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CHARLES D. WALCOTT, DIRECTOR

THE

MENOMINEE IRON-BEARING DISTRICT OF MICHIGAN

BY

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LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Madison, Wis., April 20, 1903.

Sir: I have the honor to transmit herewith the manuscript of a monograph on the Menominee Iron-bearing District of Michigan, by William Shirley Bayley. This monograph is the sixth and last one of a series treating of the iron-bearing districts of the Lake Superior region. Monographs on the Penokee-Gogebic, Marquette, Crystal Falls, Mesabi, and Vermilion districts have already been published. (See Pl. I.)

The first monograph on the Lake Superior region to be published by the United States Geological Survey was that on the copper-bearing rocks, by Prof. R. D. Irving. The completion of the original plans of the old Lake Superior Division will be marked by the publication of a closing monograph on the general geology of the Lake Superior region.

Very respectfully,

C. R. Van Hise,
Geologist in Charge.

Hon. Charles D. Walcott,
Director of United States Geological Survey.

OUTLINE OF MONOGRAPH.

Chapter I. The Menominee district is situated on the Michigan side of the Menominee River. It occupies an area of 112 square miles, lying principally in townships 39 and 40 north and ranges 28, 29, 30, and 31 west. It consists of a narrow tongue, widening to the west into the broad expanse of the Crystal Falls district, and merging to the northwest into the southwestern end of another ore-bearing district known as the Calumet area. The importance of the Menominee district as an ore producer may be inferred from the fact that since the first regular shipments of ore were made in 1877 the total quantity of ore raised from its mines has aggregated about 29,000,000 tons, nearly all of which was of Bessemer grade. The gross product in 1902 was over 3,000,000 tons.

The rocks of the district belong to the Archean, the Algonkian, and the Paleozoic systems. The iron-bearing beds are Algonkian. These are bounded on the north by a complex of gneisses and schists and on the south by a series composed mainly of greenstone-schists cut by dikes of granite, porphyry, gabbro, and diabase. The Algonkian rocks are divided into a lower and an upper series, distinguished as the Lower Menominee and the Upper Menominee, separated by an unconformity. These correspond to the Lower Marquette and the Upper Marquette series in the Marquette district and to the Lower Huronian and the Upper Huronian on the north shore of Lake Huron. The Paleozoic rocks are represented by the Lake Superior sandstone and an Ordovician limestone.

Chapter II. An abstract of the literature devoted to the discussion of the geology of the district is given in this chapter. It begins with a reference to a report by George N. Sanders, printed in 1845, and ends with a reference to a general article on the iron-ore deposits of the Lake Superior region by C. R. Van Hise, which was issued in 1901.

Chapter III. This chapter treats of the physiography of the district. The topography is simple. It consists essentially of two longitudinal ridges, with elevations of about 1,500 feet, separated by valleys, the floors of which are about 1,000 feet above the sea. Both the tops of the ridges and the floors of the valleys slope gradually to the southeast, representing, it is believed, two plains. The ridges are thus remnants of a higher plain that once occupied the entire area under discussion. The plan of the topography corresponds closely with the geological structure of the district. The residuals of the high plain are composed of hard dolomites, while the valleys are carved in soft slates.

The drainage is mainly longitudinal. The main drainage course is the Menominee River. The smaller streams are branches of this. All the streams possess the characteristic features of antecedent streams. Their courses are arranged without regard to the geology. It is evident that the present topography could not have been produced by the present drainage. It not only antedates the Glacial epoch, at the close of which the present drainage was inaugurated, but it even antedates in great measure the latest epoch of the Cambrian period, during which the Lake Superior sandstone was deposited. During this time the entire district was under water and the sand deposit covered all the hills as well as filled all the valleys that had been made prior to this period. Later, the land was raised above the water surface and erosion swept away the sandstone, except that on the tops of the hills, and the old topography was again brought to view. The present topography of the district is therefore similar to that which existed prior to Upper Cambrian time.

Chapter IV. The Archean crystallines bordering the Algonkian tongue are greenstone-schists on the south and a complex of gneisses, granites, and various schists on the north. The southern schists—the Quinnesec schists—occur in two areas. A southern area lies along the Menominee River and stretches southward into Wisconsin. A western area constitutes a wedge entering the Huronian beds from the west and extending for 6 or 7 miles along the middle line of the Menominee tongue. The Quinnesec schists of the southern area are coarse- and fine-grained basic rocks, characterized by a schistose structure of varying degrees of perfection. The coarser phases were originally gabbros, diabases, and diorites; the finer phases were basalts, diabases, and basic tuffs. Associated with these are chlorite-schists, amphibolites, gneisses, schistose porphyries, schistose felsites, and sericite-schists. The acid schists, except perhaps the sericite-schists, are apophyses from a great boss of granite which is intruded in the basic rocks south of the Menominee River. The basic schists are cut by dikes of various basic rocks and by granites.

In the western area the rocks are more massive. They are dense, grayish green in color, and uniform in their features. Some of them are ellipsoidal. All are apparently fine-grained basic lavas that have suffered extreme alteration. Most of the rocks are schistose, some slightly so but others markedly so. Their schistosity, as well as that of the southern schists, is ascribed to pressure.

The northern complex of gneisses and schists is of the usual character of Archean complexes. Banded gneisses and gneissoid granites, hornblende-schists, greenstone-schists, and a few mica-schists are intruded by dikes of diabase and by veins and dikes of granite. The gneissoid granites are of a pink and a gray variety, of which the former appears to partake largely of the nature of pegmatite. It intrudes the gray variety in irregular stringers and in series of narrow parallel veins.

When in the form last named, the two rocks together give rise to banded gneisses. A few localities are described at which the Quinnesec schists and the northern complex can be seen in good exposures.

Chapter V. The Algonkian rocks comprising the Menominee tongue are almost exclusively sedimentary, and are mainly mechanical sediments. They are separated from the underlying granites and gneisses of the northern complex by conglomerates composed largely of the débris of the underlying rocks. Their relations with the Quinnesec schists are not known, since the two series are not in contact. It is believed, however, that the sedimentary series is much younger than the schist series, because of the lithological analogies existing between the two series and corresponding series in the Marquette district.

Moreover, within the Algonkian series there is an unconformity which is revealed by the presence of a coarse quartzite containing pebbles of jasper, which must have been furnished by beds under the quartzite. No such beds in this stratigraphic position are now known to exist in the district, and hence it is assumed that they have been removed by erosion, and that a portion of their débris is now incorporated in the quartzites. This unconformity corresponds with that between the Upper Marquette and the Lower Marquette in the Marquette district, and between the Upper and Lower Huronian in the Crystal Falls area. In this district the two series are called the Lower Menominee and the Upper Menominee.

Section 1. The Lower Menominee series is subdivided from the base upward into three formations—the Sturgeon quartzite, the Randville dolomite, and the Negaunee formation (iron bearing).

The Sturgeon quartzite is found only along the northern side of the Menominee trough, where it forms a southward-dipping monocline bordering the south side of the Archean complex, and separated from it by an unconformity. Its topography is rugged. At its base the formation consists of conglomerates composed largely of the débris of granite and gneiss. These grade upward into quartzites through arkoses and graywackes. The conglomerates, the arkoses, and the graywackes are nearly always schistose, but the quartzites are practically always massive. This difference in structure is explained as due to the fact that the conglomerates, arkoses, and graywackes are nearer the contact plane with the underlying Archean than the quartzites, and hence were nearer the zone of accommodation in which movement occurred during the folding of the district.

The quartzites are principally white vitreous or saccharoidal varieties, composed of plainly fragmental quartz grains that often are enlarged by the addition of quartz on their peripheries. A few schistose quartzites differ from the predominant massive varieties in containing much sericite. At the top of the formation the quartzites pass into dolomitic quartzites, and these in turn grade into quartzose dolomites at the base of the Randville dolomite.

The major folding of the quartzite is simple. Within the formation a few divergencies of strike and dip are noted, but in the main the beds are nearly vertical. They constitute one limb of a synclinorium, the other limb of which should appear adjacent to the southern area of Quinnesec schists, and also around the western area. Its absence from these positions is supposed to be the result of the erosion which intervened between Lower Menominee and Upper Menominee time. At the western end of the district the quartzite belt turns northward around the end of the Archean anticline, separating the Menominee from the Calumet tongue. At this turn it is folded into a number of synclines and anticlines pitching west.

The thickness of the formation is estimated to be between 1,000 and 1,250 feet. The most interesting occurrences of the quartzite are to be found at the rock dam on Pine Creek and at the falls of Sturgeon River.

The Randville dolomite is identical with a similar dolomite series in the Felch Mountain and the Crystal Falls districts. It occupies three belts, called, respectively, the northern, the central, and the southern. The northern belt lies immediately south of the Sturgeon quartzite, in the valley of Pine Creek. Few exposures have been seen, as the area underlain by the belt is covered with the sands distributed by the stream. The central belt is narrow; it occupies the axis of the trough extending from a point north of Lake Antoine eastward to the bluff known as Iron Hill, in sec. 32, T. 40 N., R. 29 W. The southern and most important belt stretches from a point near the Menominee River, west of Iron Mountain, eastward to the end of the district, where it is lost under a covering of Paleozoic sediments. The most important mines of the district are just south of its southern border. On account of its resistant nature the dolomite in the southern belt, and, to a less extent, that in the central belt, gave rise to the elevations which stretch through the district in the form of the two ridges already mentioned, and which are explained as residuals of a plain once existing over the entire Menominee area.

The dolomite formation comprises an interbedded series of dolomites, quartzose dolomites, dolomitic quartzites, dolomitic slates, cherty quartzites, and talcose schists. The dolomites predominate. At the base of the series they are more or less richly quartzose. The cherty quartzites are fine-grained cherty rocks that are usually brecciated. In color they vary somewhat, but white and red shades are most prevalent. These rocks occur in but a few places, but always above the dolomites. Their absence from much of the region is accounted for by the erosion which removed them from over the most exposed portions of the surface during the interval between the Upper and Lower Menominee epochs. The slates are light-colored talcose and sericitic varieties. They are not very prominent. Occasionally they are found well down in the series, but usually they are limited to its upper portions, where they are in contact with closely similar slates belonging in the Upper Menominee series. The talcose schists have been observed only at the upper contacts of the Randville formation, where the purer dolomites are immediately beneath the basal layers of the Upper Menominee rocks, and more particularly in places where severe folding has taken place. They are soft, dark, much-jointed rocks, composed largely of serpentine and talc. They were formed, in all probability, in consequence of the fact that the dolomites were in a zone of movement where the conditions were favorable to active chemical processes. In many places the dolomites were crushed into breccias, and at one place, Iron Hill, a well-defined dolomitic conglomerate occurs.

The cherts of the Randville dolomite are identical in character with those in the Gogebic and Marquette districts and have the same stratigraphic position as these. In all three districts they are supposed to be of organic origin.

The folding of the Randville dolomite "is the key to the knowledge of the folding of the entire series of Algonkian rocks in the district." The formation occurs as a monocline in the northern belt and as anticlines in the central and southern belts. The northern belt follows closely the distribution and the folding of the Sturgeon quartzite. The central belt is the top of an anticline which is connected with the northern and the southern belts by synclines. It is terminated at both ends by plunging beneath the overlying beds. At its east end the eastward plunging anticline is plicated into several minor folds. Thus the central belt is affected by a broad anticline with a north-south axis, as well as by a narrow one with an axis trending a little north of west. The west end of the southern belt must likewise end in a plunging anticline, as slates of the Hanbury formation are known to occur a few miles west of the Menominee River on the strike of its trend. Its east end disappears under Paleozoic beds. The south side of the syncline, which must exist to the south of this belt if its structure is anticlinal, would be expected on the north side of the southern Quinnesec schists. Its absence from this position and from the border of the western area is explained in the same way as is the absence of the Sturgeon quartzite from these stretches of country.

The dolomite in all three belts is closely plicated by folds of high orders. Those of the second order are important from an economic point of view, because they determined the positions of the great ore deposits. These folds express themselves in the interiors of the dolomite areas by causing variations in the strikes and dips of neighboring beds. On the margins of the areas they are exhibited as indentations in the boundaries of the belts. These are best seen along the borders of the southern belt and more particularly on its southern side. Beginning at the west, the most important of these marginal folds have been called the Walpole, the Pewabic, the Quinnesec, the Norway, the Aragon, and the West Vulcan folds, because within them are situated the great mines of the same names. There are other less important folds along this southern border, and in addition there are known to be several important ones on its northern border. Exposures are rare, however, on the north side of the southern belt, and there is therefore much difficulty in recognizing the folding. Each of the folds is described and the reasons for regarding them as folds are given in detail. In the western portion of the area all the marginal folds pitch west; at the east end of the district they pitch east, thus confirming the view that the district as a whole is affected by a broad cross anticline as well as by a more compressed longitudinal syncline.

The thickness of the formation is probably somewhere between 1,000 and 1,500 feet.

The dolomite series is nowhere seen in actual contact with the underlying Sturgeon quartzite, but the gradation observed at the top of this formation, together with the gradation of the purer dolomites into quartzose phases at the base of the dolomite formation, indicates that the two pass into one another through dolomitic quartzites. Above, the dolomite may have passed into the Negaunee formation through the cherty quartzites, but since no rocks belonging to the Negaunee formation remain in the Menominee district the exact nature of the transition is not known. In most places the upper contact of the Randville dolomite is with the members of the Upper Menominee series. When the overlying formation is the basal member of the series—that is, when the contact is with the Vulcan formation—the transition between the two is sudden. There is no recognizable structural unconformity between them, but at the base of the upper series there is usually a conglomerate or coarse quartzite containing pebbles of chert and jasper that must have been derived from some formation beneath. Their existence is regarded as proof that there was once above the dolomite a jaspilite formation, like the Negaunee formation in the Marquette district. Thus, it is believed, there was an erosion interval preceding the deposition of the Vulcan rocks and at some time during the period when erosive agents were at work the Randville dolomite formed a land surface.

In many places the dolomite is in contact with the Hanbury slate, which normally lies above the Vulcan beds. This is the case at one place on the southern side of the southern belt and very generally along its northern side. It is also the case at the east end of the central belt, and possibly along its northern side. The absence of the Vulcan beds from those places at which it would normally be expected to occur is explained as the result of overlap along a sinking shore.

At a number of places along the contact, especially where the contact is between the dolomite and the Vulcan beds, the rocks on both sides of the contact line are severely brecciated. Both the underlying and the overlying beds are shattered and the line between them is often completely obliterated.

The Negaunee formation is represented in the district only by the pebbles in the quartzite at the base of the Upper Menominee series. There are a few jaspilites near the Curry mine, however, that are slightly different from most of the corresponding rocks in the Vulcan beds. Since their jasper layers are identical in character with the jasper pebbles in the quartzite, these jaspilites are described as affording a fair idea of the nature of the Negaunee beds that formerly must have existed in the district.

Section 2. The Upper Menominee series comprises all the beds between the top of the Randville dolomite and the bottom of the Lake Superior sandstone. It includes two formations—the Vulcan formation (iron bearing) and the Hanbury slate.

The reason for the separation of this series from the Lower Menominee series is the presence of a stratigraphical break between the Randville dolomite and the bottom of the Vulcan formation.

The rocks of the Upper series occupy the synclinal areas between the anticlines of dolomite and those between the dolomite and the two areas of Quinnesec schists. From the distribution of the series it is clear that it must occur in three synclines and two anticlines with east-west axes and the same number of similar folds with north-south axes.

Since the Vulcan formation occurs immediately above the dolomite, it should surround the dolomite areas in a continuous belt under normal conditions. At many places, however, the rocks of the Vulcan formation are lacking in this situation, and the Hanbury slate occupies the position they would naturally be expected to occupy. Wherever found, however, the Vulcan beds always lie between the dolomite and the slate. The lack of continuity of the Vulcan belt is ascribed to overlap of the Hanbury slate.

Lithologically the Vulcan formation is separable into three members, which are, in ascending order, the ore-bearing Traders member, the Brier slate, and the ore-bearing Curry member. The first comprises slates, conglomerates, quartzites, and jaspilites: the second is composed exclusively of slate, and the third consists of jaspilites and slates. Ore deposits occur in both the Traders and the Curry beds.

The Traders member is not as widely distributed as the other two members of the formation. Where one member is absent, it is the Traders member. Although this is not as continuous as the other members, nearly all the large mines of the district obtain their ores from its deposits.

The slates of the Traders member are always found in its basal portions, where they are associated with quartzites and conglomerates. These are usually light-colored phases that are with great difficulty distinguishable from some of the talcose slates at the top of the Randville dolomite. In a few places the slates are black, heavy varieties that are merely very quartzose fragmental ores. The light-colored slates grade into the quartzites and conglomerates. The latter rocks contain abundant jasper and ore pebbles. Where these constitute the main portion of the deposits the rocks pass into jaspilites, which are banded rocks, composed of alternating layers of red jasper and black ore. When the structure of the jaspilites is fairly coarse, the small grains of jasper and ore composing them can be distinguished on their bedding surface as small oval areas, producing a distinct mottling. Where shearing has taken place the ore bands have been rendered schistose, or micaceous, producing specular ores, and the jasper bands have been mashed so that the tiny grains of jasper have assumed lenticular shapes. In some places brecciation has occurred, and the rock is now a mass of jasper fragments in an ore matrix. Much of the material in the Traders jaspilites is thus of fragmental origin. In addition to the fragmental material in them, however, there is also much crystallized quartz and a good deal of newly deposited hematite. As the grain becomes finer the fragmental structure of both jasper and ore disappears, the quantity of secondarily deposited quartz and hematite increases, and the jaspilites become more like the typical jaspilites of the Marquette area, which were formed mainly by the decomposition of a cherty, ferruginous carbonate.

Under the microscope a few nodular masses of jasper and ore are observed in thin sections of the Traders rocks, and these are thought to be pseudomorphs of siderite or greenalite concretions. Their presence is evidence that some of the silica and hematite in the Menominee jaspilites was derived from an iron carbonate by metasomatic replacements. In all cases the ore bands differ from the jasper bands mainly in the greater abundance of their ferruginous component.

The Brier slate is an even-banded, heavy, black slate, occupying a belt of country adjacent to the Traders jaspilites. The rock consists of quartz grains and hematite crystals, embedded in a matrix composed of quartz, decomposed feldspar, kaolin, and a little chlorite. Here and there are a few large plates of brown biotite and white muscovite. Some specimens contain a great deal of dolomite. The Brier slate grades into the jaspilites of the Curry member through increase in the quantity of crystallized silica in the matrix and decrease in the amount of fragmental quartz present.

The Curry member is probably more widely distributed than either the Traders or the Brier member. It is found in all places where any portion of the Vulcan beds have been discovered. Lithologically the member is an even-bedded series of jaspilites and quartzose slates, besides ore deposits. Of the jaspilites two varieties are recognized. In one the jasper is dark red or purple and very fine textured and the ore a dense black hematite. These are very like the Traders jaspilites. In the other variety the jasper may be dark red, pinkish, or white. Both the jasper and the ore are sandy textured and look as though made up largely of loosely cohering grains. When examined microscopically the sandy jaspers are found to contain many oval and round masses of cherty quartz, surrounded by narrow zones of hematite and embedded in a finely crystalline aggregate of quartz. In the ore layers the zones of hematite around the chert nuclei are very broad, and the interstitial quartz is small in quantity. The quartzose slates differ from the jaspilites in being more homogeneous. They consist of a series of very thin alternating siliceous and ore layers, so that there is little or no distinction between ore and jasper bands. These rocks are found at the base of the Curry member, and are in a way gradation phases between the Curry jaspilites and the Brier slates.

The oval masses in the sandy phases of the Curry jaspilites are much more numerous than they are in the Traders jaspilites. As in the case of the Traders rocks, they are believed to be pseudomorphs of siderite or greenalite concretions. They are similar in all respects to the concretions that have been described in the Gogebic and Marquette jaspers and in the Mesabi and Gunflint Lake cherts. In the vicinity of the Curry mine all the rocks of the Curry member are cut by veins of red crystalline dolomite, and the ores are saturated with the same material to such an extent that their siliceous component has entirely disappeared, and in its place is a matrix of dolomite.

Where no marked disturbances in their relations exist the members of the Vulcan formation grade into each other by transition forms. Where, on the contrary, the members are closely folded the contact between the Traders and the Brier members is often sharp, and the rocks on both sides of the contact line are severely brecciated. This is true at the Norway mine and in the Curry location. Subsequently hematite was deposited in this crushed zone, producing marketable ores.

The Vulcan formation is a succession of beds laid down in water. The lower beds are largely fragmental, although intermingled with the fragmental material there must have been some cherty, ferruginous material that had been precipitated chemically. In some places the mechanical sediments were in great excess. In other places the chemical sediments appear to have predominated. In the course of time the latter were changed to crystalline quartz and hematite through the agency of descending meteoric waters, and the mass was enriched by deposits of hematite between the original grains.

After the Traders beds had been laid down to a thickness of several hundred feet in some places the conditions of deposition changed. The cherty material ceased to be precipitated, and the Brier slates were laid down. At the end of Brier time the conditions that prevailed at the end of Traders time recurred, and chemical sediments were again precipitated. In this period they were less contaminated with fragmental material. The abundance of concretionary ore in the Curry beds shows that some of these must have consisted almost exclusively of the chemical precipitate. Jaspilites were produced from the carbonate and the greenalite in the same manner as in the Traders beds, and some of these, after enrichment, became ore bodies.

The major folding of the Vulcan beds follows closely the folding of the subjacent dolomite. Within the formation, however, the beds are crumpled and crinkled into small folds, and upon these are superposed still smaller flutings.

Wherever folding is observed it is best preserved in the jasper bands. The ore layers between these were sheared and made schistose. Where the folding was very severe both ore and siliceous layers developed a slaty cleavage. In some places the jasper was fractured and a breccia of jasper fragments in a micaceous ore matrix resulted.

The total thickness of the Vulcan formation averages about 650 feet, divided as follows: Traders member, 150 feet; Brier slate, 330 feet; Curry member, 170 feet. The Brier and Curry members maintain an almost uniform thickness in all portions of the district where they have been encountered. The Traders member, however, varies widely in thickness, as would be expected of a series of beds deposited against a shore.

The relations of the Vulcan beds to the underlying Randville dolomite are those of a younger series to an older series, where the two are not separated by a structural unconformity. That the Vulcan beds were laid down on a shore composed partly of the dolomite is shown by the presence of dolomite bowlders within the iron formation on the seventh and eighth levels of the Chapin mine. Their relations with the overlying Hanbury slates are those of complete conformity.

In a few places the Hanbury slate is against the dolomite, the Vulcan beds being nowhere present in the vicinity. This is true east of Quinnesec and at the east end of the central dolomite belt. It is also believed to be true at a number of other places where the slate and the dolomite series have not been seen in actual contact or in exposures very close to one another. Faulting of the slate beds over the iron-bearing beds will not explain the phenomenon, because faulting is of minor importance in the district. The only explanation that suggests itself to account for all the facts of distribution of the Vulcan and the Hanbury formations is that of unconformity between the Lower Menominee and the Upper Menominee series, with a gradual advance of the Upper Menominee sea, the deposits of which slowly overlapped the earlier deposits and gradually buried the higher lands composed of the Lower Menominee rocks.

The Traders and the Curry ores are not very different. Practically all are of Bessemer grade, though some are highly siliceous and others contain but little silica. The former are especially rich portions of the jaspilites that have had their ferruginous component increased by processes of enrichment. These lean ores differ very little in appearance from the jaspilites, of which they are essentially a part. They are banded, brecciated, and often specular. The brecciated ores may consist of jasper fragments in a mass of hematite, or of hematite fragments in a mass of dolomite, or they may be composed of fragments of ore, jasper, and slate in a mass consisting largely of slate débris that has been strongly ferruginized.

The rich ores are usually bluish-black, porous, fine-grained aggregates of crystallized hematite, occurring in the troughs of pitching folds or in other situations toward which descending water is likely to be directed. Comparisons of analyses of all the ores of the district show them to consist principally of 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. The minimum silica reported in the ores of 1900 is 2.75 per cent and the maximum 38.65 per cent. Twelve analyses of cargoes of typical ores are given and four complete analyses. The latter indicate that the richer ores are mixtures of hematite, magnetite, muscovite, serpentine, dolomite, apatite, pyrite, quartz, and some manganese oxide.

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 sometimes exist 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 water courses 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 first named is greatly in excess.

The larger ore deposits all rest upon relatively impervious foundations, which are in such positions as to constitute pitching troughs. Within this district such pitching troughs may be made by (1) the marginal folds in the Randville dolomite; (2) the slate forming the bottom part of the Traders member; and (3) the Brier slate beneath the Curry beds. The dolomite is especially likely to furnish a suitable basin for the accumulation of ore bodies, where its upper member has been transformed into a talcose schist.

Smaller ore bodies may occur at contacts between the different members of the Vulcan formation and at places within the iron-bearing member where severe brecciation has occurred.

The forms of the ore bodies vary with their positions. While very irregular in shape they nevertheless conform in a general way to the shape of the foundation on which they rest. The deposits in troughs have in general a U-shaped cross section, very thick at the bottom. Where much compressed, the arms of the U may unite at the center and produce a lens-shaped deposit. Contact deposits are usually broad and sheet like, with irregular projections extending from their upper surfaces.

From the distribution, associations, and composition of the ores and the shapes of the ore deposits it is evident that the ores of the Menominee district, like those in the Gogebic and Marquette districts, were concentrated by descending waters flowing in definite channels. A portion of the iron oxide in the Traders member is of fragmental origin, being the débris of an older jaspilite formation, and perhaps a portion of that in the Curry member had a similar origin. These ferruginous bodies, however, were enriched by the addition of hematitic material from some overlying stratum, from which it was dissolved by meteoric waters and transported downward, finally being precipitated between the fragmental grains of the original sediments.

The processes of concentration were the same as those worked out by Van Hise for the Gogebic and the Marquette districts. Oxygenated meteoric waters descending through the rocks of the Hanbury and Vulcan formations dissolved iron carbonates and silicates and precipitated the metal as oxide in or near the position of the original compounds. Carbon dioxide was thus liberated and dissolved in the descending waters. These took up more iron salts. In their downward passage they were converged into trunk channels by plunging synclines, or were directed into definite courses by the contact planes between adjacent beds or by zones of brecciation. At these places the iron-bearing waters, which necessarily must have taken circuitous routes, were intermingled with water which had descended more directly from the surface, and which, therefore, had retained its oxygen, or most of it. Here the dissolved iron carbonate was decomposed and iron oxide precipitated. Thus are found pseudomorphs of hematite in place of original ferruginous concretions, and great deposits of ore in the troughs of synclines within the iron-bearing formation. Continued passage of water along the same channels purified the deposits by removing from them deleterious substances.

Topographically the ores are usually found below the crests of hills, on their slopes or in valleys which once had below them lower valleys in which the descending waters may have found an outlet. In the Menominee district, however, this relation between the position of ore bodies and the topography is not as clear as it is in the other Lake Superior iron districts.

The beginning of the concentration of the ores must have been at the close of Upper Huronian time, that is, after the folding of the Huronian rocks. It was practically completed before the beginning of the Upper Cambrian.

A critical study of the geological relations of the ore deposits of each of the mines in the district indicates that all deposits of any magnitude are situated in just such positions with respect to the surrounding rocks, as might have been prophesied, on the assumption that they were accumulated by the action of descending ground water.

The Hanbury slate occupies nearly all the low ground within the Menominee trough. It occurs in three synclinal belts lying between the anticlines of dolomite and between the southern dolomite belt and the south area of Quinnesec schists. The slate belts widen toward the west because of the westward plunging of the entire synclinorium.

The formation comprises clay slates, calcareous and graphitic slates, graywackes, thin beds of ferruginous dolomite, and small bodies of chert and hematite. The formation is cut by a few greenstones that are now greatly decomposed.

The clay slates are normal rocks. When sheared and much weathered they become light-colored sericite-schists. Many specimens are stained red in irregular patches, producing a red and white mottled rock known locally as calico slate. The calcareous and graphitic slates appear to be limited to the lower horizons of the formation, the former being nearly always associated with ore bodies. The quartzites are very siliceous dolomites. The cherts and hematite are usually closely associated. The former are gray or white. The latter is a dense-black or dark-brown variety. Where the slates are cut by greenstone they have suffered some contact metamorphism, with the production of a little biotite and actinolite.

The folding of the formation is very complicated. Folds of high orders are common—practically universal. In the eastern portion of the area the pitch of these small folds is to the east and in its western portion to the west. The distribution of the folds and their varying pitches corresponds closely to the major folding of the district. No approximately correct estimate of the thickness of the slate formation is attempted, because of the difficulty of eliminating the effects of the close folding. It is safe to say, however, that the Hanbury formation is the thickest of all the formations in the district.

Like the other members of the Menominee series, the slates are unconformably beneath the Lake Superior sandstone.

No workable ore deposits have thus far been discovered within the slate area, but there are seven or eight places at which lean ores have been obtained. These are widely distributed. Because of the interest naturally attached to the discovery of ores of any kind in the great slate areas, each of these localities is briefly described.

It is possible that ore deposits of workable size occur in the slates in very favorable situations, though no indication of their presence has yet been observed in this district. From the fact, however, that large deposits are known to exist in the Hanbury slates of the Florence, Crystal Falls, and Iron River districts, it is possible that similar deposits may occur in the Menominee district.

In exploring within the Hanbury area only the most favorable localities need be tested. These are the places where ferruginous dolomites occur, where the rocks are folded or breeciated, and where the folds involve an impervious stratum.

