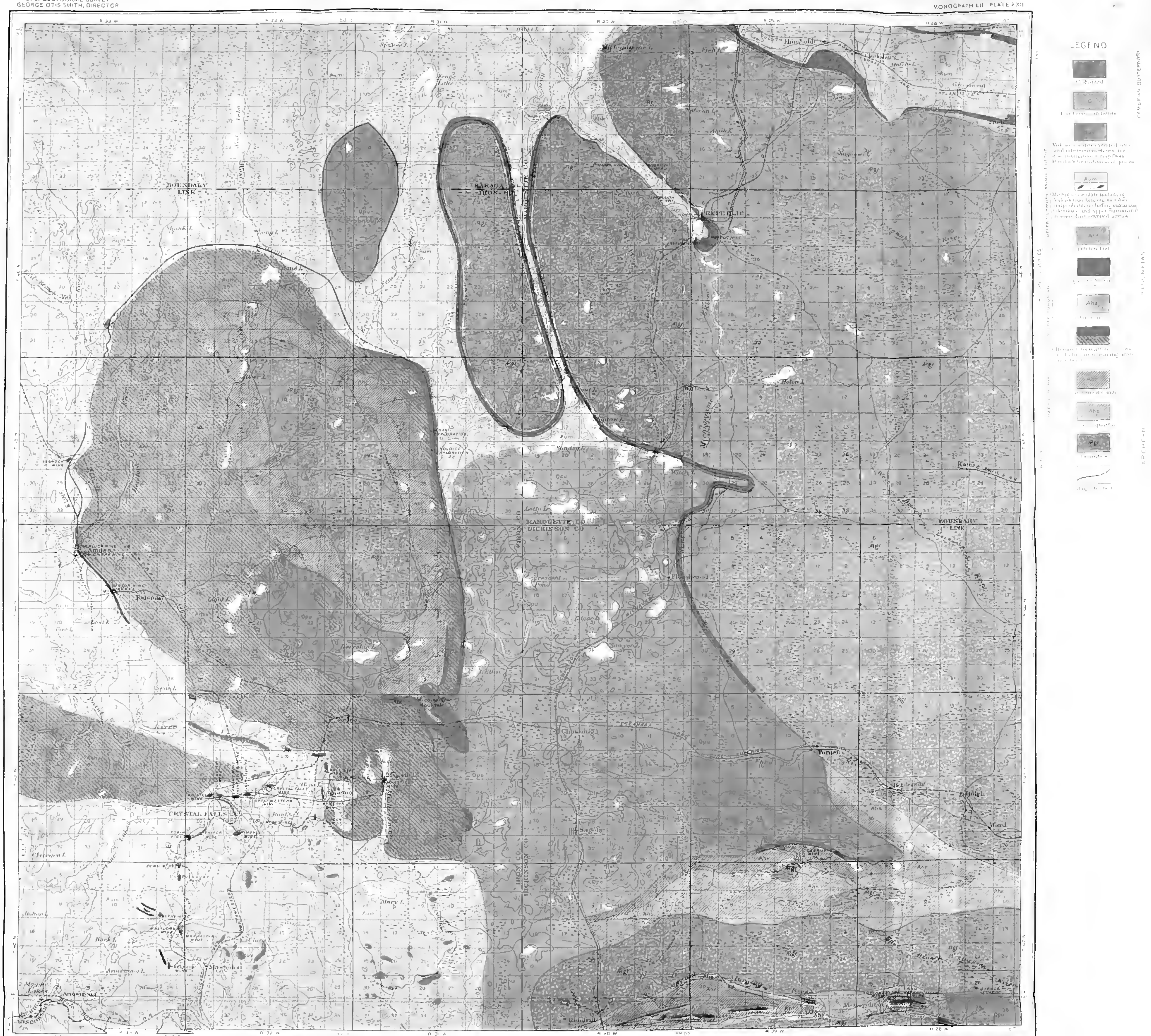
GEOLOGIC MAP
OF
IRON RIVER DISTRICT, MICHIGAN
By R. C. Allen
LEGEND
ORDOVICIAN (MIDDLE)
ALGONKIAN (Huronian series)
UPPER HURONIAN (ANIMIKIE GROUP)
LOWER HURONIAN
ARCHEAN
KEEWATIN SERIES
Michigamme slate
FORMATION NOT DETERMINED
Ols
Auh
Aup
Auv
Aug
Als
Slates
Saunders formation
Topography by U. S. Geological Survey with additions to culture by Michigan Geological Survey
Geology by Geological Survey of Michigan
R. C. Allen, State Geologist