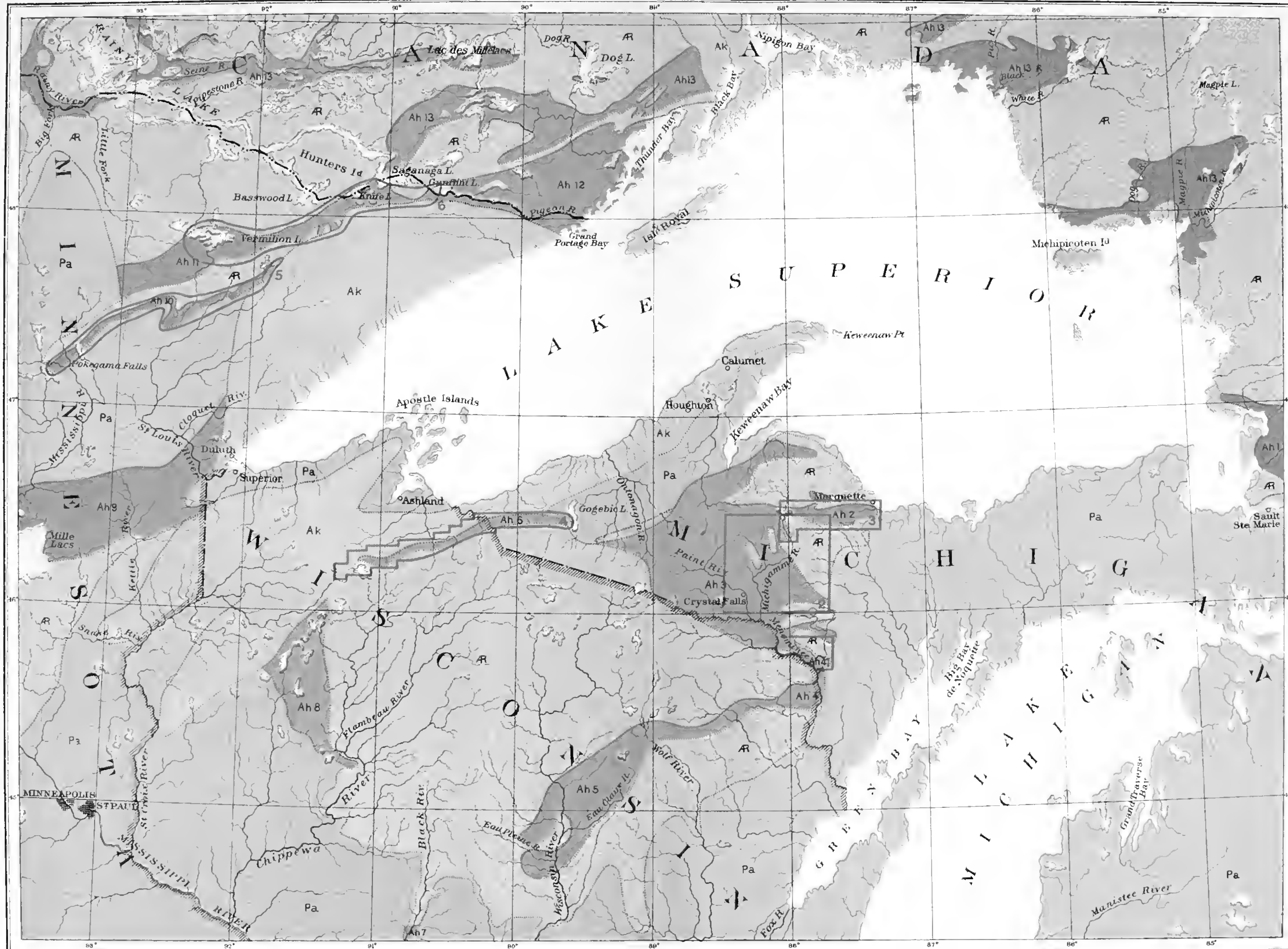
CHAPTER VI. Above the folded Algonkian rocks lie the horizontal beds of the Paleozoic sediments, with a profound unconformity between the two series. The Paleozoic series comprises the Lake Superior sandstone below and the Hermansville limestone above. These once extended over the entire district. East of Waucedah they still cover all the older rocks, but west of this place they are now found capping only the higher hills.

The Lake Superior sandstone is mainly a red sandstone. Its thickness is estimated to be 300 feet. In its lower portions are conglomerates, which, where they lie on the Vulcan beds, contain ore bowlders in such quantity that they may occasionally become sources of ore.

Fossils are extremely rare. A few fragments of trilobites and a few shells of brachiopods have been found in a few places. The former have been identified as *Dicellocephalus misa* and the latter as *Lingulepis pinniformis.* They indicate the St. Croix horizon of the Upper Mississippian series.

The Hermansville limestone is a sandstone with calcareous cement, interbedded with pure dolomite. Its maximum thickness is about 100 feet. The series is of little importance within the limits of the Menominee district, but is widely spread farther east. Rominger identified it as corresponding to the Chazy and Calciferous formations of the Eastern States.

CHAPTER VII. This chapter contains an outline of the geological history of the district. Comparison of the succession of formations in the Menominee district with the succession in the Marquette and the Gogebic districts shows that the geological history of the three districts, while alike in its major features, was very different in minor features. The attempt to correlate the events that transpired in the various iron-bearing districts of the Lake Superior region is left for a succeeding publication.



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Iron ore-bearing districts for which detail maps have been published are enclosed by red lines

1 *Menominee*
2 *Crystal Falls*
3 *Marquette*
4 *Gogebic*
5 *Mesabi*
6 *Vermilion*

ARCHEAN	ALGONKIAN: HURONIAN	ALGONKIAN: KEWEENAWAN	POST-ALGONKIAN
AR	Ah	Ak	Pa
Including considerable areas of Algonkian granite	Including considerable areas of Archean (the iron-bearing series)		

HURONIAN
- Ah 1 *Original Huronian*
- Ah 2 *Marquette iron-bearing series*
- Ah 3 *Crystal Falls iron-bearing series*
- Ah 4 *Menominee iron-bearing series*
- Ah 5 *Wisconsin Valley series*
- Ah 6 *Penokee-Gogebic iron-bearing series*
- Ah 7 *Black River iron-bearing schists*
- Ah 8 *Chippewa Valley quartzites*
- Ah 9 *St. Louis series*
- Ah 10 *Mesabi iron-bearing series*
- Ah 11 *Vermilion iron-bearing series*
- Ah 12 *Animikie iron-bearing series*
- Ah 13 *Folded schists of Canada*

GEOLOGIC MAP OF PART OF THE LAKE SUPERIOR REGION

SHOWING RELATIVE POSITION OF THE MENOMINEE AREA WITH RESPECT TO OTHER HURONIAN AREAS

Compiled from Official maps of United States, State, and Canadian Surveys

Scale

0 50 100 miles

THE MENOMINEE IRON-BEARING DISTRICT OF MICHIGAN.

By William Shirley Bayley.

CHAPTER I.

INTRODUCTION.

Scope and date of work done.—The present report is an account of the geology of that portion of the Menominee district bordering the Menominee River on the Michigan side. The district lies entirely within the State of Michigan, its western extension into Wisconsin not being discussed. A preliminary report of the district, accompanied by a geological map, was published in the year 1900 as a folio of the Geologic Atlas of the United States.[a]

The field work upon which the report is mainly based occupied the summer of 1896. In this I was assisted in the geological work by J. Morgan Clements and Samuel Weidman. Since this I have twice visited the district for supplemental work, first in 1899 and again in 1900.

Acknowledgments.—To the superintendents and engineers of the mines in the district the Survey is under many obligations for the numberless courtesies afforded the field parties and for the generous manner in which they have allowed the use of mine plats. Some of these have been reproduced as illustrations in the body of this report. All have been of value in working out the intricate structure of the district.

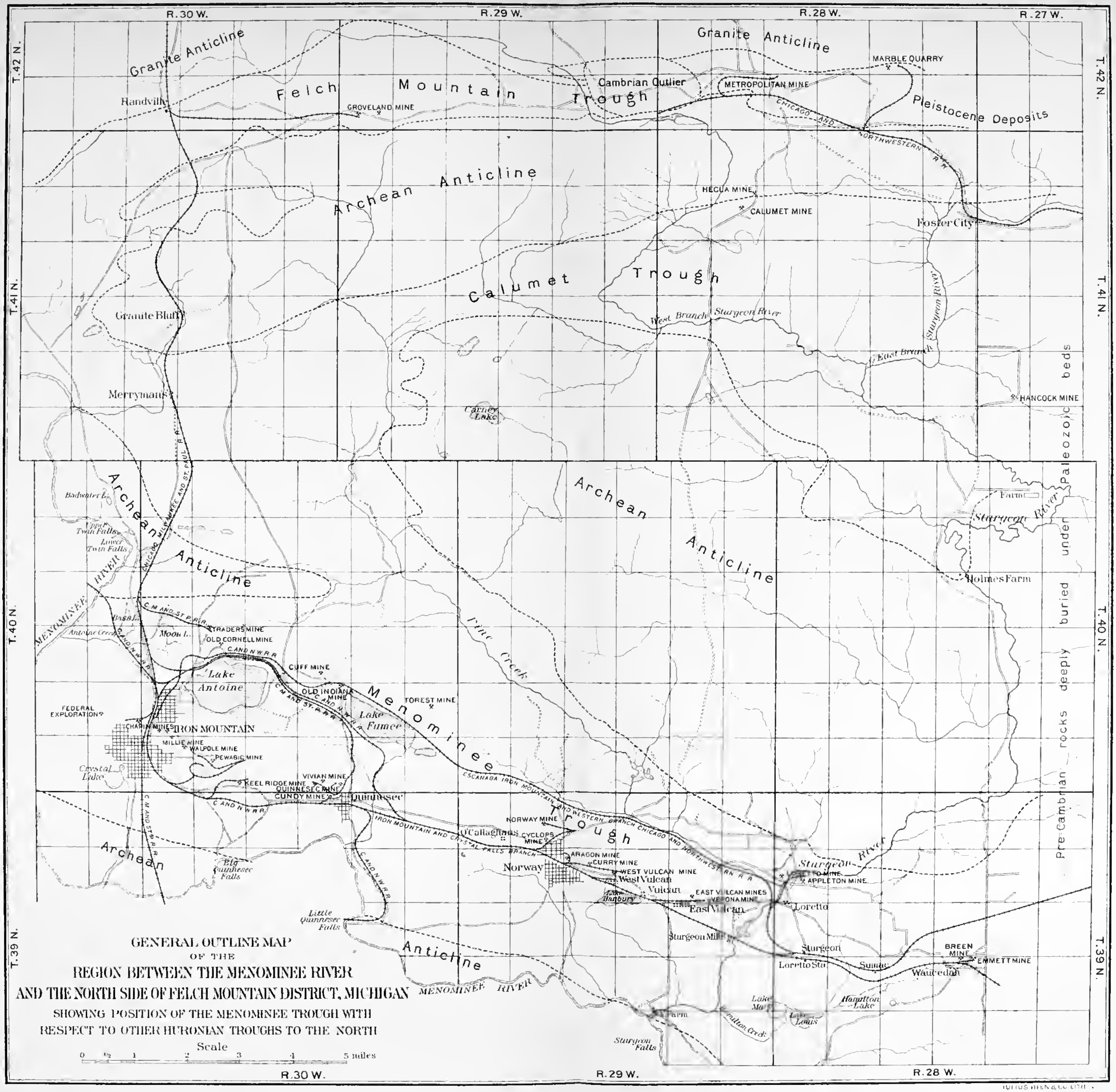
[a] Van Hise, C. R., and Bayley, W. S., Description of the Menominee district: Geologic Atlas U. S., folio 62; U. S. Geol. Survey, 1900.

To Messrs. F. A. Janson, of the Penn Iron Company; G. Helberg, of the Aragon mine; V. S. Hillyer, of the Minnesota Iron Company; and L. M. Hardenburgh, formerly of the Pewabic mine, special thanks are due for copies of maps and plats which were prepared especially for this work and furnished to the author gratuitously.

Limits of the Menominee area.—The Menominee district proper is bounded on the west by the Menominee River; on the south by the same river and the south line of the northern tier of sections in T. 38 N., Michigan; on the east by the east line of secs. 2, 11, 14, 23, 26, and 35, T. 39 N., R. 28 W., and their continuation north and south, and on the north by the north line of T. 40 N., Michigan. On the general map (Pl. II) the area represented includes a region extending 8 miles farther north, to the north side of the second tier of sections north of the south line of T. 42 N., and as far west as the west line of Ts. 41 and 42 N., R. 30 W. The geological map (Pl. IX) includes only the area of the Menominee district proper.

Relations to other iron-bearing areas.—The area designated above as the Menominee district proper constitutes a tongue of sedimentary deposits lying between a granite area to the north and a green schist area to the south. This tongue is the southernmost of five distinct tongues (see map, Pl. II) which extend eastward from the great central area of Huronian deposits in Wisconsin and Michigan, described in part in the Crystal Falls monograph.[a] The five tongues, beginning with the northernmost, are the Marquette tongue, discussed in the Marquette monograph; the Sagola and the Felch Mountain tongues, treated in the Crystal Falls monograph; the Calumet tongue; and the Menominee tongue. Each is structurally a trough of Huronian sediments lying between rims of Archean granites, gneisses, and schists. To the west they all widen out into the broad expanse of Huronian sediments referred to above. To the east all except the Marquette tongue plunge beneath Paleozoic deposits. The Calumet tongue runs a little north of east and then east through the center of T. 41 N., R. 29 W., Michigan, as a narrow belt a mile or a mile and a half in width. At the east side of the township it widens rapidly, becoming broader and broader until, in T. 41 N., R. 27 W., where it disappears under Paleozoic deposits, its width measures 7½ miles.

[a] Clements, J. M., and Smyth, H. L., The Crystal Falls iron-bearing district of Michigan, with a chapter on the Sturgeon River tongue by W. S. Bayley, and an introduction by C. R. Van Hise: Mon. U. S. Geol. Survey, vol. 36, 1899.



GENERAL OUTLINE MAP OF THE REGION BETWEEN THE MENOMINEE RIVER AND THE NORTH SIDE OF FELCH MOUNTAIN DISTRICT, MICHIGAN

SHOWING POSITION OF THE MENOMINEE TROUGH WITH RESPECT TO OTHER HURONIAN TROUGHS TO THE NORTH

JULIUS BIEN & CO. LITH.

At its west end the south side of the Calumet tongue merges with the north side of the Menominee tongue. Farther east the two tongues are separated by an elliptical area of Archean rocks.

Shape and size of the Menominee tongue.—In general the Menominee tongue is a spindle-shaped area about 17 miles long, trending about N. 55° W. Its narrowest portion is in the middle, in the vicinity of Vulcan, where it measures about 4 miles in width from its contact with the granite on the north to its contact with the green schists on the Menominee River on the south. To the east it widens gradually until, in the eastern portion of R. 28 W., its width is about 7 miles. To the west also it gradually becomes wider 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, and extends into the wide area of Huronian sediments to the west.

At its eastern end the characteristic rocks of the tongue are so deeply buried beneath later sediments that they can not be traced. Lines of magnetic attraction, however, have been obtained east of the eastern limit of the district, as given above, and these are taken to mean that the Huronian sediments continue for at least a short distance beyond the places where they are last seen on the surface.

The area covered by the tongue measures about 112 square miles. The whole area studied, including the Calumet tongue, the Archean area between the Calumet and Menominee tongues, and the narrow strip of green schists along the Menominee River, aggregates about 261 square miles. All the producing mines, however, are situated within the Menominee tongue, the three in the Calumet tongue having been idle for over fifteen years. The geology of the Calumet area will be discussed in another publication. The present monograph deals only with the Menominee tongue.

Economic importance of the district.—In 1902 the mines of the Menominee trough shipped 3,001,189 long tons of ore, and since the first shipment of ore from the Quinnesec mine in 1873 the aggregate shipments of all mines to the close of 1902 have amounted to the large total of very nearly 29,000,000 long tons. Of this aggregate by far the larger proportion of ore has been of Bessemer grade. The total shipments from the Marquette district to the end of 1902 were 66,686,502 long tons; those from the Crystal Falls, Iron River, and Felch Mountain districts in Michigan, and the Florence district in Wisconsin, taken together, have amounted to about 13,400,000 long tons; those from the Gogebic range in Michigan and Wisconsin to 37,818,274 long tons; those from the Vermilion range in Minnesota to 19,061,506 long tons; and those from the Mesabi range in the same State to 53,747,807 long tons. It will thus be seen that in proportion to its area the Menominee trough has yielded as large a product as any other of the Lake Superior districts, with the exception of the Mesabi. Since the discovery and development of the Mesabi district the demand for low phosphorus and high silica ores to serve as mixtures for the Mesabi ores has so largely increased that many lean, low phosphorus ore deposits, formerly not marketable, now find a ready sale. The Menominee district can furnish an abundance of this grade of ore, so that it is probable that the importance of the district as a mining center will increase rather than diminish in the future.

Previous work in the district.—The only detailed geological maps of the Menominee trough that have heretofore been published are those of Brooks[a] (Pl. IV) and Wright,[b] in the Geology of Wisconsin. Irving[c] published a general map (Pl. V) of the district in his introduction to Dr. Williams's bulletin on the origin of the Menominee green schists, but he made no claim that it exhibits more than the generalized structural features of the district. Wright's map shows the distribution of the green schists, some of the iron-bearing belts, and the pre-Huronian rocks of the district, while that of Brooks exhibits, in addition, the location of all the ledges of dolomite, slate, quartzite, and other sedimentary rocks met with during this author's explorations. Brooks also presents a structural sheet illustrating his views as to the sequence of the rock series and the character of the folding. This map was of great use to the field parties of the United States Geological Survey, since it enabled them to make systematic plans for the survey of the district and directed their attention to many rock ledges that might otherwise have been overlooked.

In addition to the works and reports referred to above, another valuable report on the district is that of Rominger.[d] This report, like that of the

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[a] Geology of Wisconsin, Survey of 1873–1879, vol. 3, pt. 7, by T. B. Brooks, and pt. 8, by C. E. Wright, and Atlas, Pls. XXVIII, XXIX, and XXX.

[b] Ibid.

[c] Williams, G. H., The greenstone-schist areas of the Menominee and Marquette regions of Michigan, etc., with an introduction by R. D. Irving: Bull. U. S. Geol. Survey No. 62, 1890.

[d] Rominger, C., Upper Peninsula, pt. 2, Menominee iron region: Geol. Surv. Mich., vol. 4, 1881, pp. 155–241.

same author on the geology of the Marquette district, consists mainly of a discussion of ledges and of detached statements concerning the relations to one another of the different "rock groups" met with. It, nevertheless, was of great value in the prosecution of the field work on which the present volume is based, since it called attention to the most promising exposures in the district and in many instances afforded clues as to the places at which relations could best be studied.

The reports of Brooks, Wright, Irving, and Rominger are referred to more at length in the following chapter, and in this chapter also are given abstracts of all the other important papers in which the geology of the district has been discussed. A perusal of this chapter will show that many facts bearing on the subject have gradually been accumulated; but that in no other cases than those mentioned above did the facts known concerning the distribution of the different formations warrant the construction of geological maps of the district.

Method of work.—Most of the field work on which this monograph is based was done in the months of July, August, and a part of September, 1896. The entire area whose limits have been outlined above was cut by north-south traverses at intervals of one-tenth, one-fourth, one-half, or three-fourths of a mile, or 1 mile, according to the intricacy of the geology in different parts of the district and the character of the surface exposed to view. In those portions of the district from which the forest and undergrowth have been removed the traverses were at greater intervals than in those portions covered by dense thickets of young trees and brush. In the wide expanses of slate to the south of the Chicago and Northwestern Railroad the traverses were 1 mile apart. In those portions of the district where the different rock belts are closely folded traverses were made every quarter of a mile. The iron-bearing belt was examined thoroughly, every ledge, so far as is known, and every mining pit having been studied in detail. The same careful examination was made of the contact between the quartzite at the base of the sedimentary series and the crystalline rocks to the north, and an almost equally careful search was made for a contact of the slates with the greenstones to the south. In areas where exposures are small and scattered, north-south magnetic lines were run every half mile.

During the summers of 1899 and 1900 two other visits were made to the district, but the field work was limited to the study of relations, to the running of a few additional magnetic lines, and to the investigation of the structure of small complicated areas and the study of the mines. The work was supplementary to that of 1896, and was intended simply to fill the gaps left by the earlier survey.

Though the topography of the district is simple, much of the surface is covered with a thick mantle of glacial drift through which ledges of the softer rocks rarely penetrate. Other portions are covered by a sheet of sandstone which obscures some of the most interesting contacts. Moreover, thick growths of brush hide much of the surface, especially in the northern and eastern portions of the district. The detail maps show the character, the position, and the number of ledges investigated, and it is from the evidence afforded by these and by the mine plats that the structure of the district has been worked out.

Classification of formations.—The rocks of the Menominee district belong to the Archean, Algonkian, and Paleozoic systems. The oldest series of rocks bordering the Menominee tongue comprises various schists, gneisses, and granites. These are regarded as Archean. Resting unconformably upon the Archean rocks is a succession of Algonkian sediments, which are divisible into a Lower Menominee and an Upper Menominee series, separated from each other by an unconformity. The Paleozoic rocks comprise horizontal Cambrian sandstones and Ordovician limestones. These occur in patches on the tops of the hills, capping the closely folded and truncated Huronian rocks. Both of the Menominee series are divisible into a number of formations, each representing a time during which the conditions of deposition were approximately uniform. Each of the pre-Cambrian formations has been named and is represented on the general map of the district (Pl. IX) by a distinctive color. The following table gives a list of the formations, arranged in descending order according to age. The fractional formations, or members of the Vulcan formation, are represented on the detail maps and are separately characterized in the text, but they are not differentiated on the general map.

Table showing the succession of formations in the Menominee district and their relations to general geological systems.

System.	Series.		Formation.
Paleozoic	Ordovician	Chazy. Calciferous.	Hermansville limestone.
	Cambrian	Potsdam	Lake Superior sandstone.
	Unconformity.		
Algonkian	Upper Menominee		Hanbury slate. Vulcan formation, subdivided into the ore-bearing Curry member, Brier slate, and ore-bearing Traders member.
	Unconformity.		
	Lower Menominee		Negaunee formation Randville dolomite. Sturgeon quartzite.
	Unconformity.		
Archean			Granites and gneisses, cut by granite and diabase dikes. Quinnesec schists, cut by acid and basic dikes and veins.

Names of the formations.—The names of the Upper Menominee formations and of the Archean schists are taken from localities in the district. The names of the Lower Menominee formations are those of formations in adjacent districts already reported upon, with which the Menominee formations are believed to be continuous. Beginning at the bottom, the Quinnesec schists are so named since they are typically developed at the Big and the Little Quinnesec Falls on the 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.[a] The Menominee dolomite is called the Randville dolomite because it has been practically connected with the Randville dolomite of the Crystal Falls district.[b] The assumed iron-bearing Lower Menominee formation is called the Negaunee formation because this is the Lower Huronian iron-bearing formation of the Marquette district. In the Menominee district, as will be seen, this formation has not yet been identified, although its presence is indicated by the character of the basal member of the Upper Menominee series.

In the Upper Menominee the Vulcan formation is so named since the iron formation occurs in typical development, with full succession and fine

[a] Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 398–405. [b] Ibid., pp. 406–411.

exposures, in the vicinity of West Vulcan. It is threefold, comprising a series of quartzites and fragmental ores at the base, called the Traders member; following these in upward succession, a series of slates known as the Brier slates; and above these, a set of ore beds, jaspilites, and quartzites, which has been called the Curry member, the names in each case being taken from the names of the mines near which the respective series is best exposed.

The Hanbury slates are thus named because in the vicinity of Lake Hanbury this formation is better exposed than anywhere else in the district.

References to Marquette monograph.—In the following pages references will be made repeatedly to the monograph on the Marquette district, especially in connection with the discussion of the Archean rocks. These are so nearly like the corresponding rocks in the Marquette district that a minute description of them would be little more than a repetition of what has already been recorded in the account of the Marquette Basement Complex. In order to avoid this unnecessary repetition, only brief descriptions of these rocks will be given. Those who may be interested in their petrography are referred to the chapter on the Basement Complex in the Marquette monograph,[a] and to Dr. Williams's bulletin[b] on the greenstone-schist areas of the Menominee and Marquette regions of Michigan.

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[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan, including a chapter on the Republic trough by H. L. Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 149–220.

[b] Williams, G. H., The greenstone-schist areas of the Menominee and Marquette regions of Michigan; a contribution to the subject of dynamic metamorphism in eruptive rocks: Bull. U. S. Geol. Survey No. 62, 1890.

CHAPTER II.

BIBLIOGRAPHY AND ABSTRACT OF LITERATURE.

The geological literature relating to the Menominee district is much less voluminous than that relating to the Marquette district. Nearly all of it is concerned more particularly with the general problems presented by the district. Very little of the work done has been accomplished by geologists working privately. By far the greater portion of it, including all that is of the greatest value, is the result of public enterprise. The earliest important publications are those of the United States geologists who were intrusted with the examination of the geological features of the "Chippewa land district." After these came the publications of the Michigan survey, followed by those of the Wisconsin survey, and, finally, by those of the U. S. Geological Survey. The authors who have done most toward familiarizing us with the broader features of the Menominee geology are J. W. Foster, J. D. Whitney, T. B. Brooks, C. Rominger, and R. D. Irving. Messrs. Foster and Whitney first recorded the existence of pre-Cambrian rocks within the limits of the district. Brooks separated these into the Laurentian and the Huronian groups, and published maps outlining the Huronian basin and the distribution of the principal formations represented in it. This author and Rominger both give a great many details with reference to the relations of these formations to each other, and both worked out a general theory of structure for the bedded rocks. Irving busied himself principally with a discussion of the relations of the iron-bearing formation to the overlying and the underlying series.

Brooks's map (Pl. IV) is the only detailed one of the district. Others that have been issued are mainly copies of this, except the map of C. E. Wright, which was constructed primarily for economic purposes, and which shows merely the outline of the Huronian basin and the distribution of the iron-bearing and the green-schist formations within it.

In the present chapter reference is made to all the articles that are known to treat of the district under discussion. These are abstracted in each case, and the conclusions reached are outlined. A knowledge of the contents of many articles that treat of the relations of the pre-Cambrian formations to one another in the Lake Superior region, but which do not refer specifically to the Menominee district, is of importance to the correct understanding of the history of the discussion of the Menominee geology, but they have been so fully referred to in the monograph on the Marquette district[a] that it has not been thought necessary to abstract them a second time.

The arrangement of the abstracts is chronological, the dates of publication of the original articles being regarded as the times when they were first made public. This method of arrangement is unfair to a few authors, notably to Dr. Rominger, a portion of whose work was first published, through no fault of his own, years after it was completed, and to certain others of the official geologists; but it is the only method that is practicable, since it is impossible in most cases to learn when the various articles left the hands of their authors.

The very first information given us concerning the district now under discussion was imparted through documents of Congress. The first author who left a record of his observations in the Menominee country was George N. Sanders. Following his report came the reports of the other early United States geologists in rapid succession. Then ensued a period during which little new work was done. In 1877 the discovery of ore at the Breen mine called renewed attention to the district. This is shown in the excellent reports of the Michigan and Wisconsin geologists, published between the years 1872 and 1881. The investigations begun by these surveys were continued without interruption by the United States Geological Survey, but in the Government survey the Menominee geology was studied as a portion of the broader problems relating to the entire Lake Superior region prior to the inauguration of the work on which the present volume is based.

[a] Van Hise C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan, including a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897. (See Chapter I, Geological explorations and literature, pp. 5–148.)

1845.

SANDERS, GEORGE N. Report to J. J. Abert: Sen. Docs., 2d sess. 28th Cong., 1844–45, vol. 7, No. 117, pp. 3–9.

The first known reference to the Menominee district is found in the report of George N. Sanders, who made an examination of the country along the Menominee River with a view to determine the feasibility of constructing a road from Green Bay on Lake Michigan to Copper Harbor on Lake Superior. In this report we find described the general features of the country traversed. The report is topographical rather than geological; nevertheless, the author refers to various veins of spar met with in his travels.

SANDERS, GEORGE N. Report to J. Stockton: Sen Docs., 2d sess. 28th Cong., 1844–45, vol. 11, No. 175, pp. 8–14.

This report is a reprint of the preceding one.

1849.

FOSTER, J. W. Report to Dr. C. T. Jackson: Sen. Docs., 2d sess. 30th Cong., 1848–49, vol. 2, No. 2, pp. 159–163. Dated Sept. 28, 1848.

In this article the author prints an abstract of his report to Dr. Jackson, published in full during the succeeding year. A brief description of Menominee geology is given, the reader being referred to the full report for details.

1850.

JACKSON, C. T. Report on the geological and mineralogical survey of the mineral lands in the State of Michigan, etc. Sen. Docs., 1st sess. 31st Cong., 1849–50, vol. 3, No. 1, pp. 371–624. Dated Nov. 10, 1849.

Dr. Jackson's report is devoted mainly to the region immediately bordering Lake Superior. In it, however, the author mentions having received a specimen of slightly magnetic iron ore from the Menominee River. It was given him by Mr. Barbeau, of Sault Ste. Marie, who had received it from an Indian. The ore was reported as occurring in mountainous masses somewhere between the head of Keweenaw Bay and the Menominee River. An analysis of the ore yielded 89.70 per cent Fe_2O_3; 12.20 per cent siliceous matter.

FOSTER, J. W. Notes on the geology and topography of portions of the country adjacent to Lakes Superior and Michigan in the Chippewa land district, pp. 773–801. Dated May 26, 1849.

Messrs. Foster and Hill were sent by Dr. Jackson to make a section from L'Anse to the Menominee River and to search for the iron mountain referred to in the preceding article. These geologists report that "alternating beds of hornblende and argillaceous slates" occur on the Menominee River about 1 mile below the junction of the Brule and the Michigamme. Near the south line of T. 41 N., R. 30 W., they also report the existence of a high ridge of "argillaceous slate containing amygdules of calc spar." Between this point and the Upper Twin Falls the argillaceous slates and chloritic slates largely predominate. At these falls and at the Lower Twin Falls they present good sections. About 2 miles southeast of the lower falls, near sec. 30, T. 40 N., R. 30 W., large beds of specular ore are associated with talcose and argillaceous slates. The ore is similar to that of the "iron mountain," which is now identified as Republic Mountain, in the Marquette range. Among the other rocks observed on what is now known as the Menominee range were great blocks of limestone in the Menominee River at the mouth of the Misskos (T. 40 N., R. 31 W.), ledges of "hornblende" exposed on the banks of the stream, beds of talcose slate at the foot of the Great Bekuenesec Falls (now the Big Quinnesec Falls, in the northwest portion of T. 39 N., R. 30 W.), a similar bed at the foot of the Little Bekuenesec Falls, and a third bed of the same character at the foot of the Sturgeon Falls. At the latter place the slates are "wedged out between walls of sienite." At Chippewa Island the slates again occur. Here the authors constructed a section with drift on top, followed beneath by nearly horizontal sandstone, dark-colored basalt, and argillaceous and talcose slates. The sandstone rests upon the upturned edges of the slate. Since its deposition the former rock is said to have suffered no great alteration or disturbance, whereas the slates on which it rests are contorted and altered by the protrusion of igneous rocks.

The iron ores referred to are reported to "bear upon their surfaces strong marks of their mechanical origin." The report continues:

> They are regularly stratified, * * * so that a specimen, on its cross fracture, resembles ribbon-jasper. The lines of stratification can readily be distinguished from those of lamination. Like the slates, they are often found contorted and wrinkled, and the same facts could be advanced in both cases to prove their common origin [p. 779].

This statement sounds strange in view of the author's later attempt, in conjunction with Whitney, to show that similar ores in the Marquette district are eruptive in origin.

In the systematic description of the rocks met with in the journey we find that a range of rock, supposed to be granite, was discovered running parallel to the Menominee River, in Tps. 39 and 40 N., Rs. 30 and 31 W., and crossing the river at Great Bekuenesec Falls. On both sides of this range igneous hornblende rocks were found.

1851.

FOSTER, J. W., and WHITNEY, J. D. On the age of the sandstone of Lake Superior, with a description of the phenomena of the association of igneous rocks: Proc. Am. Assoc. Adv. Sci., Fifth Meeting, pp. 22–38. 1851.

In the course of a general description of the Lake Superior sandstone the authors state that the belt of this rock is 14 miles wide where it crosses the Menominee, that it has a gentle dip to the southeast, not exceeding 3°, corresponding with the slope of the country, and that in the bed of the river it rests on vertical edges of slate rocks and of compact and igneous rocks intercalated with them.

FOSTER, J. W., and WHITNEY, J. D. Report on the geology of the Lake Superior land district, pt. 2, the iron region, together with the general geology. Dated Nov. 12, 1851. Sen. Docs., special sess. 32d Cong., 1851, vol. 3, No. 4. xvi, 406 pp., with map.

In the general portion of this report the statements made to Dr. Jackson by the senior author with reference to his observations on the Menominee River are repeated. In addition it is stated that above the Big Quinnesec Falls and just above the lower falls the rocks consist of serpentine, and that at the head of the upper falls there is a protrusion of a rock like protogine, "composed of feldspar, talc, and quartz. * * * Occasionally hornblende replaces the talc, when it [the rock] passes into a well-characterized syenite" (p. 25). Slates are mentioned as occurring between the Little Quinnesec Falls and Sandy Portage, and serpentine between the latter place and Sturgeon Falls. On the portage a ridge was crossed in which the rock has the external character of granite, but the mineralogical composition of protogine. Slates and dark-green igneous rocks alternate as the Menominee is descended, the gradations between the igneous rocks being so numerous as to prevent their proper classification. At some distance below the portage are basaltic and other crystalline greenstones which at Chippewa Island are declared to be in contact with talcose slates. Near the south end of the island the slates are described as being porphyritic with red phenocrysts, and with them are said to be associated large masses of serpentine.

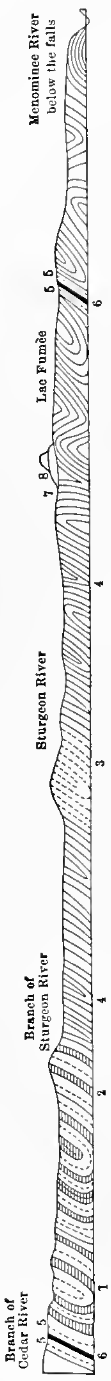


FIG. 1.—Geological section across the Menominee district from Little Bekuenesec Falls northward. After Foster and Whitney, 1851. Distance, 16 miles; the base line about 200 feet above Lake Michigan. 1 and 2, alternations of gneiss, hornblende, and quartz; 3, compact quartz; 4, talcose slates and chlorite-slates; 5, saccharoidal limestone; 6, specular iron; 7, Potsdam sandstone; 8, Calciferous sandstone.

After describing the rocks occurring along the Menominee the authors give a general account of the topographical features of the Menominee Valley, and describe a geological section (see fig. 1) across the valley from sec. 35, T. 42 N., R. 30 W., to a point near the Little Quinnesec Falls, in sec. 14, T. 39 N., R. 30 W. The description is taken from the notes of Charles Whittlesey. The quartz shown in the section is said to pass into hornblende-slate, and to the north into gneissoid rocks.

A large number of observations were made on the rocks occurring north of the river, some of which are of interest. On the north side of Lake Fumèe is a sharp and elevated ridge whose top consists of Potsdam and Calciferous sandstone resting undisturbed on the Azoic rocks beneath. In secs. 34 and 35, T. 40 N., R. 30 W., is a compact marble belonging with the Azoic, and in sec. 30 of the same town is a "conspicuous iron mountain." Iron ores were also noted in a ridge south of Antoines Lake, in the southern portion of T. 40 N., R. 30 W. These are believed to be the southernmost ores in the district. They are specular in structure and are of a bluish-black color. Between secs. 28 and 29, in T. 40 N., R. 28 W., is a great deposit of ore containing from 63 to 68 per cent of iron.

The series to which the ores, schists, limestone, and quartz rocks belong occupies a belt whose broadest expansion is not less than 80 miles in width. The rocks comprising the series are supposed to be flexed and folded, as measurement across their upturned edges would give a thickness for the series, providing it is assumed to be unfolded, too great to be regarded for an instant as correct. The entire series is considered to be metamorphic, even to the compact "hornblende," which resembles an igneous rock. Between the granite that underlies them and the Silurian sandstones that overlie them the rocks of the series—

throughout their whole extent * * * are more or less metamorphosed, presenting a series of gradations represented at one extreme by crystalline gneiss and compact hornblende and at the other by bedded limestone and ripple-marked quartz. To the presence of granitic and trappean rocks this transformation is, in a great degree, to be attributed. Much of the compact hornblende presents the external characters of an igneous product; but, since it is found to occupy an almost invariable relation to the granite axes—flanking their slopes—and to assume a fissile structure as it recedes from the lines of igneous outburst, we can not but regard it as the more highly metamorphosed portions of the dark-green chlorite-slates. This compact hornblende is not to be confounded with those lenticular-shaped masses observed in the slates which, we doubt not, are trappean in their nature.

We have seen that those igneous causes which produced numerous axes of elevation, and folded the strata into a series of flexures, had ceased to operate before the deposition of the Silurian groups, since they are found to repose in a nearly horizontal position upon the upturned edges of the slates, or to occupy the sinuosities in the granite, nowhere exhibiting traces of metamorphism or derangement of the strata.

* * * From the local details above given, it will be seen that the igneous rocks of the Azoic period, though crystalline, compact, and occasionally porphyritic in their texture, are never amygdaloidal (like the traps on Keweenaw Point), and hence we infer that they were produced under widely different conditions. The latter may have been consolidated beneath the pressure of a great ocean, while from the former a greater part of this pressure may have been removed; or it may be that both were, in the first instance, equally vesicular, but that the latter assumed a crystalline or compact structure from long-continued exposure to heat, under immense pressure. All the phenomena would seem to indicate that the eruption of the trappean rocks of this period took place beneath an ocean of great depth; or, at least under conditions widely different from those which prevailed during the formation of the trappean belts of Keweenaw Point and Isle Royale [p. 32].

After making some general remarks upon the necessity of regarding the rocks below the base of the Silurian as composing a great system, which they call the Azoic, the authors proceed to describe each rock in detail and to note its occurrence in the region examined. They repeat many of the statements above referred to, and theorize as to the origin and the relative ages of the different rocks. Their conclusions with respect to the age of the Menominee rocks are not essentially different from those reached in the discussion of the Marquette rocks—results that have been freely described in the Marquette monograph.[a] The most important of these conclusions relates to the igneous origin of the iron ore, which in the previous

[a] Mon. U. S. Geol. Survey, vol. 28, 1897.

year the senior author had argued to be sedimentary. (Cf. p. 44.) Two other igneous rocks are especially noted; one is a compact, dark, hornblendic rock, the other a light-colored rock resembling a member of the granite family, and designated a "feldstone."

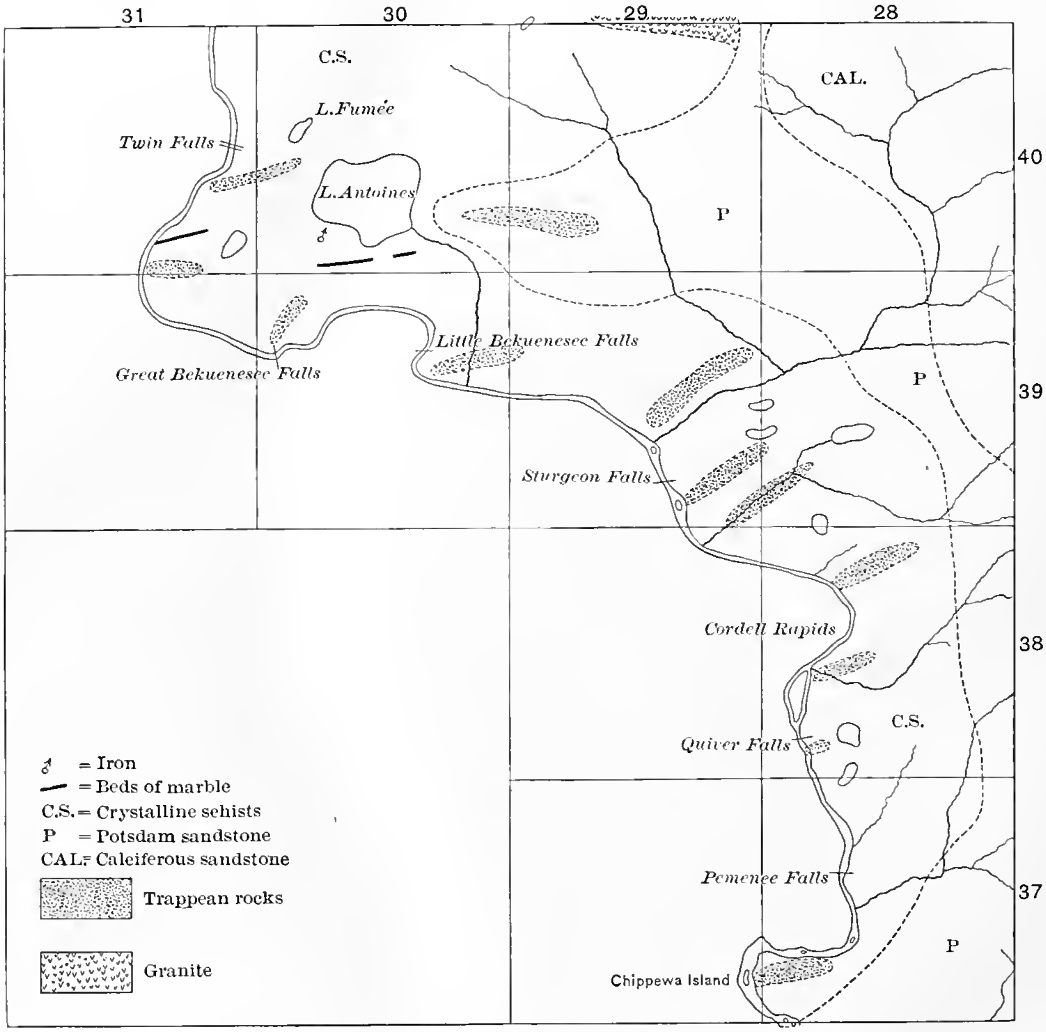


Fig. 2.—Portion of the geological map of the Lake Superior land district in the State of Michigan. After Foster and Whitney, 1851. The squares are townships, each embracing about 36 square miles.

The map which accompanies the report is intended to show approximately the distribution of the Azoic, the Paleozoic, and the igneous rocks. That portion of it which relates to the Menominee district is here reproduced without colors as fig. 2.

1855.

FOSTER, J. W. Catalogue of rocks, minerals, etc., collected by J. W. Foster: Ninth Ann. Rept. Smithsonian Institution, pp. 384–386. 1855.

As its title indicates, this article is simply a catalogue of specimens.

1860.

WHITTLESEY, CHARLES. On the origin of the Azoic rocks of Michigan and Wisconsin: Proc. Am. Assoc. Adv. Sci., Thirteenth Meeting, pp. 301–308. 1860.

In a somewhat general article on the "Azoic" rocks of the Upper Peninsula of Michigan, the author records the results of analyses of 15 rocks collected mainly from the Menominee drainage basin. By comparison of these analyses with those of the Laurentian rocks of Canada, the conclusion is reached that the Menominee "metamorphic rocks," including the slates, etc., must be of a different age from the sediments which yielded the Laurentian rocks, if these are really metamorphic. The author, however, is inclined to doubt their metamorphic origin.

Igneous rocks are described as being in contact with Potsdam sandstone in the Menominee district, and the sandstone is said to have been metamorphosed at the contact. The agent producing the change is nevertheless thought not to be heat. It appears that the author would regard the "metamorphic rocks" associated with the iron ores as igneous.

1861.

WINCHELL, A. First biennial report of the progress of the geological survey of Michigan, etc. Lansing, 339 pages. 1861.

In this report the only allusion to the Menominee district is found in the statement that "On the State boundary the Azoic belt stretches from beyond Lac Vieux Desert to Chippewa Island, in the Menominee River" (p. 49). The rocks of the system are declared to be talcose, chloritic, and siliceous slates, quartz, and beds of marble.

1868.

CREDNER, H. Die Gliederung der eozoischen (vorsilurischen) Formationsgruppe Nord-Amerikas: Zeitschr. f. die Gesammten Naturwissenschaften, vol. 32, 1868, pp. 353–405, and Habilitationschrift mit Genehmigung der phil. Fak. der Univ. Leipzig, Halle. 1869.

In connection with a general discussion of the pre-Silurian rocks of

North America, which are divided into the Laurentian and the Huronian systems, Credner describes briefly the geology of the Upper Peninsula of Michigan.

The Laurentian system of Michigan is made to consist of a series of gneisses, mica-schists, hornblende-schists, granites, and syenites, with a total thickness of over 20,000 feet. These rocks occur with many different variations of mineralogical composition, chloritic and talcose varieties being especially abundant. They all show their sedimentary origin in their present structure. Besides, at the Falls of the Sturgeon River there are typical conglomerates interbedded with micaceous and hornblendic rocks. At this point the author observed, in the midst of the gneiss series, several hundred feet of a complex consisting of thin-bedded talcose and sandy ripple-marked schists, a thin layer of protogine-gneiss, and three beds of conglomerate, each 30 feet in thickness. These conglomerates contain pebbles of gneiss, granite, and quartzite, varying in size from that of a hazelnut to that of one's fist, embedded in a talcose sandy groundmass. The conglomerate is described as conformably overlain by gneiss.

No eruptive rocks were discovered in the Laurentian of Michigan older than the coarse-grained and porphyritic granite that intrudes the gneiss.

The Huronian series surrounds the Laurentian rocks and lies upon them unconformably. It is characterized as a series of sediments intermediate in age between the Laurentian rocks below and the Silurian series above. It consists of a regular succession of quartzites, limestone, iron ores, chloritic and clay slates, and talc-schists, with a thickness of 18,000 feet, and, interlaminated with them, beds of diorite and aphanite. The series forms a major syncline, with a minor syncline extending into the embayments along the edge of the Laurentian areas.

In that portion of the Menominee district where the Huronian system is most regularly developed, this system comprises, in order, beginning with the oldest, 2,000 feet of quartzite; 2,000 feet of white or red limestone; 700 feet of schistose hematite, varying in composition from a ferruginous quartzite to a granular hematite; 1,200 feet of chlorite-schists; 8,000 feet of gray clay slates, interlaminated with layers of granular quartzite; 1,200 feet of chlorite-schists; 2,000 feet of coarse diorite; and a series of talcose clay slates and quartzose talc-schists.

The limestone contains thin layers of siliceous clay slate, bands of quartzite, and occasional inclusions of tremolite. On the south shore of Lake Antoine beds of coarse calcareous sandstone and of a conglomerate made up of limestone fragments in a quartzose groundmass are interlaminated with the limestone beds. In the upper horizon of the upper chlorite-schists are about 100 feet of diorites, and in certain places about 100 feet of talc-schists. The Huronian series, like the Laurentian, is devoid of eruptives.

1869.

CREDNER, H. Die vorsilurischen Gebilde der "oberen Halbinsel von Michigan" in Nord-Amerika: Zeitschr. Deutsch. geol. Ges., vol. 21, pp. 516–554. Map and four plates of sections. 1869.

In a fuller account of the pre-Silurian geology of the Upper Peninsula of Michigan Credner discusses the details upon which the conclusions expressed in his former paper (pp. 49–51) are based.

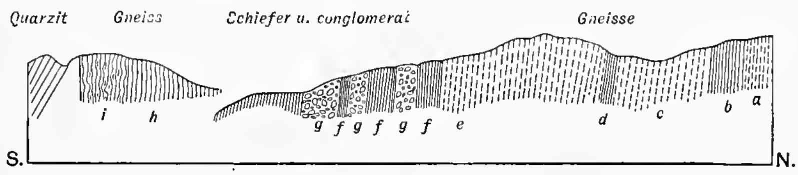


FIG. 3.—Geological section along the Falls of the Sturgeon River. After H. Credner, 1869.

The Laurentian gneisses and schists are reported to exist as islands projecting through the Huronian sediments. The most important Laurentian rocks are mica-gneisses, hornblende-gneisses, hornblende-schists, and granites, with a measured thickness of about 10,000 feet at the Falls of the Sturgeon River. Here the succession, beginning at the north, is as follows (see fig. 3):

(*a*) A great thickness of fine-grained, micaceous gray gneiss, interbanded with coarse-grained, feldspathic, red gneiss, and a few beds of hornblende-gneiss and hornblende-schist.

(*b*) Chlorite-gneiss, with streaks of chlorite-schist.

(*c*) Talc (protogine)-gneiss, through loss of talc passing into—

(*d*) Chlorite-gneiss containing bands of chlorite-schist.

(*e*) Fine-grained talc-gneiss, inclosing a mass of granular magnetite and hematite one-half foot in diameter.

(*f*) Fine-grained mottled schists ("Fleckschiefern"), composed of fine plates of talc and mica and very small grains of sand and of feldspar. In this are lenticular masses or thin bands of pure feldspar or of fine-grained talc-gneiss. The schist is thin bedded, and its bedding surfaces are marked by ripple marks. It occurs in four zones measuring from 8 feet to 40 feet in thickness. Between these are—

(*g*) Three beds of conglomerate, 15–30 feet thick, composed of a matrix similar to the "Fleckschiefern," filled with sharp-edged and rounded fragments of granite, gneiss, and quartz, varying in size between a hazelnut and a man's fist. Beds (*f*) and (*g*) dip vertically or steeply to the south.

Observations made a mile farther west show that these conglomerates are followed to the south by—

(*h*) Gneiss-granite, and—

(*i*) Fine-grained hornblende rock.

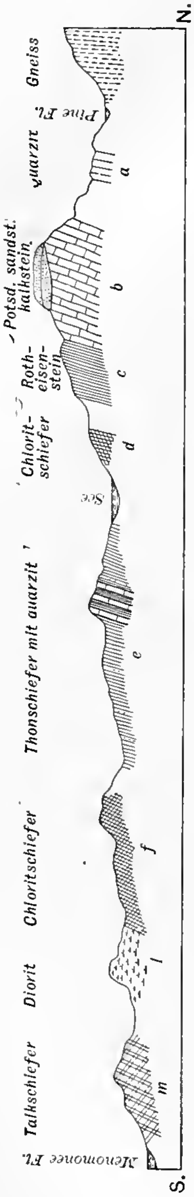


Fig. 1.—Geological section across the Menominee district. After H. Credner, 1869.

After comparing this section with several other sections observed farther north, the author summarizes concerning the Laurentian system as follows:

It consists of predominating mica-gneisses in all possible varieties that may be formed by the variations in structure and in the proportions of constituents present, of hornblende-gneisses and hornblende-schists interbedded with these, and of chlorite-gneisses and chlorite-schists associated with zones of granite, syenite, and chlorite-granite. These constitute the surface rocks over extensive areas, strike with great regularity east and west, usually dip vertically, are here and there contorted, and are intruded by younger granite.

Less broadly distributed are two series of talcose and chloritic forms. One series is composed of talc-gneiss, talcose mottled schists ("Fleckschiefern"), and conglomerates, with a sandy talcose groundmass. The other series consists of talc-chlorite-schists, with zones of crystalline, dolomitic limestone, chlorite-gneiss, chloritic hornblende rock, chlorite-schists with quartz pebbles, and foliated talc-gneiss. Between the equivalents of these as described in Canada are three limestone zones, of which the uppermost contains the *Eozoon canadense*. In the Laurentian limestones of the Upper Peninsula of Michigan I have not been so fortunate as to discover this fossil [pp. 525–526.]

The Laurentian areas are surrounded by a schist system composed of quartzite, limestones, iron-bearing rocks, and crystalline schists. Beginning at the bottom, the system consists of the following (see fig. 4):

(*a*) Dense, glassy, or sugary quartzite, thick bedded or thinly laminated, and possessing coatings of yellow mica in its foliation joints. Thickness, about 3,000 feet.

(*b*) Crystalline dolomitic limestone. Rarely pure. Generally impure through admixture of silica. Its texture varies between coarse grained and very fine grained. Its color may be yellow, red, brown, or white. Its bedding is thick or thin, and the planes between the layers are sharply marked. Sometimes there are interpolated between them thin beds of argillaceous chlorite-schist and siliceous clay slate. Quartz veins penetrate the dolomite in thin and thick seams, which are more abundant in the upper portions than in the lower parts. The variation in the amount of quartz present is exhibited in the topographic differences noted. Occasionally the dolomite contains tremolite. Thickness, 3,500 feet.

(*c*) Hematite rock. This varies from a ferruginous quartzite or a ferruginous clay slate to a pure steel-gray dense or granular hematite (Rotheisenstein). It is thinly schistose to thick bedded, but usually occurs as a series of beds about an inch thick, in which siliceous and iron-rich bands alternate. In a few zones the jasper layers are entirely lacking and beds of iron ore 30 feet thick replace them. The ore is free from phosphorus and sulphur, but it contains everywhere traces of magnetite. Thickness of the group, 600 to 1,000 feet. The quartzite underlying the dolomite is also ferruginous in places in its upper horizons and is consequently colored red. At several points the ferruginous material is thought to be sufficiently concentrated to constitute ore bodies.

(*d*) Chlorite-schist, with spots and thin stains of red, ferruginous clay. Interlaminated with the schist are layers of quartz 3–4 feet thick. Thickness, probably 1,000–1,500 feet.

(*e*) Clay slate, gray, thinly laminated and rusty brown on its schist planes; or blue, black, and very finely schistose. In the midst of the slate is a 150-foot bed of quartzite, which is very hard, granular, bluish gray, and is penetrated by veins of white glassy quartz and red orthoclase. Thickness, 8,500 feet.

(*f*) Dark-green chlorite-schist, often argillaceous. Thickness, 1,200–1,400 feet. In its upper horizons fine-grained and coarse-grained diorites in beds varying from ten to several hundred feet are associated with the schist.

(*g*) Feldspathic talc-schist, light yellow or light brown in color. Thickness, 30 feet.

(*h*) Greenish-gray talc-schist, flecked with emerald-green spots and containing rounded quartz grains. Associated with the schist are very thin lenticular laminæ of crystalline dolomite. Thickness, 30 feet.

(*i*) Flesh-colored feldspathic talc-schist, containing lenticular grains of quartz. Thickness, 40 feet.

(*k*) Fine-grained rock consisting of a feldspathic groundmass, containing plates of talc, small reddish-brown orthoclase, and gray quartz grains. Thickness, 50 feet.

(*l*) Diorite rock series, 2,300 feet thick.

(*m*) Talcose clay slate and quartzose talc-schist, 1,500 feet thick. This series is the youngest in the Upper Peninsula of Michigan. Farther south in Wisconsin the same rock series occurs, but here it dips to the north, forming a basin with the northern schists.

The beds (*g*), (*h*), (*i*), and (*k*) seem to possess only a slight horizontal extension. They are local in their development. They are most fully developed at the Big Quinnesec Falls, but rapidly wedge out on both sides along their strike. At the Little Quinnesec Falls a portion of the talc-schist series is replaced by chlorite-schist and a diorite bed 12 feet thick.

The lowermost member of the Huronian, the quartzite, lies unconformably upon the gneisses. The other members of the iron-bearing series follow the quartzite conformably. In the neighborhood of Lake Antoine they are folded into two synclines, with limbs dipping very steeply toward the axes of the folds. South of the southern fold the entire iron-bearing series is repeated, with a steep southern dip, forming the north side of a third syncline with its south side in Wisconsin.

Over the Huronian rocks in many places lie patches of horizontal Potsdam sandstone and Calciferous sandstone. Two sections showing the relations of the Potsdam to the underlying rocks are given. The entire district is supposed to have been covered formerly with Paleozoic sediments, as is the district farther east at the present time, the patches on the tops of the hills being the remnants of this covering, which have thus far resisted the combined effect of weathering and the action of the ice.

In a few words, the iron-bearing series as developed in the southern part of the Upper Peninsula of Michigan is characterized as follows: A conformable series of

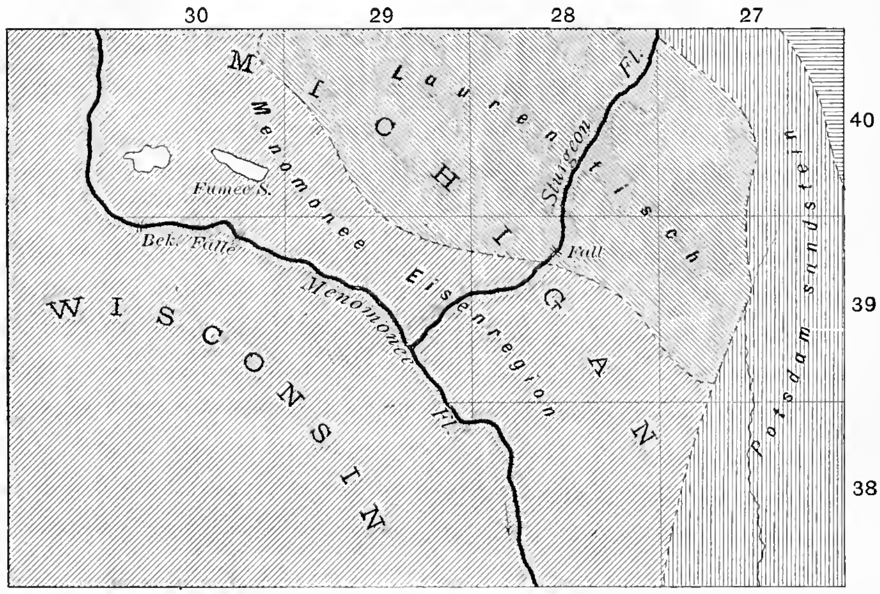


FIG. 5.—Portion of geological map of the Upper Peninsula of Michigan. After H. Credner, 1869. The squares are townships, each embracing about 36 square miles.

quartzites, limestone, hematite, clay slates, chlorite-schists, and talc-schists, the last two associated with beds of diorite and having a total thickness of 20,000 feet, overlies unconformably a gneiss series, and is in turn unconformably overlain by Silurian beds. This schist complex occupies the entire distance between gneiss and granite rims in long narrow folds. Organic remains have not been discovered anywhere in the series [p. 534].

The Menominee district is thought to have remained under water longer than the northern or Marquette district, since in the former district above the quartzite a great thickness of rocks occurs which in the northern district is not represented at all.

The map accompanying the article shows the general distribution of the Archean, the Huronian, and the Paleozoic formations in the Upper Peninsula. That portion covering the Menominee district is reproduced in fig. 5.

1870.

CREDNER, H. Ueber Nordamerikanische Schieferporphyroide: Neues Jahrbuch für Min., etc., pp. 970–984. 1870.

At the Big Quinnesec Falls of the Menominee River, in the upper portion of the Huronian series, as defined by Credner, is a belt of porphyroid schists, about 300 feet in thickness, lying between two beds of diabase (the diorite of former articles). The schists comprise 50 feet of slightly schistose orthoclase-porphyroid, 10 feet of feldspathic paragonite-schist, 30 feet of orthoclase-paragonite-schist, 15 feet of paragonite-schist, 15 feet of calcareous paragonite-schist, 30 feet of schistose porphyroid, 50 feet of calcareous chlorite-schist, and 100 feet of chlorite-schist. Above and below this schist series are diabase layers, which separate the porphyroids from an underlying series of chlorite-schists and an overlying series of siliceous talc-schists. The petrographical composition of the porphyroids is carefully discussed. All of the acid members consist essentially of quartz, orthoclase, and paragonite in varying proportions. Analyses of four varieties, the first two by Aarland, the third by Berghändler, and the fourth by Bornemann, resulted as follows:

Analyses of porphyroid and schists from Big Quinnesec Falls, Menominee River.

	Orthoclase-porphyroid.	Felds. paragonite-schist.	Ortho. paragonite-schist.	Paragonite-schist.
SiO_2	66.70	72.45	76.51	75.50
Al_2O_3	15.90	8.85	7.95	8.60
Fe_2O_3	4.70	6.20	8.88	2.60
MnO	tr.	tr.	tr.	....
CaO	tr.	tr.	.32	7.20
MgO	....	....	tr.	1.20
K_2O	8.06	9.24	1.02	30
Na_2O	5.50	3.70	4.38	3.00
H_2O	....	....	....	1.50
Total	[a] 100.80	[a] 100.50	99.06	99.90

[a] These totals are as given in the original. The correct footings are 100.86 and 100.44.

After examining the theories proposed to account for these and similar rocks, the author concludes that they are not eruptives, nor are they metamorphosed sediments. On the other hand he regards them, together with all the other Huronian rocks and all the Laurentian series, as crystalline sediments, thrown down from the waters of the pre-Silurian ocean. Later they may have suffered some alteration through the influence of mineral waters.