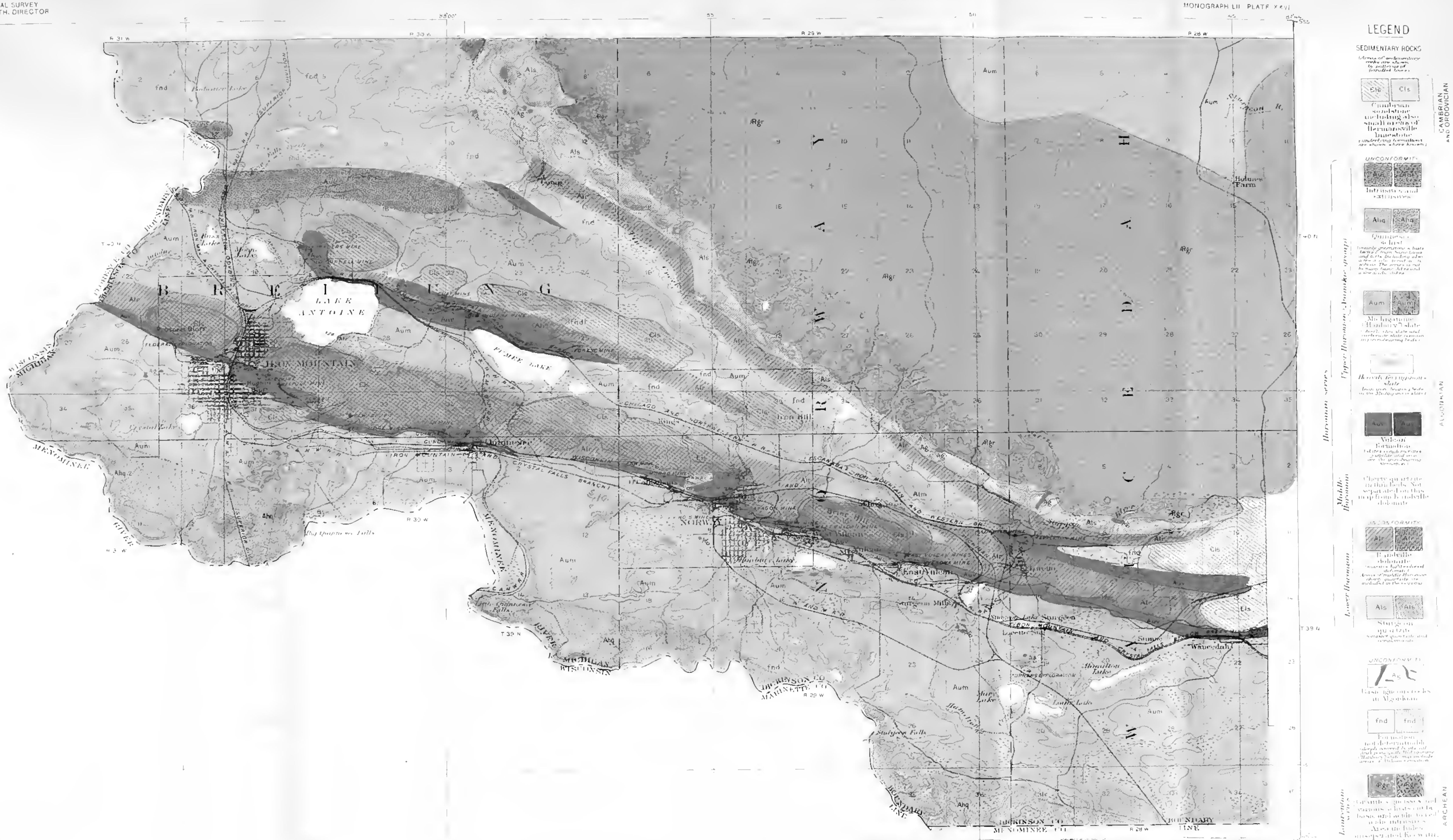
OUTCROP MAP OF THE FLORENCE IRON DISTRICT, WISCONSIN

FROM MAP BY W N MERRIAM 1904, PARTLY REVISED BY W O HOTCHKISS 1910

1910



GEOLOGIC MAP OF THE CRYSTAL FALLS DISTRICT, INCLUDING PARTS OF THE FELCH MOUNTAIN AND MARQUETTE DISTRICTS, MICHIGAN



GEOLOGIC MAP OF MENOMINEE IRON DISTRICT, MICHIGAN

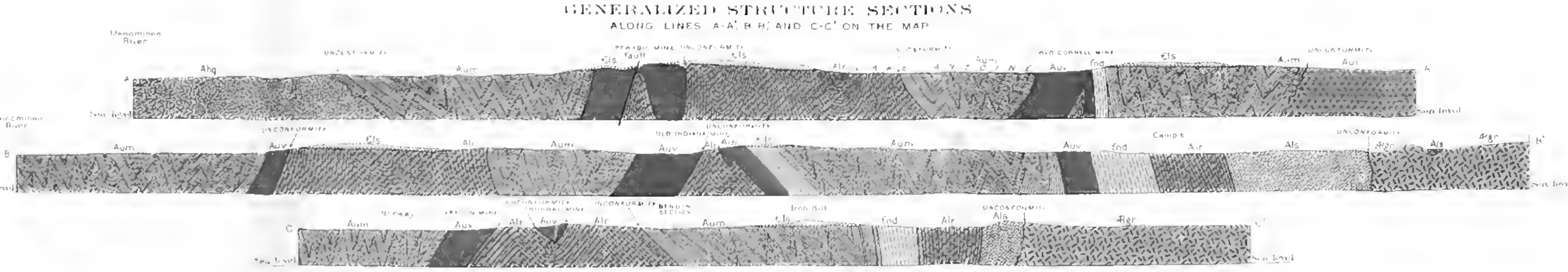
Revised to January 1, 1901

Contour interval 20 feet

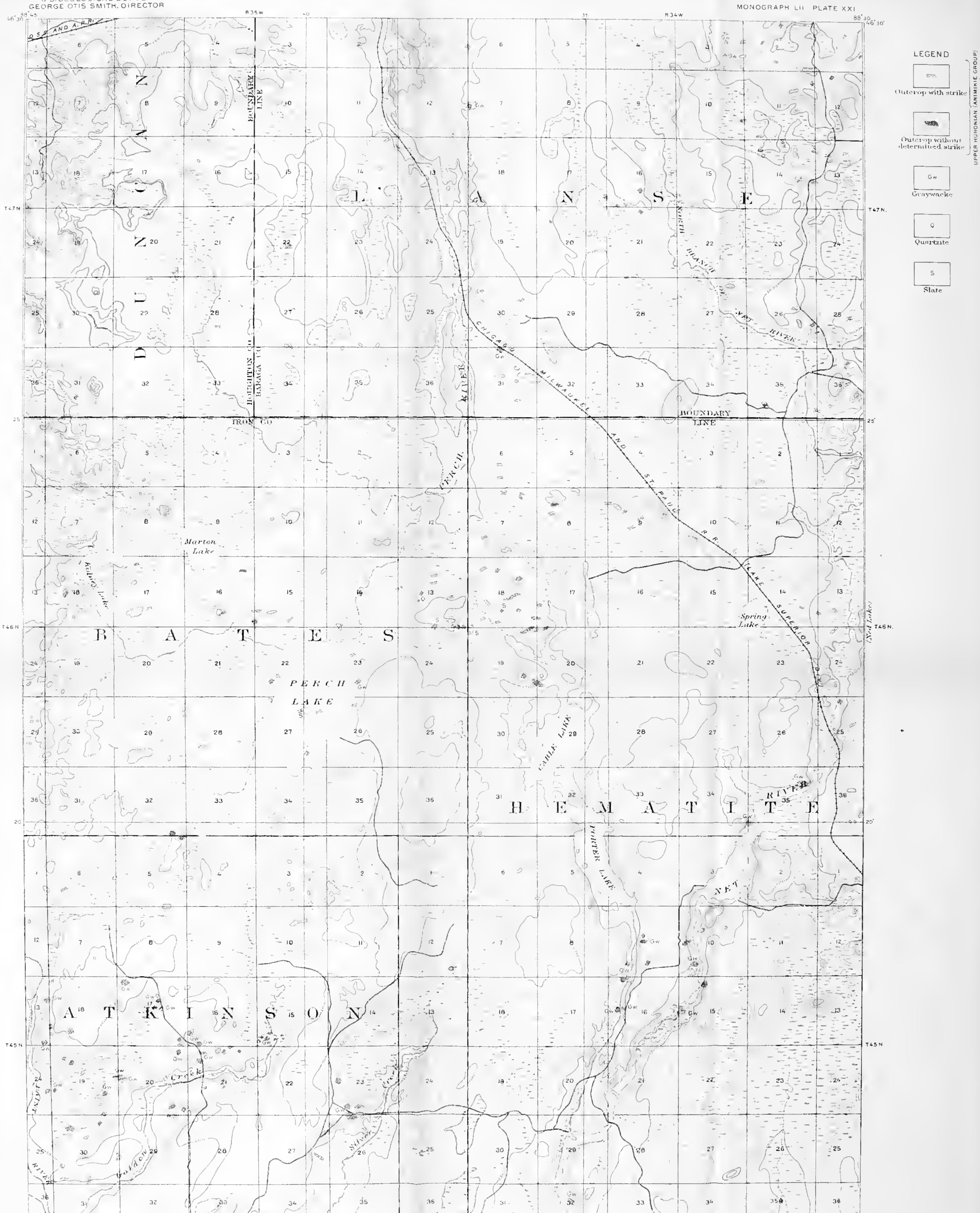
Geology by C. R. Van Hise, W. S. Bayley and J. Morgan Clements
Surveyed 1896-1899

GENERALIZED STRUCTURE SECTIONS

ALONG LINES A-A', B-B', AND C-C' ON THE MAP



Vertical and horizontal scale



Henry Gannett, Chief Topographer
Jno H Renshawe Topographer in charge
Control by Geo T Hawkins
Topography compiled by Van H Manning from surveys made under the direction of C.R. Van Hise

MAP OF PERCH LAKE DISTRICT, SHOWING DISTRIBUTION OF OUTCROPS

Compiled from commercial surveys

Contour interval 20 feet
Datum is mean sea level