1873.

Brooks, T. B. Iron-bearing rocks (economic): Geol. Surv. Michigan, Vol. I, part 1, Chap. IV, pp. 157–182. With atlas plates, three of which relate to the Menominee district. 1873.

At the time Major Brooks published his report on the Menominee district but two mines, the Breen and the Ingalls, had been opened, so that the author, in his study of the district, was compelled to rely for his data almost exclusively upon surface exposures. Many of the facts he records in connection with the geology of the district were obtained largely from a survey made by Messrs. Pumpelly and Credner for the Portage Lake and Lake Superior Ship Canal Company.

In the chapters preliminary to the one devoted to the Menominee district several facts are incidentally noted which throw considerable light upon the author's views concerning Menominee geology. The hills in the drainage basin of the Menominee River are reported to be capped with horizontal Silurian sandstone, which once also probably filled the valleys between them (p. 68). In comparison with the Marquette district the Menominee district is simpler in its geological structure, and it possesses a correspondingly less varied topography. The elevations trend nearly east and west. The south iron range is the Menominee range proper—the one discussed in the present monograph. The north range is that now known as the Felch Mountain or Metropolitan range. Its geology was discussed in the Crystal Falls monograph.[a] The southern range can be traced 15 miles in a WNW. direction through T. 39 N., R. 29 W., and T. 40 N., R. 30 W. (p. 72). Its structure is so simple that "whoever identifies the upper marble in the Menominee region has a sure key to the discovery of any ore which may exist in the vicinity" (p. 74). In Chapter IV of the report the general geology of the district is discussed, many localities of the different rock types occurring within it are mentioned, and three structural sections across the iron-bearing series are described.

[a] Mon. U. S. Geol. Survey, vol. 36, 1899.

The Menominee belt of ore-bearing rocks is separated from the more northerly belt of similar rocks by a wedge-shaped area of granite. The most easterly exposure of ore in the southern belt is at the Breen mine, in the north half of the northwest quarter, sec. 22, T. 39 N., R. 28 W. Traveling from this point toward the west, following a course running 16° north of west, several other exposures of ore are encountered before the last ore in Michigan is met with in the center of the southeast quarter, sec. 25, T. 40 N., R. 31 W. By magnetic observations the ore belt was traced across the Menominee River into Wisconsin, where its probable continuation is marked by outcrops between the Brule and the Pine rivers. Immediately north of this iron-bearing belt is a broad belt of impure marble, and north of this, in the vicinity of the Sturgeon River, are local magnetic attractions and a few iron-ore bowlders that are believed to mark the position of a second ore belt, which outcrops as a siliceous ore north of Lake Antoine. North of this second ore belt, and underlying it, is an immense bed of quartzite.

This quartzite, although believed to be geologically conformable with the ore formations, is not parallel with them, running more northwesterly, and dividing in T. 40 N., R. 30 W., into two and perhaps three ranges [p. 159].

North of the quartzite and underlying the whole series, which is Huronian in age, are the Laurentian granites, gneisses, and schists.

South of the southern belt is a bed of chloritic schist that is well exposed on the south shore of Lake Hanbury and on the Sturgeon River, and south of this is a second quartzite, very different from that to the north. South of the quartzite follows a broad exposure of argillaceous slate in a belt running nearly parallel to the ore belt. It is exposed at several points in T. 39 N., R. 28 W., and in T. 39 N., R. 29 W. Finally, south of the slates,

is a broad, well-defined belt of chloritic, hornblendic, and dioritic rocks running parallel with the iron range, the harder members of which form the barrier rocks of all the falls in this part of the Menominee, and probably those of Pine River in Wisconsin [p. 159].

Above the iron-bearing series is the Silurian sandstone, which occurs as the capping of many of the hills of the iron-bearing area and completely covers both Laurentian and Huronian rocks a few miles east of the last known exposure of ore at the Breen mine.

With regard to the structure of the district the author declares that, like their equivalents in the Marquette district, the Menominee rocks usually conform in strike with the trend of the belts and dip at high angles, thus presenting their upturned edges to the observer. The conditions are thus not favorable for working out the structure of the district, especially in view of the difficulty in distinguishing between cleavage and bedding in the slates and chlorite-schists. The north and south ranges taken together constitute a great east-west anticline, of which the Laurentian area is the great backbone on and against which the iron series reposes.

In order to picture the structure two sections across the district are described, one crossing the Menominee River at Sturgeon Falls in sec. 27, T. 39 N., R. 29 W., and the other passing just east of Lake Antoine.

The lowermost rocks in the first section (fig. 6) are unmistakably Laurentian (D). They comprise granite, syenite, various gneisses and schists, and some chloritic and talcose slates. Separating these from the

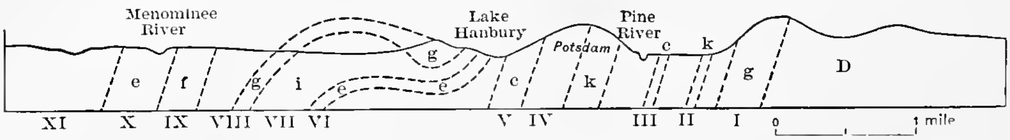


Fig. 6.—Geological section through Sturgeon Falls. After T. B. Brooks, 1873. Horizontal scale given is approximate. Vertical scale is exaggerated. For significance of letter-symbols, see Pl. III.

unmistakably Huronian sediments is a series of soft, light-gray, talcose slates underlain by four beds of conglomerates, which in turn are underlain by two beds of protogine-gneiss, separated by a bed of chlorite-schist. These rocks the author states are regarded by Pumpelly and Credner as Laurentian, though he is not certain that they are of this age.

The undoubted Huronian series includes, beginning with the lowermost, a light-gray, massive vitreous quartzite (I); a quartzose sandstone and conglomerate (II), that may be equivalent to the marble outcropping in secs. 24 and 25 in T. 40 N., R. 30 W.; magnetic ore (III), whose existence is indicated by bowlders only; a great development of thin-bedded, usually light-gray marble (IV), whose upper portions contain seams of slate; the main ore-bearing formation (V), consisting of siliceous specular slate ores corresponding very nearly to the flag ores of the Marquette district; chlorite-schist (VI); a bluish and greenish slate (VII), showing indistinctly a distorted bedding with prevailing northerly dips; a bluish-gray quartzite (VIII), dipping north at 45°–75°; magnesian schists (IX) near the Menominee River; granular diorite (X); and magnesian schists and protogine (XI). The quartzite may be simply a local bed in the clay-slate formation. Marked contortions in both the slate and the quartzite are observed, which point unmistakably to the presence of a great fold indicated in the section as a combination of an anticline with a syncline.

In the second section (fig. 7) the Huronian beds are arranged in the same sequence. First, to the north comes the quartzite (I) in a great synclinal fold; then marble (II), corresponding to the friable sandstone in the first section. Next follows a bed of siliceous red iron ore resembling the ore of formation V, but which is probably the western extension of formation III. Dr. Credner connects this bed with bed V, farther south, in a synclinal fold, but the author is inclined to regard it as an independent bed at a lower horizon than V. Above bed III is the great marble formation (IV), and then the great iron formation (V). Beds VI, VII, VIII of the first section (fig. 6) have no equivalents in the second section, their

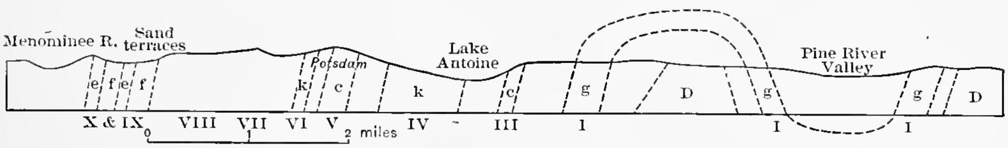


Fig. 7.—Geological section through Lake Antoine. After T. B. Brooks, 1872. Horizontal scale is approximate. Vertical scale is exaggerated. For significance of letter-symbols, etc., see Pl. III.

places being covered with drift. In the place where formation VI should occur, according to the author's hypothesis of the structure, Pumpelly observed a large ledge of marble. The existence of this marble in this place leads Brooks to suppose that there may be folds in the rocks in this vicinity not revealed by his studies. Formations IX and X are the chloritic, hornblendic, and dioritic rocks exposed at the Big and Little Quinnesec Falls.

The description of the sections concludes the discussion of the general structure of the district. There are several further references to the ores, exposures of rocks, etc., but detailed studies of them are not recorded.

Pl. VII of the volume is a magnetic map of T. 40 N., R. 30 W., showing two lines of magnetic disturbance crossing the southern portion of the township and running in a NNW. direction. Pl. IV in the atlas accompanying the report is a geological map of the district, exhibiting the author's theory of the structure. It is reproduced as Pl. III of this volume.

ROMINGER, C. Paleozoic rocks: Geol. Surv. Michigan, vol. 1, part 3, p. 102. 1873.

The author introduces his work on the Paleozoic rocks of the Upper Peninsula with a few preliminary remarks on the general geology of northern Michigan. Only a few of his statements refer to the Menominee district.

The existence of the upper beds of the Potsdam sandstone at the Breen mine is noted. The Menominee limestone is thought "to be connected with the slates and quartzite beds of the upper division of the Huronian series" (p. 100). The rock occurs in thick layers of a white, cream color or of a reddish tint. It is compact, subcrystalline, and very hard In composition the limestone is dolomitic, as is shown from the following analysis of a specimen from the Sturgeon River:

Analysis of limestone from Sturgeon River.

	Per cent.
$CaCO_3$	61.00
$MgCO_3$	34.00
Hydrated oxide of Fe and Mn	1.00
Siliceous matter	.25

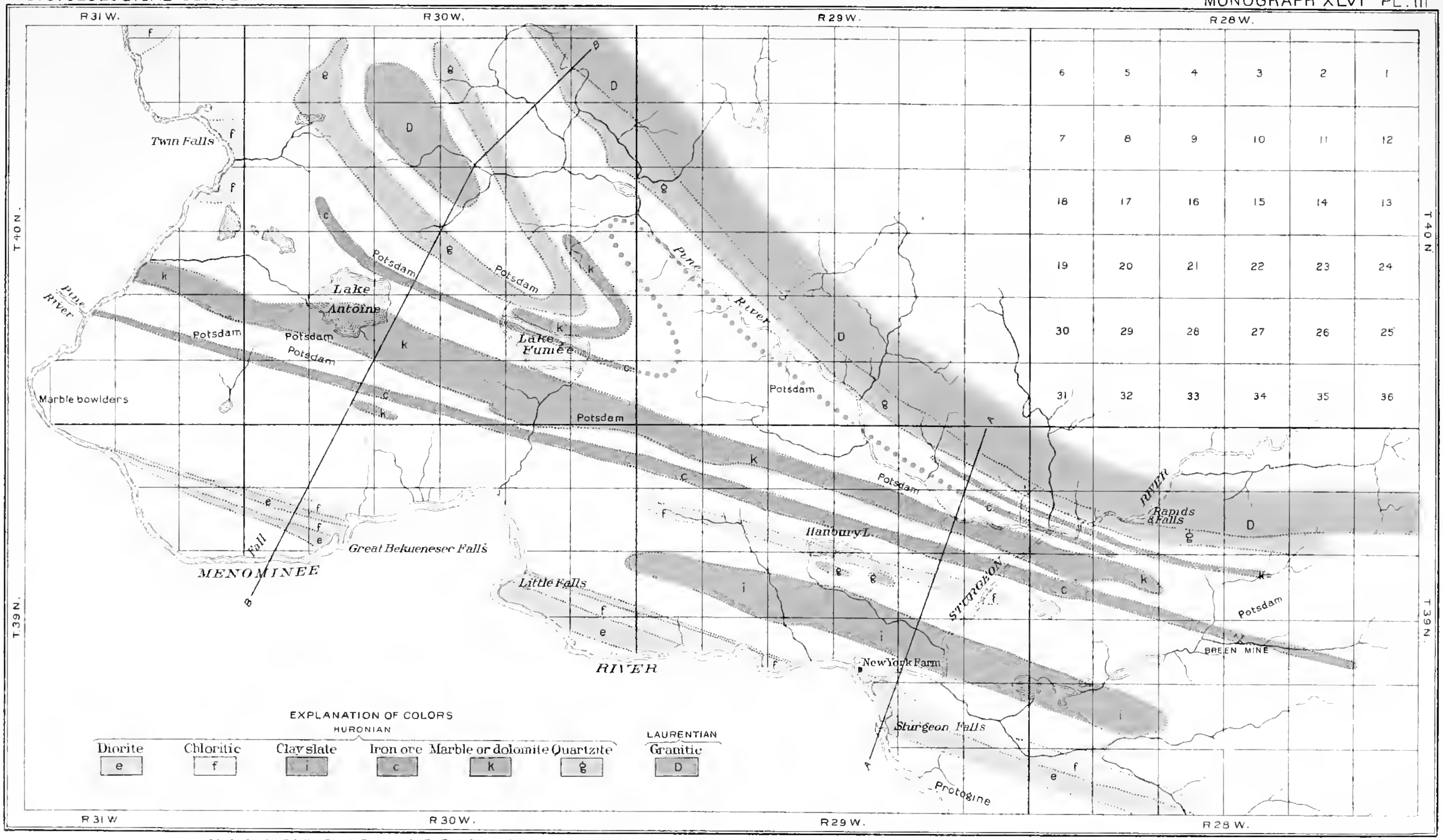
In many localities the limestone is cut by a dense network of coarse quartzose seams. On the Sturgeon River the seams are lacking, but the ledges are crossed in all directions by fine fissures.

BROOKS, T. B., and JULIEN, A. A. Catalogue of the Michigan State collection of the Huronian rocks and associated ores: Geol. Surv. Michigan, vol. 2, Appendix B, pp. 199–212. 1873.

In the description of this collection we find one of a pyritiferous talcose gneiss from the Falls of the Sturgeon River, one of a dolomite from sec. 11, T. 39 N., R. 29 W.; one of a hematite-schist from sec. 11, T. 39 N., R. 29 W.; one of an ochery hematite from the Breen mine; and one of a porphyritic speckled diorite from Sturgeon Falls on the Menominee.

JENNEY, F. B. Magnetic analyses and color of powder of Marquette ores: Geol. Surv. Michigan, vol. 2, Appendix H, pp. 257–260. 1873.

This article contains the results of the determination of the quantity of the magnetic and of the nonmagnetic constituents in 10 specular ores from the Menominee district.



PORTION OF GEOLOGIC MAP OF MENOMINEE IRON REGION, UPPER PENINSULA, MICHIGAN

BY T. B. BROOKS

1872

Scale

5 miles

Note. Reprint, without alteration of geologic data, of portion of Plate IV of Atlas accompanying Reports on Upper Peninsula, 1869-73, Geological Survey of Michigan

1876.

Brooks, T. B. On the youngest Huronian rocks south of Lake Superior and the age of the copper-bearing series: Am. Jour. Sci., 3d series, vol. 11, pp. 206–211. 1876.

In the summer of 1874 the author and Professor Wright discovered a large granitic area south of the Menominee River. On its northern side it is bounded by micaceous and hornblendic schists, the former of which are penetrated by a few small granite dikes. These schists are thought to correspond to the youngest member of the Huronian series discovered in the Marquette district, viz, bed XIX. The prevailing type of the granite is a medium- to coarse-grained gray hornblendic rock that is more or less gneissic. The granite and its associated schists bear such a close resemblance to the Laurentian rocks exposed on the Sturgeon River that at first they were thought to be of the same age as these. A careful consideration of the facts, however, inclines the author to believe that the granites and schists are Huronian, and from observations made in the Penokee district, he is inclined to regard them as the youngest members of this system. He gives reasons for this conclusion, but they are based almost exclusively upon observations made in the Penokee district.

In a footnote the author calls attention to what he considers an error in Credner's correlation of the entire Marquette series with the lower quartzite of the Menominee district. He thinks that Credner was led astray by his great overestimate of the thickness of the Menominee rocks, and by the fact that he founded his conclusions largely on a section of the Marquette series made in the neighborhood of Negaunee, where the upper members of the series are entirely lacking.

Brooks, T. B. Classified list of the rocks observed in the Huronian series south of Lake Superior, with remarks on their abundance, transitions, and geographical distribution; also a tabular presentation of the sequence of the beds, with an hypothesis of equivalency: Am. Jour. Sci., 3d series, vol. 12, pp. 194–204. 1876.

The nomenclature of the rocks mentioned in this paper is based on the investigations of Wichmann, Wright, Rutley, Hunt, Törnebohm, and Wapler. The thickness of the Menominee beds is estimated at 12,000 feet or more. The estimate of 18,000 given by Credner is thought to be excessive. In one instance, it is stated, this geologist mistook cleavage for bedding and thus "overlooked at least one synclinal and one anticlinal fold, thus counting the same bed at least three times" (p. 195). In the scheme of sequence and frequency the beds of the Marquette and of the Menominee series are divided into 20 formations, whose approximate relative ages are indicated by Roman numerals. It is unnecessary to present this scheme here as it was superseded a few years later by a new one which is outlined on pp. 65–66. The two do not differ materially except in the names of some of the rocks.

In the description of the table the rocks are divided into (1) fragmental rocks, exclusive of limestone; (2) metamorphic rocks not calcareous, subdivided into the mica-bearing series, the hornblendic series, the felsitic, epidotic and garnet rocks, the hydrous magnesian series, the quartzose rocks, and the iron ore rocks; (3) calcareous rocks; and (4) igneous rocks, including a feldspathic series, a hornblendic series, a pyroxenic series, and a schist magnesian series.

The fragmental rocks are conglomerates and sandstones. The metamorphic rocks are granites, gneiss, mica-schists, slates, syenites, diorites, diabasites (which Wichmann and Törnebohm regard as eruptives), hornblende-schist, anthophyllite-schist, protogine, talcose slate, chloritic argillite, serpentine, quartzite, jasper, magnetite, hematite, limonitic quartzose ores, and a number of other less important types. The calcareous rocks embrace only limestones and dolomites, and the igneous rocks only granites, a few doleritic, dioritic, and diabasic dikes, massive and schistose. The author states that "some geologists would include here a considerable portion of the bedded greenstones embraced under the metamorphic rocks" (p. 204).

1879.

WRIGHT, CHARLES E. First Ann. Rept. of the Commissioner of Mineral Statistics for the State of Michigan, for 1877–8 and previous years, pp. 5–24 and 110–124. 1879.[a]

In the introduction to his report the author sketches the geology of the Upper Peninsula. He divides the pre-Cambrian rocks into Laurentian and Huronian, placing all of the iron-bearing series in the lower portion of the

[a] The reports of the Commissioner of mineral statistics for the State of Michigan have appeared annually since 1879. They are concerned mainly with statistics and with statements of the progress of the work under way in the different mines. They will be noticed in the following pages only when they contain information bearing on the geology of the Menominee district, when this is not plainly a restatement of facts and opinions discussed by earlier authorities.

Huronian. The outline of the geology given is not in any respect different from that given by Brooks.

The only mines opened on the Menominee range at this time were the Emmett, Breen, Vulcan, Norway, Cyclops, and Quinnesec. Each one of these is described. At the Emmett mine there are two kinds of ore—a soft specular variety, very low in phosphorus, and a brown one containing 1.29 per cent of this element. The latter lies beneath the former. At the Breen mine sandstone is found in some places underlying the ferruginous schists. This phenomenon is accounted for in the supposition that the schists formed an overhanging cliff in the Potsdam sea, in which the sands accumulated. From the structure of some of the ore in the mine the author is inclined to regard it as having been formed by the dissolving of silica from ferruginous jaspers.

1880.

Brooks, T. B. The geology of the Menominee iron region (east of the center of R. 17 E.), Oconto County, Wisconsin: Geology of Wisconsin, Survey of 1873–1879, vol.3, pp. 429–599. With maps and plates. Atlas Plates XXVIII, XXIX. 1880.

Although primarily an account of the geology of the Menominee district on the west side of the Menominee River, this report includes also a description of the geology of that portion of this district which lies in Michigan.

The Menominee district in Michigan is divided, as in the author's earlier reports, into a north and a south belt, of which only the latter concerns us. The south belt in turn is divided into a north and a south range, in the latter of which the principal mines are opened.

The rocks of the Menominee district are grouped as follows, beginning with the youngest:

Superficial deposits (drift)		Sand and gravel (Champlain?). Bowlder clay (till), glacial.
Lower Silurian		Calciferous sand rock and limestone. St. Mary's sandstone (Potsdam).
Keweenaw (copper series)		Wanting.
Huronian (iron bearing)	Upper	Granite (eruptive?), gneiss, hornblende, actinolite, mica-, chlorite-, and quartz-schists, iron ores, clay and carbonaceous slate, quartzite, and conglomerate.
	Middle	Clay slate and quartzite.
	Lower	Dolomite, iron ore, aud quartzite.
Laurentian (not subdivided)		Granite, gneiss, and crystalline schists.

In a second table (facing p. 437) the Huronian rocks are divided into two groups—an eruptive group, embracing diorite, gabbro, granite, and diabase, and a metamorphic group, including granite, greenstone, syenite, quartzite, limestone, and the various schists so abundant in the district. In the Menominee region the granite is declared to exist as dikes, which are said to be more frequent in the upper division of the series than in the lower divisions. The diorites and gabbros occur as conformable beds. Most of them are believed to be metamorphosed sediments. The Laurentian rocks are likewise separated into an eruptive group, which includes granite and greenstone, and a group composed of metamorphosed sediments. This latter group includes gray granites, gneisses, and schists, with the addition, probably, of granulite and quartzite.

In the first chapter of the report the author describes the Huronian and Laurentian series in some detail. The Lower Huronian includes beds I–VII. Of these, beds I, III, and IV are little known. Bed II is the great lower quartzite and bed V the great marble bed, which in the Sturgeon River district is almost as prominent as the quartzite. Overlying the marble is the great iron horizon. It is coextensive with the marble. This belt is best exposed along the line of the Chicago and Northwestern Railway. It is believed to be connected with a similar ore belt north of Lake Antoine by an anticline which pitches westward under Wisconsin.

The Middle Huronian members include beds VIII–XIII. They consist of quartzites, clay slates, and schists.

The Upper Huronian embraces mica-schists, gneisses, and granites. It comprises beds XIV–XX, represented best in the exposures on and near the Menominee River. The schists of the series dip at a high angle to the south, and apparently underlie the granite and gneiss observed south of the Big Quinnesec Falls.

In consequence of the sharply folded character of the Menominee rocks, the total thickness of the series can not be estimated with a close degree of accuracy. Excluding the granite (bed XX), which the author is inclined to regard as eruptive, the thickness of the series is supposed to be from 10,000 to 15,000 feet. This estimate is from 4,000 to 9,000 feet less than that obtained by the measurement of the individual beds at different places within the limits of the district and the addition of the results thus obtained.

Approximate thickness of the Huronian strata in the Menominee region.

Bed.	Where observed.	Maximum thickness.
		Feet.
XIX	Michigamme River	4,000
XVIII	Brule River	1,900
XVII	Pine River	1,400
XVI	Sturgeon Falls	1,700
XV	Sturgeon Falls	900
XIV	Pine River	800
XIII	Fourfoot Falls	700
XII	Fourfoot Falls	200
XI	Fourfoot Falls	1,000
X		300 (?)
IX		400 (?)
VIII–VII	Lake Hanbury	1,000 (?)
VI	South belt iron formation	700
V	Marble, south belt	1,700
IV–III	Pine Creek	1,000 (?)
II	Secs. 7, 8, T. 39 N., R. 28 W., Michigan	1,000 (?)
I	Falls of Sturgeon River	300
		19,000

The character of the different formations met with in the Menominee district and their equivalency with the beds constituting the Marquette Huronian are exhibited in the following table. The correlation of the Menominee rocks with those of the Marquette, the Penokee, and the Sunday Lake series is so complete that the author thinks that it points to the fact that the rocks of these different districts were all formed in one basin under essentially like conditions.

The Roman numerals affixed indicate to which beds of the Marquette series, as worked out by the author, the Menominee beds correspond.

Table showing the character of the formations in the Menominee district and their equivalency with those of the Marquette district.

XX. Granite, rarely gneissic, perhaps also including the rocks at Peminee Falls.
XIX. Hornblende- and tremolite-schist, greenstone, gabbro, and diabase. The gabbro has the appearance of being eruptive.
XVII. Gneisses and schists.
XVI. Gabbro, diorite, diabase, and schistose greenstones.
Sericite- , magnesian, and greenstone-schists, and serpentine.

XV–VIII. Covered by drift in Menominee Valley, in vicinity of Quinnesec. At mouth of Sturgeon River covered with drift for a mile south of bed XVI. Lower portion of series consist of slates, greenstones, slates, quartzite and mica-schist, and greenstone.
VII. Hydromicaceous schist, graduating into clay slate.
VI. Iron ore.
V. Dolomitic marble.
IV–III. Covered.
II. Quartzite.
I. Chloritic gneiss, hydrous magnesian schists, slate conglomerates, quartzite, and perhaps diorite (may belong with Laurentian).
Nonconformable with Laurentian.

Many details are given concerning the exposures of each of the formations, and a number of large-scale maps are published which exhibit well the distribution of these exposures in different portions of the district.

The iron-ore rocks include magnetites, magnetic quartzose, and magnetic amphibole rocks; specular hematites and martites; siliceous, jaspery, and argillaceous hematites; and limonitic quartzose ore. Three beds have produced merchantable ore, viz, VI, XV, XIII. The magnetites and the specular hematites grade into each other through martite and the hematites into limonites, but the latter do not pass into magnetites.

The quartzites are sometimes conglomeratic and sometimes schistose.

The occurrence of conglomerates at the Falls of the Sturgeon is described in great detail. The author is now assured that they mark an unconformity between the Laurentian granites and gneisses and the Huronian beds.

The sequence of rocks beginning at the basin below the falls, i. e., between the quartzites and the granite-gneiss complex, is given as follows:

1. On the south side of this point, hence forming the north shore of the basin, is a considerable bed of a soft, fine-grained rock, apparently a chloro-argillaceous, arenaceous schist. * * * The strong cleavage planes strike N. 80° W., dip 60° S. A somewhat distinct banding had a strike N. 75° W., and vertical dip. As no rock is exposed for some distance south, this schist may have considerable thickness, and in part underlie the basin.

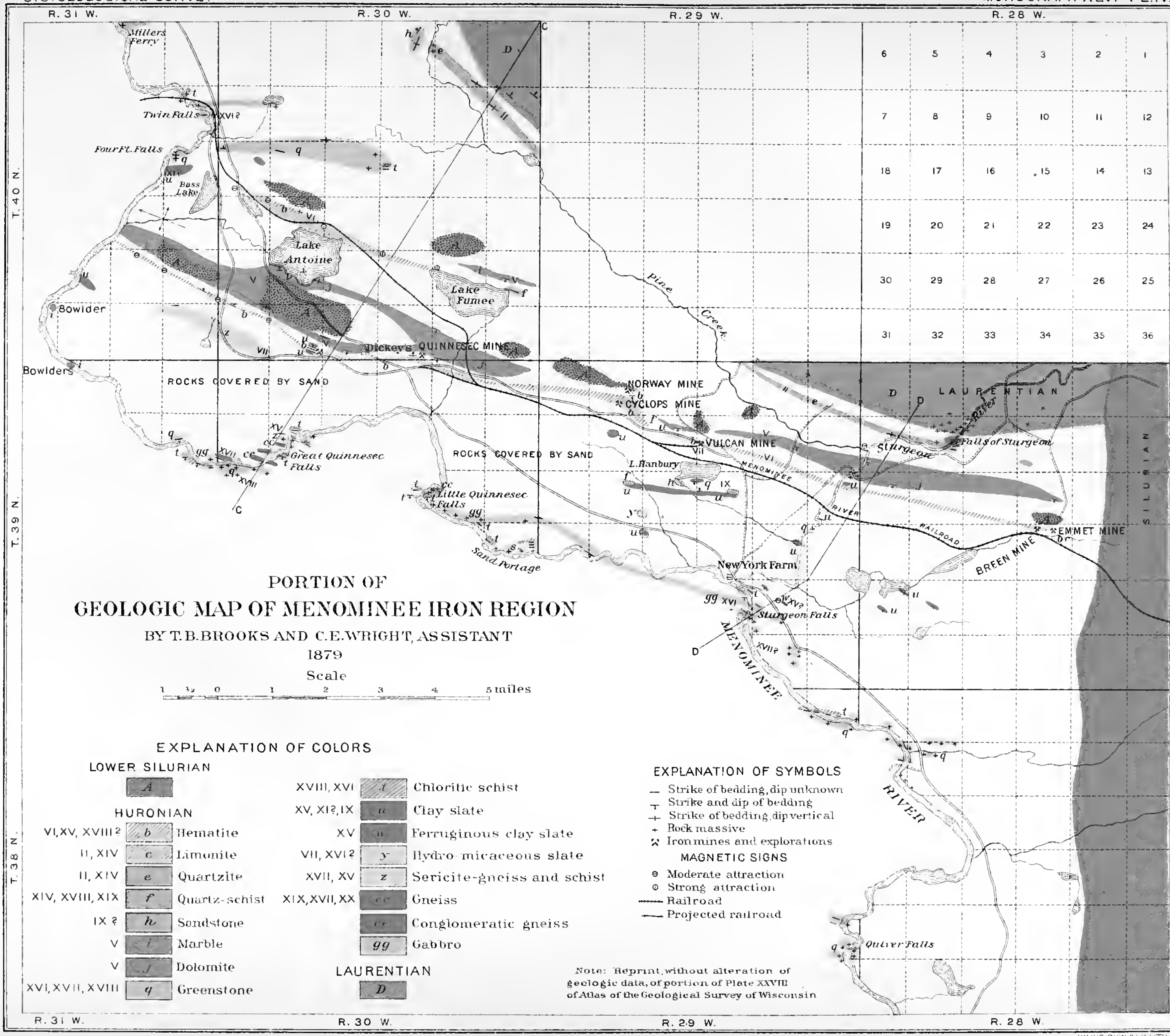
2. North of the schist is 8 feet in thickness of a reddish-gray quartzite.

3. A thin bed of a schistose conglomerate holding pebbles of what appear to be Laurentian granite and gneiss and white quartz, loosely bedded in a matrix resembling 1. * * *

4. Five feet of schist similar to 1.

5. Eight feet of conglomerate similar to 3.

6. Three feet of schist similar to 1, which brings us to a narrow part of the river and ends the series, for on the opposite side is Laurentian granitic gneiss. * * *



JULIUS BIEN & CO. LITH. N.Y.

The bedding of the conglomerate and schistose beds 1 to 6, above described, was unmistakable, being N. 80° W., with vertical dip; hence essentially parallel with the great Huronian quartzite which overlies them on the south. * * *

The structural facts in connection with the strong lithological affinities which the schist-conglomerate series bear to the Huronian, and the still more important fact that the pebbles contained in the conglomerate are unmistakably Laurentian, leave no question in my own mind but that the rocks under consideration are Huronian, and form the base of the series at this point [pp. 467–468].

The dolomitic marble is quartzitic. It is associated with beds of novaculite and clay slates. The latter rocks are found also as beds interstratified with quartzites and actinolite-schists, as layers alternating with the ores and with magnesian schists, and as independent beds constituting a distinct formation.

The chloritic rocks are so closely related to the argillaceous ones that the author finds it difficult to draw the line between the two. On the one hand the schists appear to grade through argillo-chloritic schists into clay slates and iron ores, through quartzose varieties into quartzites and through micaceous varieties into mica-schists; and on the other hand they appear to grade into diabases and diorites, of which they seem to be altered varieties.

The greenstones include diabases and diorites and a series of fine-grained undetermined rocks that appear to be connected with these. The special forms of greenstone that have been made out are diorite, diabase, gabbro, and serpentine. These grade into hornblende rock, hornblende-gneiss, mica-schist, mica-gneiss, chlorite-schists, and kersantite.

The schists occurring along the Menominee River are actinolite-schists, tremolite-schists, micaceous schists, and sericite-schists. The rocks formerly supposed to be talcose schists are now known to be sericite-schists.

Of the maps accompanying the volume in which Brooks's report is published two are by the author, with the assistance of C. E. Wright and others. The most important of these is the geological "map of the Menominee iron region," a portion of which is reproduced in Pl. IV. This map illustrates the distribution of exposures within the district studied. It is accompanied by two sections, one along the line C-C passing between Lakes Antoine and Fumee, and the other along the line D-D near the Sturgeon River. These are reproduced in figs. 8 and 9.

The second map embodies the author's views concerning the folding of the district. On it are two ideal sections illustrating his conception of the folding in the neighborhood of Quinnesec and in the vicinity of Iron Mountain. (See figs. 10 and 11.)

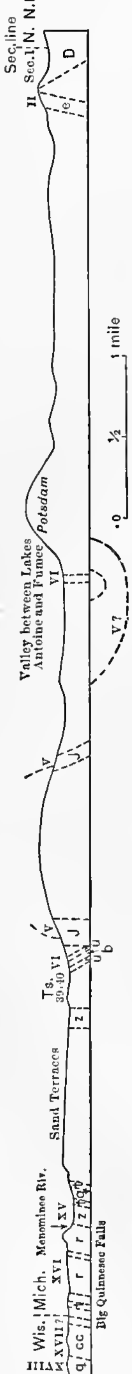


FIG. 8.—Geological section through Quinnesec. After T. B. Brooks, 1880. Vertical scale is approximately relative to the horizontal. The Roman numerals indicate the groups or formations to which the beds are believed to belong. The letter symbols indicate the character of rock as follows: b, hematite; e, quartzite; J, dolomite; q, greenstone; r, diorite; t, chloritic schist; u, clay slate and argillaceous schist; z, sericite-gneiss and schist; cc, gneiss, mostly biotitic; D, Laurentian.

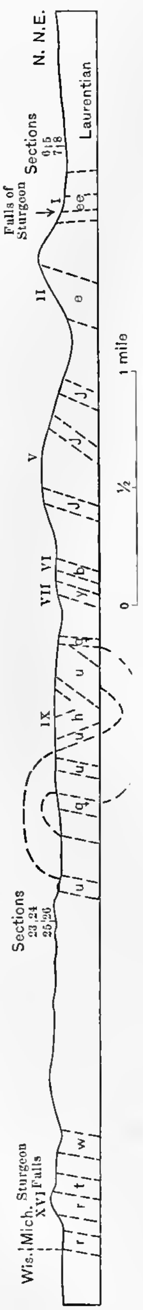


FIG. 9.—Geological section through Sturgeon River. After T. B. Brooks, 1880. Vertical scale is approximately relative to horizontal. The Roman numerals indicate the groups or formations to which the beds are believed to belong. The letter symbols indicate the character of rock as follows: b, hematite; e, quartzite; h, sandstone; J, dolomite; q, greenstone; r, diorite; t, chloritic schist; u, clay slate and argillaceous schist; w, ferruginous clay slate; y, hydromicaceous schist; ee, conglomeratic gneiss.

WICHMANN, ARTHUR. Microscopical observations of the iron-bearing (Huronian) rocks from the region south of Lake Superior. Geology of Wisconsin, Survey of 1873–1879, vol. 3. pp. 600–656. 1880.

Many of the rocks of the Marquette and the Menominee districts were submitted to Dr. Wichmann for microscopical study. His results are embodied in the paper which constitutes Chapter V of Brooks's report. Among the rocks described from the Menominee district may be mentioned siliceous dolomite, quartzite, actinolite-magnetite-schist, serpentine, diabase, quartz-diabase, mica-gneiss, sericite-gneiss, chlorite-mica-schist, calcareous mica-schist, sericite-schist, hornblende-schist, clay slates, and calcareous and ferruginous sandstones. The serpentine is said to occur in sec. 27, T. 39 N., R. 29 W.

BROOKS, T. B. Sketch of the Laurentian rocks of Michigan. Geology of Wisconsin, Survey of 1873–1879, vol. 3, pp. 661–663. 1880.

Mica-gneiss, hornblende-gneiss, hornblende-schist, chloritic gneiss, granite, and hornblendic granite are declared by Brooks to be the characteristic rocks of the Laurentian in Michigan. Hornblende-schists are said to be especially abundant in the Menominee district. By the alteration of the hornblende into chlorite, the hornblende-gneiss passes into chloritic gneiss, which also is abundant in the Menominee district. The granite is "that extreme massive variety of gneiss in which all interior evidence of bedding is obliterated by metamorphic action. I assume it to be an altered sedimentary rock, as it apparently must be from its structural relations with the other beds, the granite dikes and certain great irregular red masses not being included" (p. 662). Among the varieties of granite observed in the Menominee district, a red, massive granite, a fine-grained, white variety, and a porphyritic,

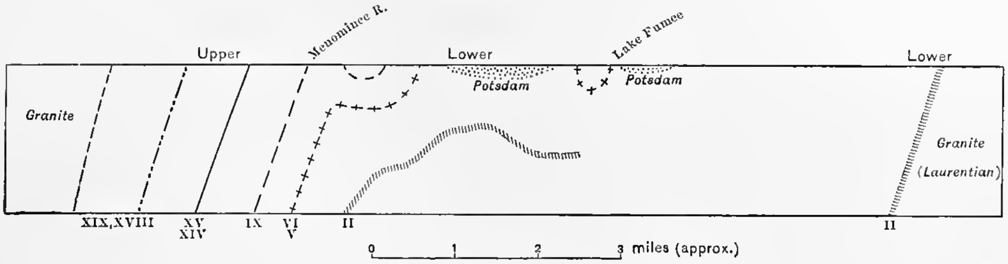


Fig. 10.—Structure section across the Menominee region through the west end of Lake Fumee. After T. B. Brooks, 1880.

gneissoid variety are most common. The hornblendic granite is not found in the Menominee district.

The superposition of the beds in the Laurentian can not often be made out, owing to the complicated folding and the uniformity in the lithological

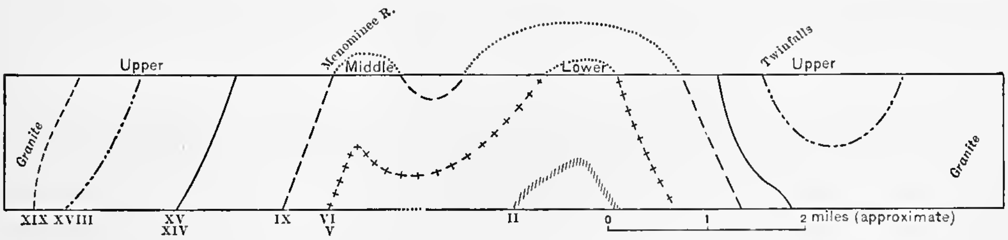


Fig. 11.—Structure section across the Menominee district in the vicinity of Twin Falls. After T. B. Brooks, 1880.

character of the different rocks. Cutting these rocks are granite and greenstone, among the latter of which are some dolerites.

Wright, Charles E. The geology of the Menominee iron region (economic resources, lithology and westerly extension). Geology of Wisconsin, Survey of 1873–1879, vol. 3, pp. 665–734, and atlas sheet xxx. 1880.

In Brooks's report the chief interest centers in the scientific problems presented by the Menominee iron region. In the present report Wright deals with the economic geology of the district. He describes the progress of the work at each of the mines in operation in 1879, gives analyses of their ores, and mentions some interesting details concerning the relation of the ore bodies to the surrounding rocks in some of the mines. At the Vulcan mine an ore lens occurs in the midst of jaspery schists, into which the former passes without any break in the stratification. The author's impression regarding the Menominee ore deposits is that they are of a secondary nature. He thinks that the ores "were originally the same as the jaspery specular schists in which they occur, and have been brought to their present condition by the dissolving out of the silica from the lean schists" (p. 671).

The author is inclined to the opinion that at the Saginaw mine, in the southwest quarter of sec. 4, T. 39 N., R. 29 W., there is a narrow syncline in the marble beds. If this is a fact, it points to the existence of a second ore belt to the south of the one on which the mine is situated, and it is on the eastward extension of this second belt that the Vulcan and Curry mines are opened. On the east side of the Norway property the formation is much disturbed and some of the beds are actually brecciated. At the Quinnesec mine the formation has a dip of 70° N. South of the ore belt the dip becomes steeper, then vertical, and then there is a southerly dip. From a consideration of other phenomena the author thinks there is here an indication of an anticline dipping west, and that this again indicates a second ore belt farther south.

Nearly all the ores are declared to be strictly first class. "Many of them contain quite a percentage of lime, magnesia, and alumina, all desirable elements as impurities. * * * The sulphur in the majority of these ores is hardly worth considering, while the phosphorous is remarkably low" (p. 678).

In Chapter II the author describes the lithology of the beds constituting the Huronian series. He divides the rocks, on the basis of a microscopical examination, into calcareous rocks, quartzose rocks, including quartzites, mica-schists and various quartz-schists, hornblende-schists, and hornblende rocks; greenstones, including diorite and diabase; and schists and slates, including chloritic, talcose, and argillaceous varieties. The chloritic schists are closely allied to the greenstones. Their manner of association indicates that they may be greenstone tuffs, although it is possible that they may be metamorphic beds. The microscopical features of all the different varieties of all these rocks are briefly described. Among the greenstones one diabase is recognized, though it does not occur on the Michigan side of the river.

The map accompanying the report exhibits only the distribution of the iron formation and the greenstones. It contains no information not on Brooks's map.

Numerical index to specimens from the Menominee region. Described by Messrs. Brooks, Wichman, Wright, and others. Geology of Wisconsin. Survey of 1873–1879, vol. 3, pp. 735–741. 1880.

This is a list of the specimens collected by the above-named authors from various portions of the Menominee district.

1881.

Rominger, C. Menominee iron region: Geol. Surv. Michigan, vol. 4, pp. 157–241. 1881.

In his report on the geology of the Menominee district Rominger does not attempt to classify the rock beds into groups, as they were arranged in the report on the Marquette district, but describes in minute detail a large number of exposures in the district and makes a few general remarks on the succession of the beds, comparing them with the succession in the Marquette district. At the Breen and the Emmett mines, the most easterly ones on the range, the ore-bearing beds are seen to dip south, the highest beds being white and red mottled hydromica-schists. Below these is a large series of thin-bedded siliceous and argillaceous rocks impregnated with hematite and martite. Interlaminated between them are seams of nonstratified, reddish-brown ore, which "are evidently a secondary product of lixiviation of the strata by percolating water" (p. 158). In the pits of the Breen mine there is a contact of the Silurian sandstone with the nearly vertical strata. The lower ledges of the sand rock generally consist of a breccia containing angular fragments of ore and of the ore-bearing rocks. Cracks and cavities in the Huronian rocks are often filled with sandstone, so that in some places the younger sandstone appears to be beneath the older schists. After tracing the ore belt to the west, he concludes that the ore-bearing series amounts to more than 1,000 feet in thickness. North of it are ridges of limestone, and north of the limestone is a large series of "flaggy rock beds, richly impregnated with bright specular iron-oxide granules." The rocks are sandy quartzose beds that are often so richly bespangled with hematite as to resemble the specular ore of the Marquette range. North of this ore belt no rocks are met with for a quarter of a mile, when a belt of quartzite ledges is reached having a thickness of not less than 1,000 feet. The quartzite dips northerly, sometimes northwest, and sometimes northeast, and rests unconformably on the granite at the Falls of the Sturgeon River.

South of the East Vulcan mine, on the west line of sec. 13, T. 39 N., R. 29 W., crystalline diorites are apparently interbedded with slates and quartzites. They are regarded as intrusive.

The rocks west of the East Vulcan are the same in character as those east of the mine, and their relations to one another are the same. In the western of the Vulcan pits the ore beds dip only 20° to 30°, though in the eastern pits they are nearly vertical. The hills south of Lake Hanbury are formed of "a large succession of dark, blackish-colored clay slates, merging into various modifications of lighter gray-colored, pale silky-shining micaceo-quartzose and feldspathic schists, which contain a considerable proportion of carbonate of lime, or of sparry carbonate of iron, and of numerous interlaminated belts of dark-colored granular quartzites" (p. 164).

The author agrees with Major Brooks in supposing a repetition of strata in this belt of exposures, one-fourth of a mile wide, due to plication, although he could observe "no synclinal and anticlinal position of the ledges." On the north side of the ledges the dip is clearly southward, in the center of the ledge it is vertical, and on the south side in many places a northern dip is observed, but no significance is attached to the phenomena.

North of the Curry mine it is noticed that the upper layers of the limestone formation are quartzitic and sometimes brecciated. Occasionally beds of conglomerate are interbedded with the series, whose thickness here amounts to about 400 to 500 feet. In the pits of the Saginaw mine in the southwest quarter of sec. 4, T. 39 N., R. 29 W., the ore belt is inclosed in well-laminated, thin-bedded, partly siliceous, partly argillitic beds rich in iron oxides. At the Norway mine the limestone appears to be underlain by light-colored reddish, gray, or greenish slates, interbedded with which are arenaceous seams rich in mica scales.

At the Cyclops mine is another unconformable contact of the Silurian sandstone upon the Huronian schists. Here the latter rocks are hollowed out into a trough in which the sandstone is deposited.

The creek draining Lake Fumee passes through the limestone formation in sec. 35, T. 40 N., R. 30 W., exposing several successive synclinal and anticlinal arches, the measured thickness of the beds being 600 to 700 feet. The limestone here is dolomitic. It contains large belts of calcareous breccia, and is often full of quartzose seams parallel to the stratification. Certain ledges consist exclusively of flinty quartz.

The author also notes the existence of a range of limestone hills north of Lake Fumee and an outcropping of quartzite south of it. The quartzite is considered to be identical with the upper quartzose beds of the limestone formation, and not to be equivalent to the lower quartzite at the Falls of the Sturgeon River.

This limestone ridge, surrounded on both sides by low, swampy lands, is directly north of the limestone belt which underlies the ore formation at the Norway and Stephenson mines, a little over a mile apart from it, with a swamp valley between them. Both belts dip to the south. We must therefore either suggest a rupture of the rock belt in the intervening space, or an intervening synclinal trough connecting the two. The same correspondence in dip exists between the limestone bluffs on the roadside near Quinnesec and the equivalent quartzose belts on the north side of Lake Fumee; but in that case we can prove by natural exposures the occurrence of a repeated plication of the rock belt in the intervening space. Besides the locality already mentioned in which this plication of the beds is seen, there is another one handy for observation in the southeast quarter of the northeast quarter of sec. 34, on the roadside to Lake Antoine, where the limestones dip northward in anticlinal position with the more southern outcrops. An anticlinal position exists also between the limestones exposed in the south slope of the Quinnesec ore range and those on the north slope of the range dipping under the bed of Lake Antoine, and great probability exists for the occurence of a synclinal trough of limestone in the place where the basins of Lake Antoine and Lake Fumee are now [p. 181].

Recapitulating the so far ascertained facts, we have become acquainted with three distinct groups of rock, one succeeding the other conformably, or at least in direct superposition on the other. The most southern, seemingly uppermost, is a series of dark, gray-colored slaty or schistose beds, with interlaminated quartzose belts, amounting to a thickness of perhaps over 2,000 feet, which I will call the *Lake Hanbury slate group*. A second group next succeeding it consists in the upper part of light-red, or whitish, or gray-colored, hydromicaceous and argillitic strata; in the lower, of siliceous beds richly impregnated with iron oxide in the amorphous hematitic condition, or in the crystalline form of martite, with metallic luster, which lower series incloses seams almost exclusively composed of martite granules, constituting the economically valuable ore deposits. This group I will name the *Quinnesec ore formation;* it amounts to a thickness of not less than 1,000 feet, but locally, perhaps, it is much thicker. The third group is formed of a series of light-colored quartzite and limestone beds of a siliceous character, usually in part of a brecciated structure, and also amounting to at least 1,000 feet in thickness, which I will call the *Norway limestone belt.* All these strata are upheaved in a certain axial direction, which is about west-northwest, and dip southward, if we consider them as a body, and overlook folds of the strata and other local irregularities [p. 182].

The author is not certain that the succession here given and the succession as marked out to the north and to the south of this known belt is correct, because of the difficulty of deciding properly as to the relative positions of the rock beds, on account of folding, faults, and the covering of critical areas by drift.

North of the limestone, in the southwest quarter of sec. 7, T. 39 N., R. 28 W., the author finds an occurrence of siliceous specular flag ores dipping southward under the limestone, which also has a southern dip. Again, north of the Norway mine is a belt of micaceous slaty argillites over 200 steps in width, and in the southeast quarter of the southeast quarter sec. 32, T. 40 N., R. 29 W., is a series of siliceous flags, argillites, and quartzose beds, consisting of alternating narrow bands of a jaspery quartz and of a compact siliceous iron ore. North of this bed again is a bed of graphitic slate 8 feet wide, beds of banded micaceous quartz-schists, and again graphitic slates. This recurrence of beds to the north of the principal iron-bearing formation is explained as due to a synclinal trough, supposed to exist in the limestone. This supposition requires the turning over of the series as usually seen. To quote the author:

> The hitherto described rock series of the Menominee iron range allows a much more simple and harmonious explanation of its structure if we suggest a synclinal trough of limestone in this place and revert the generally observed order in the superposition of the rock beds, considering the most southern, apparently highest rock beds of the Lake Hanbury series as the lowest, directly succeeding above the diorites south of the Menominee; next higher would be the iron formation, and highest or youngest the limestone formation and strata north of it. This order is actually exhibited on the east side of Sturgeon River * * * and in the Chapin mine and Quinnesec mine. In all other described localities, according to this theory, which I believe to be the fact, the strata have been placed in an overtilted position by the upheaval acting most powerfully from south to north, whereby the limestones came to lie beneath the others, and were by me at first mistaken for the oldest in the succession [p. 186].

Immediately north of Pine Creek, in T. 40 N., R. 29 W., are ridges of quartzite, and north of them, and apparently in discordant contact with the quartzites, are bluffs of granite. This great quartzite, over 1,000 feet thick, begins in sec. 10, T. 39 N., R. 28 W., and runs westward in an almost continuous ridge to the Falls of the Sturgeon River and beyond for the distance of a mile or so. Of the limestone belt shown in Major Brooks's map south of the falls Dr. Rominger did not see the slightest evidence.

The relations between the quartzite and granite at the falls are thus described:

> The bed rock of the falls is granite, which evidently forms here an arched, bubble-like protrusion, dipping in all directions; the sedimentary strata above this bubble have likewise been pushed aside with the same irregularity. They have in places become entangled between the granite, and seem to dip under it, but the same ledges are seen in another place dipping in a different direction and to lie above the granite. * * * Interstratified with the granite are belts of dark diorite-like rock, consisiting of quartz, white, probably anorthic feldspar, and of a large proportion of black mica. * * * In intimate, seemingly conformable contact with the granite occurs a series of schistose beds, which are exposed at the foot of the falls in an almost vertical position, but they seem to be in an anticlinal position on the two sides of the river. On the west side are stratified red-colored feldspathic rocks, crowded with granules of magnetite and with iron pyrites in small cubes; with them occur narrow seams of a rich granular magnetic ore contaminated with iron pyrites. This belt amounts to about 8 or 10 feet, and the strata dip under the granite. Next and below it is a rock belt, 10 feet wide, of schistose, feldspathic, and sericitic beds; then comes a seam of compact, finely granular, red feldspar 20 feet wide. * * * Under it succeed silky, shining gray sericite-schists, with a feldspathic groundmass; then a break in the formation occurs, and the same feldspathic sericite-schists dip in an opposite direction, away from the granite, and farther on in this direction we soon come to quartzite ledges, apparently incumbent on them. On the east side of the river we find similar hard sericite-schists, with interlaminated granular feldspar seams, and with several belts [of] a coarse conglomerate rock formed of red granite pebbles and of white quartz pebbles, some of them opalescent. The cement is the schistose sericite. Some of the granular feldspathic beds of the schists are distinctly ripple marked. Going across this schistose belt, which amounts to about 100 feet, we come again into granite, which seems to be in conformable contiguity with the schists. We have here evidently a series of sedimentary beds deposited on a granitic substratum, which during the upheaval became wedged in between the plastic granite mass, tilting and overlapping them locally, so as to appear as the lower beds [pp. 190–192].

North of the falls for miles nothing but granite was seen, except where this rock is replaced by gneiss and is cut by "doleritic" and other basic dikes.

Passing to the green schists exposed so abundantly on the Menominee River, the author recounts their occurrence in order, beginning with the outcrops at Twin Falls. The greenstone-schist or diorite formation is rarely in contact with the iron formation, and even when in contact the relations between the two rock series are not clearly ascertainable.

* * * The dioritic rocks generally play the part of an intrusive rock with regard to the strictly sedimentary rock beds of the Huronian series. A superposition of the diorite formation on the Lake Hanbury rock series, which adjoins it the whole length of the Menominee Valley from the Upper [Big] Quinnesec Falls to the Sturgeon Falls, asserted by Major Brooks, is not observable; the nearly vertical strata of both formations are even never seen in contact. There is always quite a large covered interval between them. The nearest exposures of the two groups are observable in sec. 26, T. 39, R. 29, where, in the center of the section, a hill is formed of the vertical ledges of ferrugino-siliceous flagstones and slaty beds representing the Lake Hanbury series, and about two or three hundred steps from these exposures we find, on the south side of the road to Menominee, small hillocks of diorite. * * *

My reasons for holding the dioritic rocks south of the iron formation as older than the latter are based on the lithological similarity of this formation with the dioritic group of the Marquette district, and on the degree of metamorphism exhibited by the two groups, the dioritic and the iron-bearing. In the great succession of strata commencing with the Hanbury slate group and upward, we rarely find a bed so much altered that its sedimentary structure is altogether obsolesced, and the majority of the strata shows it very plain, while in the dioritic rocks, considered to be the younger, a stratified structure is also recognizable, but not one of these thousands of feet of ledges exhibits its original sedimentary lamination with any degree of distinctness like the others; they have evidently been transformed under cooperation of heat and partially brought into a plastic condition. * * * One might object: If the diorites are the older beds, why don't we find them just as well developed on the north side of the upheaved beds, between the quartzite and the granite? The sandy and conglomeratic nature of many of the strata of the quartzite and iron formation proves them to be shore deposits, while the dioritic group consists only of the finer material of deep-sea deposits, which explains the point in question. Moreover, the dioritic rocks are not altogether missing on the north side of the ore formation, as we can see by the occurrence of the 6-mile-long chain of diorite extending eastward from the Twin Falls. * * *

The equal dip of the strata to the south in these adjoining formations is not necessarily proof of the younger age of the most southern beds. The whole succession is so near to a vertical position that in many instances it has been left uncertain which way they dip, but suppose their dip is conformable to the south; the upheaval of the diorites by the eruption of the still more southern granite masses pushing the whole incumbent rock series north until all tipped over, is the hypothesis by which I explain the succession of beds as an inverted one, the seemingly lowest beds being actually the youngest [pp. 208–210].

The author describes the exposures along the Menominee River in detail as fine- and coarse-grained greenstone-schists, micaceous chlorite-schists, light-colored, grayish-green porphyritic schists containing well-formed orthoclase crystals, micaceo-feldspathic seams, and beds of pale-red schists composed of orthoclase, hydromica, and quartz, etc. At the Big Quinnesec Falls are also massive diorites. These and the diorite-schists have the same composition, and neither, according to the author, should be classed with the diabases. The whole series of rock beds exposed at these falls "evidently represents one inseparable group of altered sedimentary deposits formed from bottom to top of the same material, in different molecular form and different proportion in the intermixture of the component mineral substance" (p. 214).

The rocks at the Little Quinnesec Falls and at the Sturgeon Falls are similar to those above described. Some little distance below the mouth of the Sturgeon River are said to be exposures of serpentine, and below these are great outcrops of feldspar, porphyries, granites, etc., some of which are thought to be like the granite and porphyry dikes cutting the greenstone schists of the "diorite group" in the Marquette district.

Reviewing what we have seen of the formations along the Menominee River, said to be the youngest of the Huronian group, I again point out the great similarity in the composition and structure of this very large series of rocks with the dioritic formation of the Marquette district; also its intersection by the serpentine group, which in the Marquette district is under similar circumstances associated with the diorite formation. Further in favor of this analogy is the intersection of the Menominee diorites by porphyritic granite in dike form, as is the case with the diorite group of Marquette. These porphyritic granites are in their part in close relationship with the felsite porphyry of the Pemenee Falls, merging by insensible gradations with the granite, which is only a more completely crystallized form of the same lava mass. On the other hand, there exists not the slightest resemblance between the dioritic rock belt of the Menominee River and those rock beds of the Marquette district which represent subdivisions 15 to 20 of Major Brooks.

The exact order in which the different rock masses composing the dioritic formation succeed each other—whether the dark-green diorites of the Twin Falls and in other places are the lowest and the lighter-colored diorites at the Quinnesec Falls the higher ones—is at the present state of our knowledge uncertain, but it is most likely the case; so the dark-colored, coarsely crystalline hornblende rocks exposed a mile above the Pemenee Falls may be older beds than those at the Quinnesec Falls. The massive belts of this series of altered sedimentary rocks, interlaminated with the schistose members, can, as I think, not all be considered as regular links in the stratified succession; some of these, and particularly the larger masses, as they occur at the Quiver Falls, I believe to be intrusive, in the same qualified sense in which I have considered some of the massive dioritic rock belts of the Marquette district, and still in another sense they represent only a more altered portion of the stratified beds connected with them. Considering the granite on the south and west side of Menominee Valley as an eruptive rock, like the porphyry of the Pemenee Falls, I can agree fully with Major Brooks in this part of his chronological system: these rocks undoubtedly came to the surface after all the other Huronian strata of sedimentary origin were formed, as their eruption to the surface caused the upheaval of the others. I therefore have always represented the dike granites of the Marquette district as actually the youngest rocks in the group, but I suppose this was not the original meaning of Major Brooks's system. In all his stratigraphical descriptions he has not made a proper distinction between sedimentary succession and interstratification, counting up the beds just as they came in a crosscut; his groups VII, IX, and XI are a proof of this assertion [pp. 221–222].

In conclusion the author compares the rocks of the Menominee with those of the Marquette district, all of which are regarded as Huronian in age.

1883.

Irving, R. D. Iron ores: Geology of Wisconsin, Survey of 1873–1879, vol. 1, pt. 3, pp. 613–636. 1883.

After describing in general the iron ores found in Wisconsin, Irving describes briefly the geology of the different iron-ore districts. In the Menominee district the principal Huronian rocks are said to be hornblendic and micaceous schists, clay slate, chloritic schist, actinolitic schist, limestone, diorite, diabase, and iron ore. The diorite and diabase are thought by the author always to be of eruptive origin, and to occur in part as interbedded contemporaneous flows and in part as intrusions. The schists are intricately folded. Any mapping of the folds must be in a large measure hypothetical, because of the numerous faults by which the beds are crossed and because of the existence in them of masses of eruptive material.

The ore bodies of the range are irregular, lens-shaped masses or portions of the belt richer than the rest. These lenses, with one or two exceptions, differ from most of those met with in the Marquette region, in that the latter are distinctly intercalated, the beds above and below them closing about them, while in this case the iron oxide simply impregnates certain areas of the stratum, whose subordinate layers continue undeflected through the ore bodies. The ores are of the peculiar "soft specular" variety already noted as found only in the Menominee region [p. 621].

There are two ore horizons in the district according to Brooks, the lower of which was numbered VI in the series. This is the horizon on which all of the Michigan mines are located. The second horizon is higher in the series, but its exact position is unknown.

On a later page in the same article several analyses of Menominee ores are given, most of them being copied from Wright's report.

CREDNER, H. Elemente der Geologie, pp. 400–410. Leipzig. 1883.

Credner divides the pre-Cambrian formations into the Urgneiss formation (the Laurentian) and the Ur-Schiefer formation (the Huronian). In the latter he places the Menominee rocks, stating that the dolomitic limestone in this district is near the lower limit of the series. He gives a section across the district from north to south, which is a copy from his paper on this district. The Ur-Schiefer formation in the Menominee, as well as elsewhere, is unconformable under Lower Silurian sediments. In this district the iron ore is overlain in places by sandstones and conglomerates, which are found sometimes extending down into cracks in the ores. A section is published to illustrate this relation. A few other references are made to the Menominee rocks in the author's discussion of the Archean, but nothing new is recorded concerning them.

IRVING, R. D. The copper-bearing rocks of Lake Superior: Mon. U. S. Geol. Survey, vol. 5, pp. 392–400, with maps, including a general map of the Lake Superior region. 1883.

In connection with his discussion of the Keweenawan rocks, Irving briefly describes the characteristics of the lithology of the Marquette and of the Menominee Huronian. The rocks belonging to these series afford, at first glance, a strong contrast to the Penokee Huronian. Close study, however, shows that there is a general stratigraphical equivalence between the three series, and perhaps even a direct connection between them. The author compares the different series and shows their points of resemblance and of difference. The diorites of the Marquette and Menominee regions he suspects to be altered diabases. The granite of the Menominee district has not been satisfactorily shown to be Huronian. It may be eruptive. Many of the less common kinds of rocks in the Marquette and Menominee districts are thought to be due to metamorphic changes, which may be connected with the complex folding observed.

In the Menominee, as well as in the other Huronian areas, the Huronian schists are limited by granites and gneisses. Usually the latter rocks are unconformably beneath the schists and in all cases, save that of the so-called Huronian granite in the Menominee district on the south side of the

Menominee River, the granite and gneiss complex plainly rises from beneath the schists. Most of the crystalline schists associated with the granites and gneisses are older than the Huronian schists.

1884.

Winchell, N. H. The crystalline rocks of the Northwest: Am. Nat., vol. 18, pp. 984–1000. 1884.

In this article there is nothing new concerning the geology of the Menominee district. The author simply classes all the crystalline rocks of the Lake Superior region into six groups and states his views as to the equivalency between these groups and those established by other writers on the different crystalline areas of the Northwest, among which is included the Menominee area.

Irving, R. D., and Van Hise, C. R. On secondary enlargements of mineral fragments in certain rocks: Bull. U. S. Geol. Survey No. 8, p. 39. 1885.

One of the specimens described by the authors to illustrate their contention that fragments of minerals in clastic rocks are often enlarged by the deposition of secondary material around them is from the bed of Cambrian sandstone immediately above an unconformable contact with Huronian iron ores at the Cyclops and Norway mines, near Norway, in the Menominee district. It is described as—

a very much indurated, buff to brown sandstone—at times almost a vitreous quartzite. The thin section is composed almost entirely of interlocking grains of quartz each with its distinctly outlined fragmental core. There is a little independently deposited interstitial quartz and a little fragmental feldspar.

Whitney, J. D., and Wadsworth, M. E. The Azoic system and its proposed subdivisions. Bull. Mus. Comp. Zool. Harvard College, vol. 7, pp. xvi and 331–565. 1884.

One paragraph in this volume which is an argument in favor of the indivisibility of the pre-Cambrian formations criticises Rominger's views relating to Menominee geology. The authors declare that Rominger's—

idea that the Marquette and Menominee schists are Huronian means nothing beyond this, that they appear to him to be lithologically similar to the rocks called Huronian in Canada; while so far as his actual work goes he reaches conclusions regarding the relations of the granitic and schistose rocks indentical with those advocated by Foster and Whitney thirty years ago. The result of Rominger's work is decidedly opposed to the division of the Michigan Azoic into two or more formations [p. 494].

1885.

Swank, James M. Iron ores in the United States: Mineral Resources U. S. for 1883–84. 1885.[a]

In his summary description of the iron-producing districts of the United States the author declares that the Menominee district ranks second in productiveness to the Marquette district. About 1876 the Menominee Mining Company of Milwaukee obtained control of a large extent of country in this portion of Michigan and at once began active operation. In 1877 only 10,405 tons of ore were shipped, but thereafter the output increased rapidly, until in 1882 it rose to 1,032,611 tons, falling in 1884 to 698,047 tons. The Chapin mine was the largest producer in the entire Lake Superior region in 1883 and 1884, its product being 265,830 tons in 1883 and 290,972 tons in 1884. The ores are generally red hematites, partaking of the same general characteristics as the similar ores of the Marquette district, except that they are, as a rule, softer. Analyses of specimens of ore from the Vulcan, Cyclops, Norway, and Quinnesec mines are given (pp. 265–266).

Irving, R. D. Preliminary paper on an investigation of the Archean formations of the Northwestern States: Fifth Ann. Rept. U. S. Geol. Survey, pp. 175–242, with general map of Lake Superior region. 1885.

The problems that confront the investigator of the ancient rocks of the Lake Superior region are outlined by Irving in this paper and the progress made in solving them is stated. General descriptions are given of the series of supposed Huronian rocks in the different areas, among them descriptions of those occurring in the Marquette and Menominee areas, which are grouped together.

Their rocks are highly folded and their structure is often very difficult to work out. Moreover, the metasomatic changes which the crystalline members of the series have undergone have often been extreme, added to which difficulties are frequent interruptions by drift covering.

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[a] "Mineral Resources of the United States" has been published annually by the United States Geological Survey since 1883. Up to and including the year 1894 it appeared as an independent publication. Later it was published as part of the "Annual Report of the Director," and beginning with the year 1900 it is again issued as an independent report. It contains statistics of the ore production in all the mining districts within the United States and occasionally descriptive notes concerning these districts. In this monograph only those volumes will be referred to which contain new information of geological interest concerning the Menominee district.

The greenstone-schists and the greenstones at the Big Quinnesec and the Little Quinnesec Falls are believed to be eruptive, the schists "representing merely an extreme degree of metasomatic change, which in some measure has influenced all the greenstones."

While declining to acknowledge the possibility of establishing a scheme of stratigraphy for these districts without the aid of good maps, Irving thinks that there is no question that Brooks's scheme is faulty with respect to the various greenstone layers included among the sedimentary beds. These greenstones are believed by Irving to be altered basic eruptives, some of which are contemporaneous flows, and others intrusive masses. The jaspers and ores of the Menominee, like those of the Marquette district, are believed to be of sedimentary origin. In the Menominee district much of the silica in the jaspers is chalcedonic, and many great belts of ferruginous rocks seem to be mainly composed of it. The Menominee area is thought to connect westward with the area of the upper Wisconsin Valley, but detailed mapping of this westward extension had not been completed when the author wrote his paper.

One plate in the report illustrates an unconformity between the ores and the Potsdam sandstone at the Cyclops mine, Norway.

In the petrographical portion of the paper the author refers to the existence in the Menominee district of clay slates, some of which are fine-grained graywackes in which the feldspathic ingredients are largely represented by kaolinized material, while others present distinct gradations into true mica-slates and mica-schists, in which at least a considerable proportion of the material is of original crystallization. Other rocks are also described, but only the limestones are referred to as existing in the Menominee district proper. The cherts, however, are mentioned as being in part at least of direct chemical origin. All the quartzites in the Huronian are thought to be—

merely sandstones which have received various degrees of induration by the interstitial deposition of a siliceous cement, which has generally taken the form of enlargements of the original quartz fragments, less commonly of minute independently oriented areas, and still less commonly of an amorphous or chalcedonic silica, two or even all three forms of the cementing silica occurring at times together in the same rock * * *. It appears that they have undergone no other alteration than that found to affect sandstones in the newer, undisturbed, and generally unaltered formations [p. 236].

1886.

IRVING, R. D. Origin of the ferruginous schists and iron ores of the Lake Superior region: Am. Jour. Sci., 3d series, vol. 32, pp. 255–278. 1886.

Although the argument in this paper is based particularly on observations made in other districts, the author, nevertheless, refers to the Menominee ores as having resulted from the alteration of an iron carbonate whose origin was sedimentary. The Menominee rocks are much folded, like those of the Marquette region, and in them the alteration of the carbonate has proceeded much further than in the unfolded series of the Penokee and other districts. In these districts all the phases of the altered carbonates are met with, but the quantity of unaltered material is much less than it is in the less folded rocks. The process by which the alteration has been effected and the proof that this alteration is responsible for the existence of the ores need not be referred to in this place. An account of these discussions is given in the literature chapter of the Marquette monograph.[a]

The author refers to the Menominee iron-bearing series as being so folded that the rock belts for the most part are in an approximately vertical position. The most abundant of the ferruginous rocks are cherty schists charged with varying quantities of magnetite, hematite, and brown oxide of iron, and containing more or less iron carbonate. These schists graduate into graphitic and carbonaceous slates that are sometimes highly contorted and at other times are nearly free from contortions.

> These contortions have no parallel in the adjoining layers, and often seem to have little relation, in axial directions, to the general system of folding of the strata. They are taken to indicate the relatively great resistance to folding offered by these schists, on account of the siliceous induration they received prior to the folding process [p. 265].

The iron carbonate occurs in the schists as an original ingredient in varying proportions. Actinolite is present in some of them. The siliceous matter in them is more commonly cherty or flinty than jaspery, but at times it is jaspery over large areas. The iron ores lie in these schists, not as lens-shaped masses around which the schists bend, but as irregular bodies lying directly in the course of the schistose banding or as layers within the schists. The ores appear to have originated in one of two ways,

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[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 5–148.

or in a combination of them, viz, from direct oxidation of the bands of carbonate in place, and from deposition within the schist of oxide of iron from percolating waters. All the indications point to the derivation of both ferruginous rocks and iron deposits by a process of silicification from stratiform shales impregnated with carbon and iron carbonate.

PUMPELLY, R. Report on the mining industries of the United States (exclusive of the precious metals), etc. Rept. Tenth Census U. S., vol. 15. With maps. 1886.

PUTNAM, BAYARD T. Notes on the samples of iron ore collected in Michigan and northern Wisconsin. Rept. Tenth Census U. S., vol. 15, p. 421. 1886.

In his introduction to the discussion of analyses of Menominee iron ores Putnam gives a brief outline of the geology of the Menominee district. He recognizes two belts of iron-bearing rocks, as did Brooks before him. The Southern belt embraces the region now known as the Menominee district. Since the completion of the Chicago and Northwestern Railway to Quinnesec in 1877 the mines on the eastern portion of the Southern belt have been extensively wrought, yielding, as Pumpelly declares in his introduction to the general discussion of the iron ores, 491,347 tons during the census year 1880. The ores consist—

> principally of a soft, specular, blue hematite, which runs high in iron and low in phosphorus. Although quite soft, the ore usually resists hydration and rarely changes color except in handling. * * * When examined fresh from the mine the ore is seen to be made up of innumerable fine crystalline particles of specular hematite, which are somewhat loosely agglutinated. * * * The ore usually occurs in irregular pockets or lens-shaped masses in a banded quartzose ferruginous schist, which is often magnetic [p. 437].

Sketch maps of the Emmett and Breen mines, of the Vulcan, the East Vulcan, the Curry, the Saginaw and Stephenson, the Norway, the Quinnesec, the Chapin, the Ludington, and the Cornell mines, and sections through many of them, illustrate the paper. At the Emmett mine the ores consist of an upper blue variety and a lower brown variety, both of which dip southward under a swamp. The blue ore is protected from the action of the swamp water by a covering of clay, while the brown ore is saturated with ground water which rises through the underlying schist. The blue ore contains but 0.008 per cent of phosphorus, while the brown ore contains 0.103 per cent of this element. At the Vulcan mine the ore lens dips south and pitches west. One of the ore samples from this mine contains a small proportion of titanium, thus proving an exception to the Menominee ores in general, which are usually free from this metal. In one of the pits of this mine the ore is overlain by a ferruginous siliceous schist, which is so richly impregnated with iron near the ore body that it sometimes itself constitutes a lean ore. At the Norway mine the ore is between a foot wall of soap rock and a hanging wall of "conglomerate ore," composed of irregular angular pieces of hard specular ore cemented by soft brown hematite.

1887.

Birkinbine, John. The iron ores east of the Mississippi River: Mineral Resources U. S. for 1886, pp. 65–67. 1887.

The author gives a brief history of the operations in the Menominee district since 1877, describes the work done at the Hamilton mine, and furnishes the usual statistics of the output of the principal mines on the range as well as of the district as a whole.

Irving, R. D. Is there a Huronian group? Am. Jour. Sci., 3d series, vol. 34, pp. 204–216, 249–263, and 365–374. 1887.

In this article Professor Irving gives his reasons for regarding the series of nonfossiliferous sediments lying between the top of the Archean crystalline schists and the bottom of the Potsdam sandstone in the Lake Superior region as worthy of being considered a distinct system coordinate in importance with the Paleozoic, etc., with the Huronian as a distinct group in the system. The arguments made use of have been outlined in the Marquette monograph.[a] In his description of a section through the Menominee district, the author declares that the chief difference existing between the Marquette and the Menominee rocks lies in the much closer folding of the latter. All the arguments that apply in favor of the existence of the two formations in the Marquette district apply also in the Menominee district. A more detailed elaboration of the arguments is given in the paper on the classification of the pre-Cambrian formations, referred to below.

1888.

Irving, R. D. On the classification of the early Cambrian and pre-Cambrian formations; a brief discussion of principles, illustrated by examples drawn mainly from the Lake Superior region: Seventh Ann. Rept. U. S. Geol. Survey, pp. 365–454. With maps, including a general map of the Lake Superior region. 1888.

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 110–112.

The main portion of this paper is a discussion of the value of unconformities in classifying nonfossiliferous sedimentary beds. The illustrations taken from the Lake Superior region afford examples of great unconformities in all the areas that have been recognized as Huronian.

In the Menominee district there are many outliers of the Potsdam sandstone reposing horizontally on the upturned edges of the Huronian schists. A picture (p. 410) illustrates the appearance of a contact of sandstone on the steeply inclined beds of the iron-bearing schists near Norway. At the immediate contact of the two series the sandstone is filled with fragments of the schists. The iron-bearing rocks are thus demonstrably older than the sandstones.

Beneath the Huronian is another series of rocks, comprising granites, gneisses, and hornblendic and micaceous schists. These rocks are closely folded, and upon them, in eroded basins, the Huronian schists are deposited. The upper series is a relatively little-altered iron-bearing series and the lower one a deeply altered series of gneiss and schists, cut by immense masses of intrusive granite. There is evidently a great discordance between the two series—a discordance that is further marked by the existence of a great basal conglomerate at the Falls of the Sturgeon River. The folding in this district is often so sharp that there is a seeming conformity between the upper and the lower series in many places. A generalized cross section of the Menominee rocks in the vicinity of Quinnesec illustrates the author's interpretation of the geology of the district (p. 435).

LARSSON, PER. The Chapin iron mine, Lake Superior: Trans. Am. Inst. Min. Eng., vol. 16, pp. 119–128. Map and cross sections. 1888.

Larsson's article is devoted mainly to a description of the methods employed in mining at the Chapin mine, although in its introduction brief reference is made to the geology of its ore deposits. Up to July, 1887, the ore of this mine had been found in three lenses, conforming in dip and strike with the Huronian clay slates and jaspers associated with them, and pitching about 30° west.

A cross section of the ore formation shows on the north or hanging side of the ore about 200 feet of clay slates, and farther north a heavy belt of magnesian limestone. The slates and the dolomite are generally separated by a conglomerate of broken dolomite and soft slates.

The foot-wall rock is also a soft slate, containing a higher percentage of iron and less magnesia than the hanging slate. Farther south occur alternate beds of slates and lean ore or jasper [p. 119].

The paper is accompanied by a geological map of the Chapin mine property, a longitudinal section of the workings, and two cross sections exhibiting the geological relations between ore, slate, and dolomite.

Fulton, John. Mode of deposition of the iron ores of the Menominee iron range, Michigan: Trans. Am. Inst. Min. Eng., vol. 16, pp. 525–536, with 9 figures. 1888.

According to this author the Menominee range is composed of three distinct groups of Huronian rocks. The "supporting group" consists of 1,200 feet of light-colored, siliceous limestones, called the Norway limestone belt.

The next or flanking group which is estimated at a thickness of 1,000 feet is called the Quinnesec ore formation. It consists, in the portion next to the limestone, of siliceous or jasper slates, largely impregnated with iron oxide. These are succeeded by argillaceous hydro-mica black and flesh-colored slates. This formation embraces the deposits of the iron ores.

The third group consists of a series of dark-gray, slaty, or schistose beds, with occasional quartzose bands, having a thickness of 2,000 feet. It is called the Lake Hanbury slate group [p. 525].

The three groups succeed one another conformably, dipping at high angles to the south in that portion of the range east of Quinnesec and to the north in that portion west of this town. Their relative ages can not be determined from their relative positions, as "the limestone is the floor of the series east of Quinnesec, while west of this it is uppermost" (p. 527). There is a well-marked unconformity between the Huronian rocks and the overlying Potsdam sandstone, but the geology of the older rocks is complicated by "frequent and violent flexures and strangely postured dips" (p. 527).

The rocks of the three groups are sedimentary. The iron ore at the Quinnesec mine is thin bedded, as are also the foot-wall jasper slates. The limestone is thick bedded. The ore occurs at two or three horizons, which, so far as is known, are not constant. At the East Vulcan mine one of the ore bodies is at the contact between the siliceous or jasper slates and the aluminous slates or "soapstone." A second is in jaspers south of the black slates. At the Curry mines there are also two horizons at which the ore occurs. The first, most northerly, is in jasper slates and the second at the contact between the jasper and black slates.

The Norway deposit is peculiar, being separated from the limestone by about 10 to 40 feet of brown sediment, locally termed "soap rock." The ore body is mainly composed of a brecciated deposit of red and blue iron ore, occasionally mixed with jasper slates, and cemented in great masses [p. 531].

The underground workings reveal the existence of a fold in the limestone.

The large open pits of Cyclops are very peculiar, as they are the residuum of a period of denudation and destruction of the ore body. These pits occur in the jasper slates, without any regularity. * * * The ore was evidently carried into them by some eroding current from the wreck of an original deposit. Just where it came from, or under what conditions it was swashed into these large pits can not be determined. * * * The example of a pool of ore at East Vulcan illustrates the supposed condition of these Cyclops deposits [p. 532].

At the Quinnesec mine a similar "pool" of ore is found infolded in the Potsdam sandstone. A little east of this mine a flexure occurs in the Huronian rocks, west of which fold the beds dip north.

The blue ores of the Quinnesec and of the West Vulcan mines are in the form of lenses whose tops have been eroded. These are thought to represent the original form in which all the ore in the range once occurred. They are embedded in jasper and clay slates, and are stratified like these rocks.

After thus describing the characteristics of many of the deposits the author proceeds to outline a theory to explain their origin.

The most acceptable exposition indicates that their normal form was that of thinly bedded ferriferous carbonates, with some admixture of dusty magnetite, and that they have been wholly altered to hematite by heat in their lower geological horizon, together with the heat evolved in the pitching and folding of the rock-measures in which they are found. Chemical agencies also contributed to this result [p. 535].

The author concludes by declaring that the structure of the range can not be explained as "a continuous monoclinal structure." "The more evident structure should consist of a series of crust flexures, repeating the iron-ore measures at intervals, as they rise on the crests or flanks of anticlinal waves" (p. 536).

The paper is accompanied by a map of the district and nine geological sections through mines.

Fulton, John. Methods of mining in the Menominee range, Michigan: Trans. Am. Inst. Min. Eng., vol. 16, pp. 891–905, with 8 figures. 1888.

The introductory portion of this paper describes the position of the ore bodies with respect to the jaspers and slates in the Menominee district. These ore bodies are reported as being found in three or more horizons in the jasper slates and also on the contact between these and the clay slates that usually overlie them. The remainder of the paper is devoted to a description of the methods of mining on the range.

1889.

Lawton, Chas. D. Mineral resources of Michigan, 1888, pp. 190–208. 1889.

In this report on the mines and mineral resources of Michigan the author announces the discovery of a large percentage of gold in the rock from a pit near the bank of the Menominee River, south of Quinnesec. He also gives an account of the condition of the iron mines on the Menominee range at the close of the year 1888. In his introduction to that part of the paper which deals with the Menominee district he outlines the geology of the district as worked out by Brooks.

Winchell, N. H., and Winchell, H. V. On a possible chemical origin of the iron ores of the Keewatin in Minnesota: Proc. Am. Assoc. Adv. Sci., Thirty-eighth Meeting, pp. 235–242. 1889. Also Am. Geologist, vol. 4, pp. 291–300. 1889.

Although this paper is devoted mainly to a theory in explanation of the origin of the iron ores in Minnesota, Professor Winchell nevertheless argues against Irving's view that the ores of all the iron-ore districts in Michigan and Wisconsin are derived by metamorphic processes from an iron carbonate.

Browne, D. H. The distribution of phosphorus in the Ludington mine, Iron Mountain, Michigan: Am. Jour. Sci., 3d series, vol. 37, pages 299–310, with figures. 1889.

The ore of the Ludington mine occurs in several lenses lying in clay slates. The main deposit, which is 700 feet long and about 60 feet wide, strikes N. 75° W. and pitches 45° W. Its dip is 70° to 80° N. The ore is of a soft, laminated hematite, whose layers alternate in places with thin seams of calcium-magnesium carbonate. The contact of the ore body with the hanging wall is curved, while that with the foot wall is more nearly a plane surface. Upon mapping the phosphorus contents of the different samples of ore taken from the mine it was found that the foot-wall sides of the deposits are apt to contain less phosphorus than the hanging-wall sides, and that the western (lower) ends of the lenses contain less phosphorus than the eastern (upper) ends. The ore increases in phosphorus from the foot wall to the hanging wall, and from the west to the east. Sometimes a streak of ore rich in phosphorus crosses the high-grade ore, but in general the relations just mentioned obtain. These relations are illustrated in the paper by a large number of sections through the different rooms in the mine from which ore has been removed.

The explanation offered to account for the regularity in the distribution of the phosphorus is as follows: The ores were aqueous deposits upon the hanging-wall slates.

> If we suppose that the ore was formed in hollows in the hanging wall, and was covered by the foot-wall slates, and that this bed has been tilted up from the north side through an angle of 100° to 110°, it will be readily understood that the original trend of the deposit becomes the complement of the present pitch of the ore. This supposition explains * * * the fact that what is now the hanging wall seems to have been the original bed of the deposit. It is improbable that the tilting has been from the south side upward through an angle of 70° to 80°; for if this had been the case the ore would pitch east at the same angle at which it now pitches west [p. 306].

The author does not think that Van Hise's explanation of the origin of the ores in the Gogebic district can be applied to the conditions in the Menominee district, because the slates associated with the Menominee ores contain no unaltered carbonate. The suggestion of Irving that the ore was washed into its present position from previously precipitated beds of carbonate appears to him more plausible, but he would modify the theory by making the original deposits hydrous oxides and carbonates of iron intermixed with calcareous materials. By the action of acidulated waters upon these the iron was dissolved and the solutions thus formed were evaporated in shallow lakes or valleys, yielding the ore deposits now worked.

> The theory of the aqueous deposit of these ore bodies, as drawn from chemical evidence, is then briefly as follows: From previously deposited beds of bog iron ore, by the action of acidulated water, iron, lime, silica, and phosphorus were dissolved. The first solution contained a large amount of phosphorus in proportion to the

amount of iron dissolved. On coming into hollows in the surface of the exposed slates the acid solution, losing acid by evaporation, deposited iron, as hydrated oxide, which carried down an amount of phosphorus proportionate to the amount of iron precipitated. As the acid became still weaker crystals of carbonate of lime and magnesia settled out, forming a layer of carbonates. A second inflow of water would tend to dissolve these crystals and precipitate another layer of iron. In similar manner, by successive inundations, the depressions became filled with alternating layers of iron ore and calcium-magnesium carbonates, each layer being as a rule lower in phosphorus than the preceding one. * * * Moreover, as both calcium and iron phosphate are of lower specific gravity, and more soluble than the hydrated oxide of iron, the tendency of the water was to carry these phosphates toward the lower end of the lake, and to deposit them in shallow water, along banks of previously precipitated silica and in places where precipitation was most rapid. * * * After the deposition was complete, further action of the water would stir up the upper layers of ore and mix them with suspended sand or clay, while the iron and phosphorus were carried further along, to be deposited in other depressions to the northeast. As jasper occurs as vein matter, and in laminæ cleaving in the same line as the ore, it would seem either that the jasper has been produced by precipitation with the iron, or that subsequent action of water has eroded the beds of iron thus formed and substituted silica for the iron removed.

A study of the vein map of the sixth level at the Ludington mine * * * seems to show that the jasper is a later formation than the ore. It will be seen by reference to fig. 17 [figure 22 in the article] that the jasper deposit widens toward the foot wall. * * * The greater width of the jasper at the foot wall also suggests an erosion of the original ore bed and a subsequent deposition of silica. Had the silica been the primary deposit the ore would be widest at the foot wall instead of at the hanging [pp. 307–308].

For the explanation of the silica deposits "bedded in the same plane with the ore," the author adopts Van Hise's hypothesis, "with the provision that subsequent erosion must be taken into consideration." The "surface deposits or washes of ore formed at Keel Ridge, Quinnesec, and Norway mines" are thought to be accumulations of the detritus worn away from outcropping edges of ore during the glacial erosion. After the deposition of the ore it was greatly modified in its chemical peculiarities by the action of surface water, removing phosphorus in one place and adding it in another.

The theory of aqueous deposit will explain, as will no other, the marked regularity of isochemic lines [lines drawn through those portions of the deposit containing equal quantities of phosphorus] and their peculiar curves, the regular decrease of phosphorus from hanging wall to foot, the alternation of carbonate of lime and oxide of iron, the ripple-marked hanging wall, the uniform lamination of the ore, and the hydrated muddy deposit next the foot wall. It also suggests explanation of the general features of the Menominee range, and the gradual change from high phosphorus and low iron ores resembling altered bog ores at its western extremity, through regular deposits of high iron and lower phosphorus, to the immense washes and surface deposits of exceedingly low phosphorus ore which mark its eastern termination (p. 309).

1890.

Irving, R. D. The greenstone schist areas of the Menominee and Marquette regions of Michigan; explanatory and historical notes: Bull. U. S. Geol. Survey No. 62, pp. 11–30. Map of Menominee district opp. p. 24. 1890.

In this introductory note to Dr. Williams's study of the greenstone-schists of the Marquette and Menominee districts Irving gives an historical summary of the views held by his predecessors with respect to the relations existing between these schists and the bedded sedimentary rocks associated with them. The general problems connected with the subject have been outlined in the Marquette monograph.[a] These green schists occur intermingled with granites and also form large continuous areas, which they entirely occupy, except for some unimportant dikes that intrude them. Some of these rocks are now hornblende-schists, others are chlorite-schists, while still others are massive greenstones. In the Menominee district the schists occur south of the ore belt. They are well exposed at the Big and the Little Quinnesec Falls and at the Sturgeon Falls on the Menominee River, and again in the vicinity of the Fourfoot Falls, north of Bass Lake. These schists, it will be remembered, were regarded by both Brooks and Rominger as layers of sedimentary material that have been metamorphosed since their deposition. By Brooks they were considered to be the uppermost beds of the Huronian series and by Rominger as the basal layers of this system. To Irving the regularity of the alternations in the schists seems less than one would think to be the case from Brooks's maps. The rocks seemed to him to grade into one another and into the massive beds. The schistosity appears to be of secondary origin and the original structure of the rocks seems to have been massive. In the Menominee district a series of detrital iron-bearing rocks lies between the green schists and great areas of granite and gneiss to the north. The iron-bearing rocks are similar to those of the Marquette district. They

[a] Mon. U. S. Geol. Survey, vol. 28, 1897.

are, however, rarely intruded by greenstone eruptives, and are much more crumpled than are the Marquette rocks.

In the same region are two belts of greenstone-schists closely analogous in general appearance with those of the Marquette region. The southern one of these borders for a long distance the southern granite area, separating the granite from the detrital rocks farther north. The inclination of the greenstone-schists is almost vertical, there being generally a slight southern departure from verticality. Very high southern dips, often approaching verticality, also prevail among the layers of the detrital succession itself, although here frequently occur reverse dips to the northward, often at a flatter angle [p. 25].

With respect to the age of the greenstone-schists, Irving writes:

In my own studies in the Menominee region, made in the summers of 1883 and 1885, I became early impressed with the close similarity between the greenstone-schists of the Menominee River and those which underlie the iron-bearing series of Marquette; with the entire similarity between the rest of the stratiform rocks of

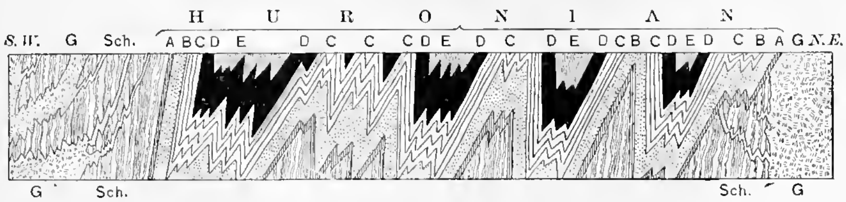


Fig. 12.—Hypothetical section across the Menominee region in the vicinity of Quinnesec Valley. After R. D. Irving, 1890; A, basal sericitic quartz-slates; B, quartzite; C, limestone; D, iron horizon; E, slates and quartzites; G, granite; Sch, schists of the Laurentian. Scale, 13,000 feet to the inch.

the region and those of the Marquette district; with the essential identity in character of the granite areas lying, respectively, on the northern and southern sides of the Menominee River; with the granitic intrusions met with in the greenstone-schists bordering the southern granite, and with the striking contrast between the nature of this contact and that of the northern granite and the detrital rocks which border it to the south. In the latter case, the granite, instead of sending intrusions into the rocks which rest against it, has furnished fragments to them, as may be most beautifully seen at the Falls of Sturgeon, Sturgeon River, on the eastern side of sec. 8, T. 39, R. 28 W., Michigan. These considerations naturally led me to the conclusion that the whole structure in this district is similar to that already described as obtaining in the Marquette region, namely, that the granitic masses had intruded themselves in the shape of great bosses into rocks now represented by the greenstone-schists, after which followed a protracted period of disturbance and denudation before the deposition of the overlying detrital and iron-bearing rocks of the region. Taking Major Brooks's detailed map of the Menominee district, published in the atlas of the Wisconsin survey, I platted on it all of the exposures described by

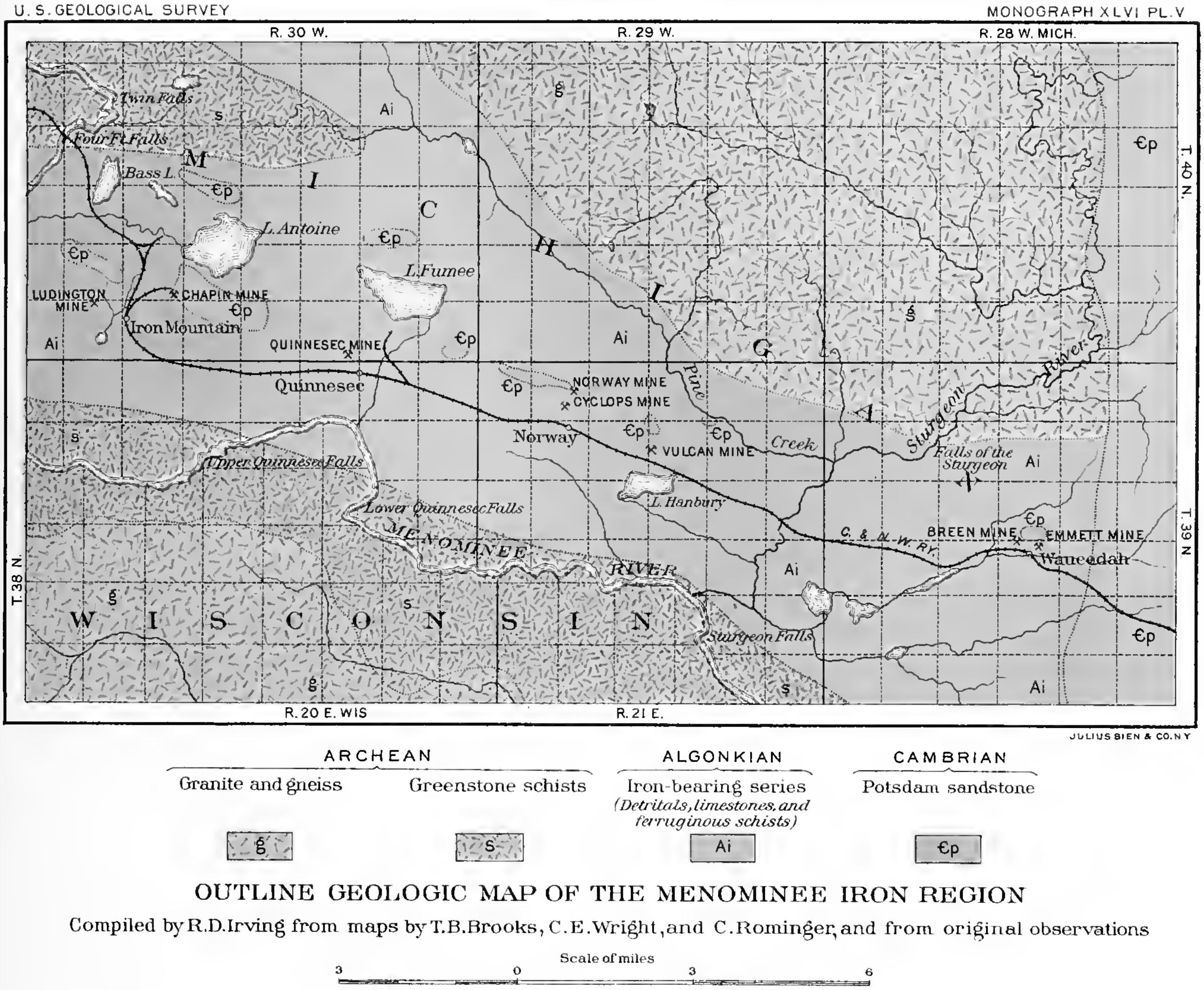
Rominger and not mapped by Brooks, which exposures amount in all to a large number. Examining, then, the more important of the exposures of the region, I encountered still others, which were also platted upon the same map. Two sections were then constructed across the district from southwest to northeast, upon which were platted all of these exposures, with their dips; and it should be said that very many new facts in this direction have been developed of late years by mining

It has thus become evident that a structure such as is indicated in the accompanying fig. 3 [reproduced as fig. 12, p. 93] would not only coincide with the recorded facts as well as the sections of Brooks * * * but very much better than those [pp. 29–30].

With reference to the conglomerates at the Falls of the Sturgeon, the author says that the granitic fragments occur in a fine-grained, slaty rock, in which there is a great deal of sericitic material, which at times gives the slate somewhat the look of a crystalline schist. This fact, together with the slight inclination from the vertical toward the north, led Credner to include the conglomerates with the Laurentian granite. Brooks's view is regarded as the correct one—i. e., the conglomerate is at the base of the sedimentary series. The granite sheet described by Rominger as interleaved with the conglomerates could not be found. Irving also points out the fact of Rominger's inconsistency in making the same granite yield fragments to the sedimentaries and subsequently to intrude them. The nature of the pebbles and the structure of the matrix which holds them are clear evidence to Irving that "we have here to do with a detritus derived by water action from the granitic and gneissic area immediately to the north. The slight inclination from the vertical toward the granite which these conglomeratic schists sometimes show is, of course, no argument against their having been deposited upon the granite as a substratum." (Footnote, p. 30.) The map accompanying the paper shows the distribution of the Archean, Algonkian, and Cambrian areas within the district. Although largely a compilation, it outlines definitely for the first time the limits of the iron-bearing series. A reproduction of it forms Pl. V.

Williams, G. H. The greenstone schist areas of the Menominee and Marquette districts, Michigan: Bull. U. S. Geol. Survey No. 62, pp. 31–131 and 192–217. 1890.

Dr. Williams's work is purely microscopical. The aim of his paper is "to trace each of the rock types represented within the areas studied from its least altered to its most altered form, and to discover what may have



OUTLINE GEOLOGIC MAP OF THE MENOMINEE IRON REGION

Compiled by R.D. Irving from maps by T.B. Brooks, C.E. Wright, and C. Rominger, and from original observations

1890

been the agencies which produced the changes noticed." The object of the author's investigations "was to discover, if possible, the origin of the greenstone-schists of the Lake Superior region, and at the same time to afford a contribution to our knowledge of the metamorphism of basic eruptive rocks in general" (p. 31).

The areas in the Menominee district selected for special study are five in number, embracing the vicinity of the Sturgeon Falls and the areas around the Little and the Big Quinnesec Falls, the Fourfoot Falls, and the Twin Falls. At the Sturgeon Falls the rocks on the Michigan side of the river consist of five bands of saussuritized gabbro and four bands of greenstone-schists. The gabbro constitutes Brooks's bed XV. In thin section it shows a gradation from an almost massive pyroxene-bearing saussuritized gabbro to schistose varieties composed of saussurite, quartz, and hornblende. The green schists associated with this gabbro are plainly the result of dynamic agencies. In some of them broken feldspar crystals may be detected, but others are now composed exclusively of chlorite, quartz, and calcite. These schists are believed to be derived from the gabbro by pressure and shearing. Associated with them are several bands of light-colored sericite-schists which the author considers as having been produced from the same gabbro by chemical processes that are essentially different from those that gave rise to the green schists.

At the Little Quinnesec Falls the rocks are mainly diorites, diabases, chlorite-schists, and sericite-schists. The great gabbro ridge of Major Brooks, described as extending along the Michigan side of the river, is in composition a diorite, originally containing a brown hornblende that has been replaced by a green variety of the same mineral. It is possible, according to the author, that the brown hornblende may in turn have been derived from diallage and the rock may have been a diabase. By further alteration the green hornblende passes into a tremolitic mineral and into a colorless chlorite. The schists are believed to be pressure-changed diabases. The slaty rocks recorded by Brooks as occurring here are thought to be altered basic eruptives, since they grade into massive diabases, and under the microscope their thin sections show evidence of the close relationship existing between them and the massive beds. The author gives a clear statement of the evidence from which he concludes that the massive rocks pass into schists by pressure action. He illustrates his remarks by the picture of a hand specimen taken from the western end of the "diorite ridge" near the falls. It shows a rock traversed by cross gashes, which the author explains as due to the stretching of the rock after solidification.

At the Big Quinnesec Falls the rocks below the falls are dark, more or less schistose greenstones that were once diabases. At the falls and for a half a mile above them are exposed light-colored granular greenstones which graduate into sericite-schists. At the Horserace Rapids the rocks forming the steep walls of the gorge are coarse-grained diorites. These rocks and those at the falls are cut by bands of granite, gneiss, and schistose porphyries that are closely related genetically with the granite south of the Menominee (Brooks's Huronian granite bed XX). The rocks below the falls show the effects of pressure in a striking degree. They were once diabasic, but at present they show only obscure traces of their ophitic structure. The barrier rock of the falls was regarded by Credner as very similar to a gabbro. Williams, however, finds it to be essentially a diorite, although originally it may have been a hornblende-gabbro, or possibly a normal gabbro. The coarse-grained diorites of the "Horserace" (above the falls) are dioritic varieties containing talc, which has been derived from hornblende. The rocks appear to be much-squeezed diabases. The green schists are cut by dikes of granites and of quartz-porphyries that are usually foliated like the schists themselves. Usually their foliation is parallel to the foliation of the surrounding rocks without respect to the direction in which the dikes run; thus it may sometimes be parallel to the sides of the dikes and at other times may be inclined to them. Most of the acid bands are regarded as apophyses of the granite to the south. If they are offshoots of the granite, this rock is younger than the schists; and if the schists are the uppermost members of the Huronian series, the granite must be the youngest rock in this series. The writer does not attempt to decide as to the age of the green schists, however, and consequently he makes no supposition as to the age of the granite with respect to the sedimentary beds of the Huronian.

With reference to the acid dikes, the author writes:

The dikes when small are fine grained and felsitic, but when larger their texture is coarser, and they have frequently a well-developed schistose structure parallel to that of the adjoining schists. After a careful examination of this locality and of the exposures between it and the river, there is no doubt in the writer's mind that the granite, "Augen-gneiss," biotitic gneiss, and schistose porphyry (or "porphyroid," as Credner called this rock) visible near the Upper [Big] Quinnesec Falls and along the Horserace are also dikes or apophyses connected with the main southern granite area. The schistose or banded structure of these rocks, where such exists, is a secondary feature, produced by the same dynamic agencies which rendered the greenstones themselves schistose [p. 111].

The granite of the main southern granite area is a typical granite with a tendency to a porphyritic structure. Like all the rocks in the vicinity it bears the marks of having been crushed.

At the Fourfoot Falls the greenstones are again well exposed. On the Wisconsin side of the river they are schistose and on the Michigan side on the strike of these schists the rocks are massive. A quarter of a mile below the Chicago and Northwestern Railway bridge is an exposure of black slate with the typical structure of a sedimentary rock. Above the railroad bridge a few steps begin the greenstone-schists, which are entirely different from the slate, but are similar to the green schists already described. At the Twin Falls the greenstones are of a dark, aphanitic variety, and when schistose, resemble a chloritic slate. Transitions between massive diabases and greenstone-schists and between these latter rocks and chlorite-schists are traced by the author step by step, so that there can seem to be no question but that the schists are squeezed eruptive rocks.

In summarizing the evidence as to the origin of the green schists derived from their study in the field and laboratory, the author shows that the foliation of the schists is no proof of their sedimentary character. The foliation of these rocks is parallel to the foliation of the sedimentary beds of the iron-bearing formation, but not always to the strike of their bedding. Both the schistosity of the greenstones and of their associated granites is a phenomenon due to pressure, which probably acted in two different periods, in one of which the genuine sediments received also their foliation.

The most convincing proof that the rocks of the Menominee and Marquette greenstone areas are of igneous origin is not to be derived, however, from their field relations, but rather from their microscopical structure. It is true that there are many cases where rocks of widely dissimilar origin resemble one another so closely that not even the minutest study of their internal structure is able to distinguish them with certainty; nevertheless there are in other cases well-marked peculiarities of structure which may be regarded as unfailing indications that the rock possessing them has crystallized out of a molten magma [p. 195].

The structures that are characteristic of eruptive rocks and that have been recognized in the Menominee greenstones are the ophitic, the porphyritic, the micropegmatitic and granophyric, and the poikilitic. The original rocks still recognizable in the Menominee district and those from which the schists have been derived are gabbros, diabases, diabase-porphyries, diorites, and diorite-porphyries among the basic phases, and granites, granite-porphyries, and quartz-porphyries among the acid areas. The evidence of the microscope indicates that the greenstones solidified at the surface.

In the Menominee Valley this evidence consists (1) of the fine texture of the rocks, and (2) of the alternation of bands of different types, which probably in their original position represented successive flows. Fineness of grain is universal in the Menominee greenstones, and we may be certain that it was a primary feature in spite of the extensive alteration of these rocks. It is especially noticeable in the case of the gabbro, which is almost always a coarse-grained rock when it has solidified at any depth. The succession of massive beds, like the pale gabbros and the dark diabases seen at the Lower [Little] Quinnesec Falls, are difficult to account for except by supposing that they were once horizontal sheets that flowed over one another and which were subsequently elevated into their present nearly vertical position. Traces of tuff material are not as distinct here as in the Marquette region, although indications of its existence are by no means wanting. We might reasonably expect that any original scoriaceous or amygdaloidal structure would have disappeared in the course of the profound chemical changes through which these greenstones have passed [pp. 200–201].

The author's paper is illustrated by maps of the districts studied and by 12 lithographic reproductions of thin sections of characteristic rocks.

1891.

Van Hise, C. R. An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy: Am. Jour. Sci., 3d series, vol. 41, pp. 117–136. 1891.

The author believes that many of the difficulties that have arisen among geologists with respect to the correlation of the pre-Cambrian rocks is due to the neglect to note the existence of a physical break in the series of strata placed by Irving in his Huronian group. He shows that such a break occurs in the Marquette district and that here there is a well-defined upper and a distinct lower series, separated from each other by a great unconformity and a basal conglomerate. In the Menominee district the evidence of this break is lacking, possibly because the knowledge of the relations existing between the Menominee rocks is less exact than it is in the case of the Marquette sediments. It is thought probable, however, that in the Menominee district the equivalents of both the lower and upper Marquette rocks occur. The Menominee proper—that is, the portion of the Menominee district east of the Menominee River—is thought to correspond in position with the Lower Marquette and that portion west of the river with the Upper Marquette.

GOETZ, GEORGE W. Analyses of Lake Superior ores: Trans. Am. Inst. Min. Eng., vol. 19, pages 59–61. 1891.

The author records the results of analyses of ores from 24 mines in the Menominee district on both sides of the Menominee River.

1892.

VAN HISE, C. R. Correlation papers—Archean and Algonkian: Bull. U. S. Geol. Survey No. 86, pp. 72–208, 470–529. With general map of Lake Superior region. 1892.

This volume contains a summary of all the work done on the pre-Cambrian rocks of North America up to within a few months of the time the volume was published. The evidence collated from the writings of those geologists who had investigated Lake Superior geology is discussed and conclusions are drawn from it by the author. With the abstract of the literature we have nothing to do in this review, nor with the matter dealing with the classification of the pre-Cambrian formations in the Lake Superior region. The latter subject is freely discussed in the chapter on literature in the Marquette monograph,[a] where the discussion rightly belongs, since many of the conclusions arrived at with reference to the separation of the pre-Cambrian series were reached very largely by studies prosecuted in the Marquette district. There are, however, a few direct references made to the Menominee district which should be considered here.

In 1890 the author examined the rock succession at Iron Mountain, finding above the ore formation at the Ludington and Chapin mines a conglomerate which bears fragments of ore and jasper. "It therefore appears that after this material reached its present condition in the ore-bearing series it was eroded and furnished débris for a newer series" (p. 156). In company with Professor Pumpelly he again in 1891 and 1892 examined the ore formation. In a quarry east of the Chapin mine, and also in the deeper

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 5–148.

workings of this mine, it was discovered that the ores resting almost directly upon the limestone bear a considerable percentage of carbonates, and in the first-mentioned locality they grade directly downward into the limestone.

It is therefore probable that the ore formation of these districts, in part at least, is but an upward continuation of the limestone formation, perhaps differing from it originally only in that the upper part contained a greater quantity of original carbonate of iron.

Above the ore formation at Quinnesec, test pits show the presence of a typical chert and jasper conglomerate, in every respect like the basement conglomerates of the Upper Marquette [p. 156].

The additional evidence with respect to the physical break in the clastic series lying between the green schists and the Potsdam sandstone is summarized as follows:

In the Menominee district as evidence in favor of a physical break within the clastic series are the conglomerates described by Brooks at the Pine and Poplar rivers district, and in the Commonwealth section. * * * Also, the structural break indicated by these conglomerates is supported by Brooks's major divisions of the Menominee rocks. His inferior Huronian comprises the lower quartzite of great thickness, a great marble formation, and the great iron-ore horizon, consisting of magnetitic, hematitic, and jaspery schists, with deposits of iron ore. In this formation are the Norway, Quinnesec, Ludington, Chapin mines, etc. Brooks's middle Huronian, presumably above the unconformity, includes quartzites, clay slates and obscure soft schists. Within these soft slates is the upper iron-bearing horizon, including such mines as the Commonwealth, those at Crystal Falls, etc. [Pp. 180–181.]

The author does not believe that a correspondence can be made out between the subordinate members of the Menominee and Marquette districts, and yet he thinks that the Menominee district in Michigan corresponds as a whole to the Lower Marquette series.

Van Hise, C. R. The iron ores of the Marquette district of Michigan: Am. Jour. Sci., 3d series, vol. 43, pp. 116–132. 1892.

Although this article deals mainly with the manner of occurrence of the ore bodies in the Marquette district, those of the Menominee district are referred to in a few words. The ores of this district are said to occur in two formations, one of which belongs with the Lower Menominee and the other with the Upper Menominee. From the general work done in the district it seems that the ores are all secondary concentrations upon impervious formations. They are particularly likely to be of large size when the impervious beds are folded or when two of them combine to form pitching troughs.

1893.

Winchell, N. H. The crystalline rocks—some preliminary considerations as to their structure and origin: Twentieth Ann. Rept. Minnesota Geol. and Nat. Hist. Survey for 1891, pp. 1–28. 1893.

The first part of this article is a general discussion of the nature of the evidence that should guide the geologist in his conclusions as to the origin of the metamorphic rocks. The second part illustrates the author's use of this evidence. He declares that field evidence is of more value in determining the sedimentary origin of a banded rock than the evidence of a microscope. He illustrates by reference to the greenstone-schists of the Menominee district. He reproduces the figure of the hand specimen with cross gashes published by Williams, and seems to conclude that the rock which Williams declared to be a squeezed gabbro is a squeezed sedimentary rock. The greenstones, it seems from a careful reading of the author's words, are thought to be sedimentary deposits, in large part tuffaceous.

Wadsworth, M. E. Sketch of the geology of the iron, gold, and copper districts of Michigan (dated March 26th, 1892): Report of State Board of Geol. Survey for the years 1891 and 1892, pp. 75–174. 1893.

The Azoic or Archean rocks of Michigan, according to the author, embrace three distinct formations, named, from their typical exposures in the Marquette district, the Cascade, the Republic, and the Holyoke. The Cascade is the oldest. In the Menominee district it contains gneisses in which are embedded gneissoid fragments, and true granites which hold an intrusive relation to the gneisses and other foliated rocks. In sec. 2, T. 40 N., R. 30 W., a basic dike, now an amphibole-schist, was seen to be intrusive in quartzite, and in its turn to be cut by a felsite dike. The Republic formation corresponds to Van Hise's Lower Huronian.

The heavy quartzite which extends in the Menominee district from Sturgeon River along Pine River * * * is thought to belong to the base of the Republic formation, as it is found in various places close to the Cascade gneiss and granite, dipping away from that formation, and is cut by dikes of the granite on sec. 12, T. 41, R. 30 W. This quartzite is probably Republic, if the overlying ores are Republic, which they are here considered to be, although no direct proof of this supposition has yet been obtained. The ground for this belief rests chiefly on the physical character of the ore formation [p. 103].

In addition to the quartzite and iron ores the dolomites so abundantly exposed in the Menominee district are also placed in the Republic formation. The author calls attention to the existence of "eruptive argillite or schist" in dikes at the Cyclops and Norway mines. In connection with the discussion of the origin of the greenstone-schists, Wadsworth states that the rock on the Michigan side of the Menominee River, below the Little Quinnesec Falls, and at the Big Quinnesec, is a conglomeratic greenstone or a tuff, and not an eruptive diabase or diorite, as Williams supposed. Similar tuffs are very common in the Marquette district.

HUBBARD, L. L. Macroscopic minerals of Michigan: Report of State Board of Geol. Survey for the year 1891 and 1892, pp. 174–176. 1893.

In this list of minerals occurring in Michigan the author mentions chalcopyrite, pyrite, quartz, hematite, limonite, martite, laumontite, malacolite, orthoclase, staurolite, tourmaline, azurite, calcite, dolomite, siderite, and malachite as existing in the Menominee district.

PATTON, H. B. Microscopic study of some Michigan rocks. Report of State Board of Geol. Survey for the years 1891 and 1892, pp. 184–186. 1893.

As the result of his investigation of thin sections of Marquette and Menominee rocks Patton identifies a great variety of schists in these two districts, besides slates, graywackes, and several kinds of eruptive rocks, but he gives no details with respect to any occurring in the Menominee district.

WILLIAMS, G. H. The microscope and the study of the crystalline schists: Science, vol. 21, p. 1. 1893.

In a reply to Professor Winchell's article on the crystalline rocks, referred to above, Dr. Williams takes exceptions to some of Winchell's remarks with respect to the comparative value of field and microscopical evidence in the study of the crystalline schists. He calls attention to the fact that the figures reproduced by Winchell from the author's paper are figures of specimens taken from rock masses that were so clearly eruptive in origin that there was no necessity for their study under the microscope. In conclusion, he writes:

In reality, what are known in the Lake Superior region as "greenstones" and "greenstone-schists" are not one thing, but a great variety of different things. Some of them are massive lavas, others accumulations of ash material, stratified by gravity or water. They possess structures of diverse origin, which may to the field geologist appear very much alike.

Birkinbine, John. Iron ores: Mineral Resources U. S. for 1891, pp. 10–46. 1893.

The author, besides giving the usual statistics concerning the iron-ore industry in the United States, abstracts from Commissioner Lawton's reports on the Michigan iron mines several statements relating to the distribution of the ore-bearing beds in the Menominee district, but no information is given concerning the iron-bearing series in addition to that given in the reports of Brooks, Wright, and Rominger.

Van Hise, C. R. An historical sketch of the Lake Superior region to Cambrian time: Jour. Geol., vol. 1, pp. 113–128, with general geological map of the Lake Superior region. 1893.

In this general sketch of the geology of the Lake Superior region the Lower Menominee rocks are made equivalent to the Lower Marquette and to the Lower Huronian in other portions of the region. The map is the same as that published in the Correlation Paper.

Van Hise, C. R. Sketch of the pre-Cambrian geology of the Lake Superior region, with references to illustrative localities: Compte-Rendu, Fifth Sess. Inter. Geol. Cong., pp. 489–512, with maps. 1893.

In this paper the author gives a synopsis of the knowledge concerning the pre-Cambrian geology of the Lake Superior region. The facts recorded in it are not very different from those mentioned in the Archean-Algonkian Correlation Bulletin and in other papers by the same writer. With respect to the Archean of the Menominee district, of which Irving's map is reproduced, the author makes the following statement:

In the Menominee district the schists and granites of the Basement Complex may be seen in typical exposures both south and north of the Huronian rocks. The northern schist area is well exposed at Twin and Fourfoot Falls, 3–5 miles northwest of Iron Mountain, while the northern granite appears some miles northeast of Iron Mountain. The southern schists are finely exposed southeast of Iron Mountain at the Upper [Big] Quinnesec Falls, at the Lower [Little] Quinnesec Falls, at Sturgeon Falls, and near the crossing of the Menominee by the Milwaukee and Northern Railway. At the Horserace, above Upper Quinnesec Falls and one-half mile to the south, before the solid granite is reached, numerous dikes of this rock may be seen cutting the schists. On the Milwaukee and Northern Railway the granite rocks appear about 4 miles south of Iron Mountain. At this point and east and west of the railroad the intrusive relations between the granitic and schistose rocks are finely shown [p. 494].

The Lower Huronian consists of (1) conglomerates, quartzites, quartz-schists, and mica-schists; (2) limestones; (3) various ferruginous schists; and (4) basic and acid eruptives, which occur both as deep-seated and as volcanic rocks. The Lower Menominee belongs here.

It may be best studied at Iron Mountain and vicinity and at Norway and vicinity. At these places the iron-bearing member and the limestone are well exposed [p. 496].

In the Menominee district the only locality at which the supposed Lower Huronian is known to be in direct contact with the Basement Complex is at the falls of Sturgeon River. Here the Basement Complex has its typical character. It consists of coarse, black, hornblendic gneiss, which is cut through and through by red granite. Both occur in large masses, and along the numerous contacts the granite and gneiss are often minutely interlaminated, evidently by the intrusion of the latter. At many places dikes of granite may be seen passing from large granite masses and penetrating the schists, and then gradually dying out. In places the schists are so cut by stringers of granite as to have a genuine pegmatized appearance. Upon the irregular eroded surface of this Basement Complex rest masses of the broken ledge 2 or 3 feet thick, which pass upward into a schistose conglomerate containing numerous well-rounded bowlders and pebbles of the granite-gneissoid schist, in every respect like these rocks in the Complex below. The matrix of the schist is sheared and crystalline, but the larger pebbles and bowlders of granite have escaped any considerable crushing. There are several alternations of coarse conglomerate and fine siliceous schist before the conglomerate finally grades into the overlying quartzite. The geology has not been worked out in detail here, and that this formation is the lower quartzite of the Lower Huronian rests upon the authority of Brooks [pp. 499–500].

The Upper Huronian is not as well exposed on the Michigan side of the Menominee River as it is on the Wisconsin side. "The lowest formation of the Upper Huronian may be seen above the Lower Huronian iron formation at Iron Mountain and Quinnesec. The series can, however, best be studied about the Commonwealth mine and 2 or 3 miles to the westward in the vicinity of Lake Eliza" (p. 503). The Upper and the Lower Huronian are often separated by unconformities and basal conglomerates. "In the Menominee district the basal conglomerate of the Upper Huronian is not well exposed, but has been detected at the Chapin and Quinnesec mines by shafts and drill holes" (p. 506).

Hulst, N. P. The geology of that portion of the Menominee Range east of the Menominee River: Proc. Lake Superior Min. Inst. for March, 1893, pp. 19–29, with map. 1893.

The author gives an abstract of the general geology of the Menominee district as worked out by Brooks and adds detailed sections of several of the mines in that portion of the district east of the Menominee River. The ore bodies are described as being found in beds of banded lean jasper, which is always associated with the richer ore. The ore may occur anywhere within the jaspery horizon. It is crossed by the stratification planes, which are extensions of those in the jasper. Often there are spots in the jasper composed of a substance that appears to be in a transition state between jasper and ore. The silica seems to be gradually disappearing from the jasper by solution, leaving a mass continually growing richer in the ore material.

The ore bodies usually pitch west at from 30° to 50°. Some of them rest upon a foot wall of soapstone or are under a hanging wall of this substance. Others possess no distinct walls, the merchantable ore suddenly giving away to the lean ore, or vice versa, according to no rule. The productive portions of the range appear to be located at points where the formations have been faulted, eroded deeply, or sharply folded.

The limestone is thought to be beneath the ore-bearing formation and not above it. The northerly dip of this rock at the Quinnesec, Pewabic, Chapin, and other mines in the western portion of the district is explained as due to an overturn of the series. Attention is called to the fact that the discovery of bowlders of limestone in the iron formation by Wright is corroborative evidence in favor of this view.

The descending succession at the Chapin and the Pewabic mines, obtained by cross sectioning, is as follows:

Section at Chapin mine.

	Feet.
Quartzite	140
Jasper	
Quartzite	
Quartzite and jasper	
Quartzite, slate, and jasper	
Slate	
Quartzite and slate	
Quartzite and jasper	
Banded ore, containing Millie ore body	300
Quartzite and slate	55
Slate	
Jasper	170
Ore body	
Gray slate	75

Section at Chapin mine—Continued.

	Feet.
Ore Gray slate Jasper Gray slate Jasper Gray slate Jasper Ore Gray slate Limestone	185

Section at Pewabic mine.

	Feet.
Quartzite Red slate	600
Jasper and ore, containing Pewabic ore body	215
Gray slate	112
Quartz Gray slate	about 15
Quartzite	77
Quartz and slate	about 10
Slate conglomerate	50
Red slate	77
Quartz and gray slate Quartzite Quartz and sand Slate conglomerate	85
Quartzite conglomerate	116
Red slate	50
Jasper Red, gray slate Limestone	40

The normal dip of the iron-bearing series is to the south. The cause of this southerly dip the author ascribes to the southern granite, the Huronian granite of Brooks. This is supposed to have flowed out upon the sediments when they were approximately horizontal, and by its weight to have caused them to sink beneath it.

Although the principal iron-bearing horizon is above the limestone, a second one is surmised to exist below this bed, since the Loretto mine on the Sturgeon River has been opened in rocks dipping south, apparently under the limestone north of the main ore belt.

The map accompanying the article is practically a reproduction of the Brooks map.

1894.

WINCHELL, H. V. Historical sketch of the discovery of mineral deposits in the Lake Superior iron region: Second Ann. Rept. Proc. Lake Superior Min. Inst. 1894. Also Twenty-third Ann. Rept. Minnesota Geol. and Nat. Hist. Survey for 1894, pp. 116–155. 1895.

After quoting from Messrs. Foster and Whitney's description of the geology of the Menominee district, the author states that in 1866 Messrs. Thomas and Bartley Breen discovered the first workable deposit of ore on the Menominee range, but not until 1870 was any systematic work done on the deposit. In that year the first openings were made that afterwards led to the development of the Breen mine. The Vulcan and the West Vulcan ore bodies were discovered by Dr. N. P. Hulst in 1872, the Quinnesec in 1873 by Mr. J. L. Buell, and the Chapin in 1878 by Dr. Hulst.

SMYTH, H. L. Relations of the Lower Menominee and Lower Marquette series in Michigan (Preliminary): Am. Jour. Sci., 3d series, vol. 47, pp. 216–223. 1894.

Nearly all writers on the geology of the Marquette and Menominee districts have maintained the general equivalency of the iron-bearing series in the two districts. This opinion is based on the unconformability of the clastic series in each district above a series of gneisses and crystalline schists, and upon the lithological similarity that exists between certain members in both series.

The author's work north of the Menominee River iron-bearing area confirms Van Hise's view that there is an unconformity in the Menominee series corresponding to the unconformity between the Lower and the Upper Marquette rocks. The sequence in the two districts is represented to be as follows:

Marquette district.	*Menominee district.*
Upper Marquette.	Upper Menominee.
Unconformity.	Unconformity.
Lower Marquette.	Lower Menominee.
Unconformity.	Unconformity.
Archean.	Archean.

Although the sequence appears to be similar in both districts the rocks of the one region have not been traced into the other, so that it can not be said that this similarity proves the formations in the two districts to have been formed contemporaneously. The likeness of the Lower Menominee to the Lower Marquette formations is rendered more striking when their lithological similarities are compared more carefully than has heretofore been done. The Lower Menominee (which is that portion of the Algonkian most prominent in the district under consideration) consists of the following strata:

(1) A basal quartzite from 700 to 1,000 feet thick.

(2) A crystalline limestone from 700 to 1,000 feet thick.

(3) Red, black, and green slates, not known to exceed 200 to 300 feet in thickness. In these slates occur the iron ores of Norway and Iron Mountain.

(4) The highest member (except the volcanics) is a jasper, best developed at Michigamme Mountain in sec. 4, T. 43 N., R. 31 W., and in sec. 33, T. 44 N., R. 31 W.

Iron ores occur at three horizons—(1) in upper portion of the quartzite near its contact with the limestone; (2) in the slates; (3) in the Michigamme jasper (not present in the Menominee district as defined in this monograph). Lean martite ores are widely distributed at the first horizon, but only one workable deposit has been found in this position in the series. The important deposits are those occurring in the slates.

"These occur as local concentrations in a ferruginous rock, composed of banded jasper and iron ore, which, perhaps, is the modified representative of portions of the slates carrying a large proportion of nonclastic material of original deposition."

The lithological similarity of the Menominee with the Marquette series is thus expressed:

Menominee.	*Marquette.*
Michigamme jasper.	Jasper banded with ore. } (iron formation).
Slate (principal iron formation).	Magnetic-actinolite schist } (iron formation).
Limestone.	Quartzite.
Quartzite.	
Archean.	*Archean.*

The correspondence is not as close as it was supposed to be, the absence of limestone from the Marquette district being especially noticeable.

The Michigamme jasper was traced north by its magnetic properties into an area where the rock exposures consist of a lower quartzite and an upper magnetite-actinolite rock. The magnetic line corresponding to these beds was traced still farther north until it comes within 2½ miles of a line of magnetic attraction passing through the actinolite-schists of the Marquette series. The Menominee rocks dip eastward while the Marquette rock is thought to dip west. The intervening space between the two magnetic lines is covered with drift, but presumably beneath it is a synclinal fold, with the Michigamme jasper and the Marquette actinolite-schists on the corresponding opposite sides. If this supposition is correct the quartzite composing the lower portion of the Michigamme jasper on the Menominee side of the syncline is the same as the quartzite under the magnetite-actinolite-schists of the Marquette series, and as a consequence the whole of the latter series is represented in the Menominee district by the higher members of the Menominee series.

The conclusions of the author as summarized by himself are as follows:

1. The Lower Menominee quartzite, limestones, and slates are all older than any formation in the Marquette area.

2. The Michagamme jasper was deposited in a continuous sheet over both [Marquette and Menominee] districts, and in the Marquette district constitutes both the iron-bearing formation and, for most of the area, the lower quartzite.

3. The principal ore horizon of the Menominee has no equivalent in the Marquette district.

Van Hise, C. R., Summary of current pre-Cambrian North American Literature: Jour. Geol., vol. 2, p. 453. 1894.

This article consists of a résumé of Hulst's article on the Menominee district supplemented by the following comments:

The sections give additional evidence that in the Menominee district, as in the Marquette, there are two unconformable series. The Chapin, Ludington, and Hamilton appear to belong to the Lower Huronian. The horizon of quartzite, slate, and conglomerate is evidently the basal conglomerate of the Upper Huronian. The Millie, Pewabic, and similar ore bodies are in the Upper Huronian. That the ore bodies occur in disturbed areas and frequently rest upon soapstone or other impervious formations accords perfectly with what has been previously ascertained as to the manner of concentration of the Lake Superior iron ores.

1895.

Rominger, C. Geological Report on the Upper Peninsula of Michigan, exhibiting the progress of work from 1881–1884; Iron and copper regions: Geol. Survey Michigan, vol. 5, pp. 1–84. 1895.

In this report Dr. Rominger supplements his earlier report on the Marquette and Menominee districts by recording his observations made between the years 1881–1884. Very little additional information is given concerning the Menominee rocks, most of the author's time having been spent in the Marquette and the Gogebic districts.

The "granite seams intersecting the dioritic rock series" south of the Big Quinnesec Falls and the porphyries of Pemenee Falls are identified as "analogous" to the granites and porphyries cutting the green schists north of the city of Marquette. At Pemenee Falls the porphyries occur not only in dikes, but in "a succession of porphyritic beds of immense thickness" (p. 7).

With respect to the diorite group the author states that the fine-grained dioritic rocks near the Quiver Falls are all augitiferous, as is also the range of diorites running across the N. ½ of T. 40 N., R. 30 W. "The hornblende in them appears to be the result of alteration of the augite." The rocks of the Big and of the Little Quinnesec Falls are typical diorites, but the barrier rock of the Sturgeon Falls is a gabbro, as are also the so-called diorites in sec. 35, T. 39 N., R. 29 W., and in the northwest quarter of sec. 16, T. 38 N., R. 28 W. Diallage was recognized in dikes of a dark-green rock, supposed to be serpentine, which cut the green schists a short distance above the Sturgeon Falls and in exposures of a similar rock in the W. ½ of sec. 26, T. 39 N., R. 29 W., near the road leading to Menominee. This rock and certain other finer-grained ones in the vicinity consist of blades of diallage in a cement of serpentine. The rock in sec. 12, T. 39 N., R. 30 W., that in sec. 9, T. 37 N., R. 28 W., on the Menominee River, and at many other places in the district, also contains more or less augite.

The ore-bearing rocks of the Menominee district east of the Menominee River are regarded as younger than the Felch Mountain ore beds, as young, perhaps, even as the older beds of the author's mica-schist group. In the northwest quarter of sec. 17, T. 41 N., R. 31 W., a little beyond the limits of the district studied in this volume, the micaceous schists have been explored for iron. No "real good ore" was found, but interlaminated with the schists in their "lowest position right in the surface of a superficially decomposed diorite belt underlying these beds, and in clefts of the diorite, pockets of a compact hydrated iron ore [were found], which to all evidences has been a secondary deposit of infiltration a long time after the deposition of this schistose series" (p. 37).

The arenaceous slate group, comprising the "upper series of the

Huronian sedimentary layers," contains even a greater quantity of limonitic ore than had been supposed. "This younger group of sediments, inclosing limonitic ore deposits, shows by its topographical distribution an independence from the preceding lower strata, which proves considerable changes in the ocean level during the time intervening between the deposition of the first and the latter" (p. 73).

In the Quinnesec mining district no interruption in the progress of formation of sedimentary layers is indicated, as we find on the north side of the—

Quinnesec iron range, its latest strata, the great belt of compact siliceous limestones, conformably succeeded by this very large group of sericite-argillite-schists, graphitic slate-rock layers, chert and quartzite belts, with interposed accumulations of limonitic iron ore, but farther northwest, partly in Wisconsin territory, the most common case is to find this upper series of rock resting on dioritic and granitic masses, and none of the lower strata developed (pp. 73–74).

Winchell, N. H. The origin of the Archean greenstones: Twenty-third Ann. Rept. Minnesota Geol. and Nat. Hist. Survey for 1894, pp. 4–35. 1895.

The author again (see p. 101) turns to the subject of the origin of the greenstones in the Lake Superior region. He begins his article with a misstatement of the conclusions reached by Williams in his discussions of the Menominee and Marquette green schists, asserting that "the tendency of the conclusions reached by Dr. Williams is to refer the greenstones as a body to dynamic metamorphism of massive irruptive rocks" (p. 4). The object of the present paper is to give the reasons of the author's present belief "that the great bulk of the 'greenstones' as an Archean terrane ought to be classed as pyroclastic, i. e., that they originated from eruptive agencies, as tuff and all kinds of volcanic débris, sometimes very coarse, and were distributed and somewhat stratified by the waters of the ocean into which the materials fell" (p. 5). The main point of Professor Winchell's paper seems to be a criticism of Williams for not spreading his conclusions respecting the origin of the Marquette and Menominee greenstones over the greenstone-schists of the entire Lake Superior district, and for not recognizing tuffs among the Menominee rocks, although he distinctly regarded the latter as of surface origin. Winchell again criticises Williams's explanation of the cross gashes in the hand specimen figured by him, and declares that the schistosity of the Menominee greenstones is not always an effect of pressure and shearing. (See pp. 94–98.) The author argues against the general conclusion that the phenomena observed in these rocks are due principally to dynamic metamorphism, but in doing so he misinterprets many of Williams's statements, and evidently puts meanings into them that they were never intended to convey. Everywhere the author argues against the "irruptive hypothesis" for the greenstones, presumably supposing that this was Williams's hypothesis, whereas it was in reality mainly an eruptive hypothesis. The only fault that the present paper really shows to exist in Williams's work is the neglect of the latter to observe the fragmental structure of certain greenstones in the neighborhood of the Little and the Big Quinnesec Falls, and this neglect had already been referred to before by Wadsworth. Professor Winchell finally agrees with Williams that the present condition of the greenstone-schists is due to dynamic metamorphism, although he does not distinctly say so. He emphasizes the fact that the rotted condition of the schists is due to weathering, a fact which Williams also admits.

The paper concludes with a discussion of "the greenstones as a geological terrane," but the discussion is mainly with respect to these rocks in Minnesota, a subject with which we are not here concerned.

Van Hise, C. R., and Bayley, W. S. Preliminary report on the Marquette iron-bearing district of Michigan, including a chapter on the Republic Trough by H. L. Smyth: Fifteenth Ann. Rept. U. S. Geol. Survey, Chap. V, pp. 631–650. 1895.

In his discussion of the general geology of the Marquette district Van Hise correlates the Lower Marquette series with the Lower Menominee of Smyth. He places the succession as follows, attempting no correlation between the upper series:

Upper Marquette.	*Upper Menominee.*
——Unconformity.——	
Lower Marquette.	*Lower Menominee.*
Negaunee iron formation, 1,000 to 1,500 feet	Michigamme jasper. Slates bearing rich ores.
Siamo slate, in places including interstratified amygdaloids, 200 to 625 feet thick Ajibik quartzite, 700 to 900 feet Wewe slate, 550 to 1,050 feet	Slates and altered volcanics, maximum thickness, 2,000 feet.
Kona dolomite, 550 to 1,375 feet	Crystalline dolomite, 700 to 1,000 feet.
Mesnard quartzite, 100 to 670 feet	Basal quartzite, 700 to 1,000 feet.

The succession for the lower series would thus be very closely parallel in the two districts, with the following exceptions:

(1) The Wewe slate, the Ajibik quartzite, and the Siamo slate are placed opposite one member of the Menominee series. These three formations are, however, all fragmental, and are equated with a fragmental formation. Together they mark a time of mechanical deposition in each district between the nonfragmental limestone and the nonfragmental iron formation, and thus include the physical change involved in passing from a nonfragmental to a fragmental, and then again to a nonfragmental formation. The chief difference is that in the Marquette district two layers of mud were separated by a layer of sand. Another difference is that in the Menominee district volcanics are much more important, and this may account for the absence of conditions favorable to sand deposits. However, it is interesting to note that amygdaloids are found in the Lower Marquette series in the Siamo slate—that is, toward the higher part of this great fragmental formation. The Fence River volcanics in the Michigamme district occupy a similar horizon.

(2) The pure, nonfragmental iron formation of the Marquette district is equated with slates bearing the rich ores of the Menominee district and the Michigamme jasper. The only substantial difference, however, is that in the Menominee and Michigamme districts both the slates and the jasper bear, with the nonfragmental, a considerable amount of fragmental material. In other words, the conditions in these districts were not favorable to pure nonclastic sediments as they were in the Marquette district [p. 649].

1896.

Van Hise, C. R. Summary of pre-Cambrian North American literature: Jour. Geol., vol. 4, pp. 748–750. 1896.

The author, commenting upon Smyth's article on the relations of the Lower Menominee and the Lower Marquette series, declares that additional evidence seems to be necessary to prove that the iron-bearing slates of the Menominee district are the equivalents of the slates associated with the eruptives farther north. If these are not equivalent, the Michigamme jasper and these iron-bearing slates are the equivalents of the iron-bearing formation and the quartzite below it in the Marquette district, in which case the iron-bearing horizon of the Menominee may have an equivalent in the Marquette district.

Van Hise, C. R. Summary of the pre-Cambrian North American literature: Jour. Geol., vol. 4, pp. 753–754. 1896.

In criticism of Winchell's conclusions that the greenstone-schists of the Lake Superior region constitute a single terrane, and that the bulk of them are pyroclastic, Van Hise declares that south of Lake Superior they constitute three distinct terranes in three distinct and unconformable series. Some of them are pyroclastic, some are extrusive, and some are intrusive in origin.

NEWETT, GEORGE A. Mines and Mineral Statistics, pp. 47–62. With map. 1896.

This is the report of the commissioner of mineral statistics for Michigan. So far as the Menominee district is concerned, it consists principally of a description of the condition of the various mines in the district. The map is an outline map showing the location of the principal mines on the range. Several sections through the Aragon mine and two through the Pewabic accompany the report. The longitudinal section through the Pewabic mine exhibits the distribution of the high and the low phosphorus ores.

BIRKINBINE, JOHN. Iron ores: Seventeenth Ann. Rept. U. S. Geol. Survey, pt. 3, pp. 23–43. With maps. 1896.

The report of Birkinbine is almost wholly statistical. It, however, contains several maps of interest, one of which exhibits the location of the active, suspended, and abandoned mines in the Menominee district.

W. S. GRESLEY. Organic markings in Lake Superior iron ores: Science, n. s., vol. 3, pp. 622–623. 1896.

The author announces the discovery of markings resembling traces left by organisms in fragments of iron ore from the Chapin mine, Iron Mountain. The specimens showing the markings were picked up from the ore piles on the docks at Erie, Pa. They were submitted to Messrs. H. S. Williams, of Yale; Charles Schuchert and C. D. Walcott, of Washington; and C. R. Van Hise, of the University of Wisconsin. Some of them were pronounced by these gentlemen to be very similar to the trails left by worms in mud rocks.

[WINCHELL, N. H.] Supposed pre-Taconic organisms: Am. Geologist, vol. 18, pp. 123–124. 1896.

Professor Winchell refers to the above note by Gresley in an editorial in which he declares that while the markings may be of organic origin, they will nevertheless "not be admitted as a demonstration of Archean life without a many-sided scrutiny, the more as all other similar claims seem to be so rapidly crumbling."

VAN HISE, C. R. Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 2, pp. 743–843. With maps and illustrations. 1896.

The major portion of this article is a discussion of the relations existing between the different rock series in North America that are of pre-Cambrian age. Among others, the Lake Superior region is discussed, but no special description is given of the Menominee district, although mention is made of it in several places. The Huronian in this district is divided into the Upper and the Lower Menominee series, the latter of which is in general equivalent to the Lower Marquette series, the corresponding members in the two being as follows:

Lower Marquette.	*Lower Menominee.*
Negaunee iron formation, 1,000–1,500 feet.	Slates bearing rich ores.
Siamo slate, including interstratified amygdaloids, 200–625 feet.	Michigamme jasper.
Ajibik quartzite, 700–900 feet.	Slates and altered acid and basic volcanics, maximum thickness, 2,000 feet.
Wewe slate, 550–1,000 feet.	Crystalline dolomite, 700–1,000 feet.
Kona dolomite, 550–1,375 feet.	Basal quartzite, 700–1,000 feet.
Mesnard quartzite, 100–670 feet.	

1897.

Van Hise, C. R., and Bayley, W. S. The Marquette iron-bearing district of Michigan, with atlas, including a chapter on the Republic Trough, by H. L. Smyth. Mon. U. S. Geol. Survey, vol. 28, pp. 575–579. 1897.

In this volume the same discussion is given concerning the correlation of the Menominee and the Marquette rocks as is found in the preliminary account of the Marquette district, published by the same authors in 1895.

Gresley, W. S. Traces of organic remains from the Huronian (?) series at Iron Mountain, Mich., etc.: Trans. Am. Inst. Min. Eng., vol. 26, pp. 527–534. 1897.

This article contains descriptions of the fossil markings the discovery of which was announced by the author in 1896 (p. 114). For several years the ore piles on the docks at Erie, Pa., had been industriously examined with the view to discovering fossils that might be present in the ores. Since no ores are used at Erie except those of the Lake Superior region, it appears probable that the specimens obtained came from this region. On the authority of the dock superintendent the majority of the specimens described in the article are declared to have originated in the Chapin mine, at Iron Mountain. The markings are of various kinds, most of the varieties being represented by drawings on four plates. Of those thus represented some are thought to be the impressions of plants, others of corals, and others of footprints. The greatest number are thought to be trails left by crawling animals. One specimen resembles the mold of sun cracks. The best characterized of these markings are reproduced as Pls. VI and VII.

1899.

Clements, J. Morgan, and Smyth, Henry Lloyd. The Crystal Falls iron-bearing district of Michigan; with a chapter on the Sturgeon River tongue, by William Shirley Bayley, and an introduction, by Charles Richard Van Hise: Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3; pp. 1–151. With 2 maps, 9 plates, and 6 illustrations in text. 1899.

In his introduction to this report Van Hise correlates the formations of the Marquette, Crystal Falls, and Menominee districts as follows:

Marquette District.	Crystal Falls District.	Menominee District.
Upper Marquette series.	*Upper Huronian.*	*Upper Menominee.*
(1) Michigamme formation, bearing a short distance above its base an iron-bearing horizon, and being replaced in much of the district by the Clarksburg volcanic formation.	(1) Michigamme formation, bearing a short distance above its base an iron-bearing horizon.	(1) Great slate formation.
(2) Ishpeming formation, composed of the Goodrich quartzites in the eastern part of the district and of the Goodrich quartzite and the Bijiki schists in the western part of the district.	(2) Quartzite in eastern part of district.	
(Unconformity.)	(Unconformity.)	(Unconformity.)
Lower Marquette series.	*Lower Huronian.*	*Lower Menominee.*
(1) Negaunee iron formation, 1,000 to 1,500 feet.	(1) The Groveland formation, about 500 feet thick.	(1) Vulcan iron formation, containing slates.
(2) Siamo slate, in places including interstratified amygdaloids, 200 to 625 feet thick.	(2) Hemlock volcanic formation, 1,000 to 10,000 feet thick. In western part of district also occupies the place of (1) and (3).	
(3) Ajibik quartzite, 700 to 900 feet.		(2) Antoine dolomite.
(4) Wewe slate, 550 to 1,050 feet.	(3) Mansfield formation, 100 to 1,900 feet thick.	
(5) Kona dolomite, 550 to 1,375 feet.	(4) Randville dolomite, 500 to 1,500 feet thick.	
(6) Mesnard quartzite, 100 to 670 feet.	(5) Sturgeon quartzite, 100 to 1,000 feet thick.	(3) Sturgeon quartzite.
(Unconformity.)	(Unconformity.)	(Unconformity.)
Archean.	*Archean.*	*Archean.*

PLATE VI.

PLATE VI.

ORGANIC MARKINGS IN THE LAKE SUPERIOR IRON ORES. AFTER GRESLEY.

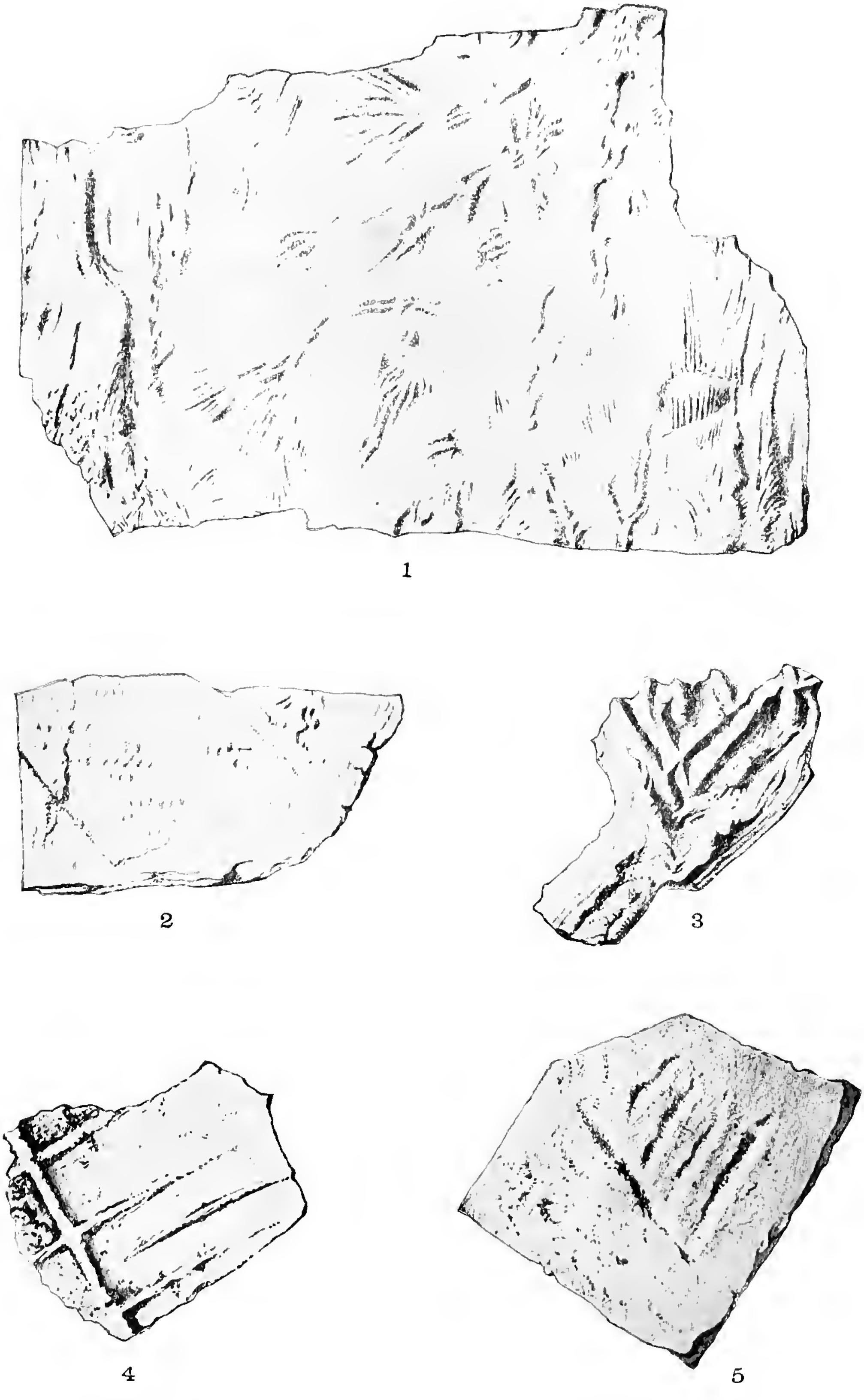
Fig. 1.—Probably remains of marine plants or corals (?). *Oldhamia* (?). On a thin layer of softish, fine-grained, sandy, purplish iron ore. Locality, Chapin mine, Iron Mountain, Mich. Magnified two diameters.

Fig. 2.—Shows roughly-parallel rows of small, shallow depressions; some plant (?), or possibly flattened tracks of some crawling animals, on the surface of a layer or band of red, earthy iron ore. Locality uncertain.

Fig. 3.—Perhaps casts of remains of plant stalks. On the surface of a fragment of purplish-red ore. Locality uncertain, but the same as that of fig. 2.

Fig. 4.—Perhaps filled-up sun cracks. Occurring as ridges on laminæ of a fragment of soft, blue iron ore. Locality unknown, but the same as that of figs. 2 and 3.

Fig. 5.—Perhaps the imprint of the cast or mold of a fragment of a marine plant. On the surface of softish laminæ of red hematite. Locality unknown.



ORGANIC MARKINGS IN THE LAKE SUPERIOR IRON ORES. AFTER GRESLEY.

PLATE VII.

PLATE VII.

ORGANIC MARKINGS IN THE LAKE SUPERIOR IRON ORES—AFTER GRESLEY.

Fig. 1.—Tracks of crawling animals on nearly flat surface of a slab of bluish-purple laminæ of sandy iron ore. Note the parallelism of these tracks. The grooves running diagonally across them may have been made by plants scraping over the bottom of the sea or lake. Locality, Chapin mine, Mich.

Fig. 2.—A few individual footprints of 1, enlarged four times.

Fig. 3.—Possibly plant remains, or animal tracks (?) apparently somewhat side squeezed. On a surface of a fragment of a band of fine-grained purplish-red iron ore. On the reverse or opposite side of this specimen (which is about three-fourths inch thick) are very uniform parallel striæ of fine grooves, very suggestive of flattened bark or ribbed plant structure. Locality, Chapin mine, Iron Mountain, Mich.

Fig. 4.—Probably track of some crawling animal. Upon a bedding plane of a bit of soft, sandy, purplish iron ore. Locality uncertain.

Fig. 5.[a]—About one-eighth of the surface of one side of a fragment of soft, bluish, fine, sandy iron ore, exhibiting side-squeezed (?) or distorted animal footprints (?), distorted rain spots (?), or shriveled plant remains (?). Locality uncertain.

Fig. 6.—Possibly a bit of a marine plant. On the surface of purplish laminæ of ore. Locality, Chapin mine (?), Iron Mountain, Mich.

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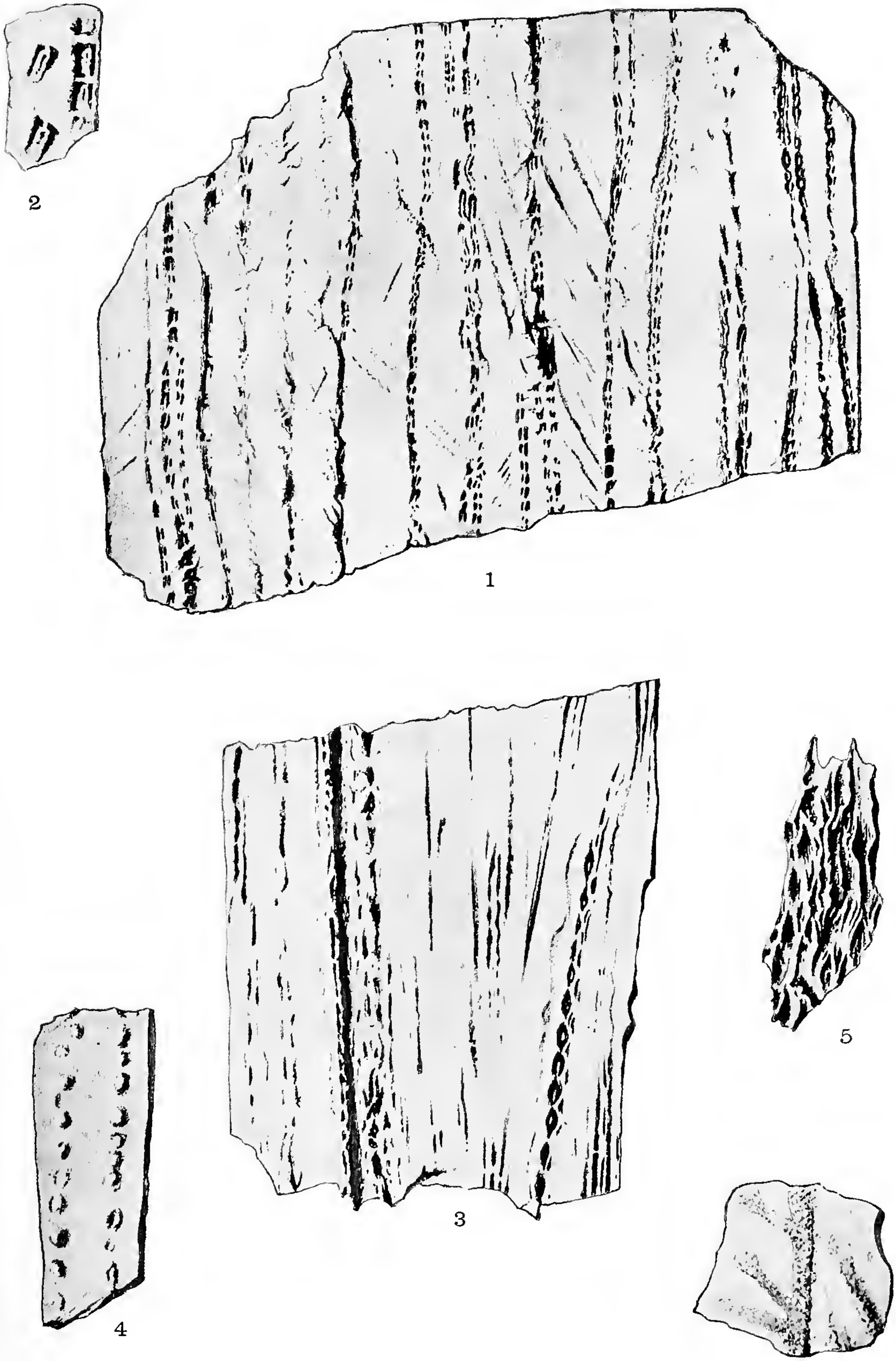
[a] Compare with this parts of figs. 1 and 2 of Pl. VI.



ORGANIC MARKINGS IN THE LAKE SUPERIOR IRON ORES. AFTER GRESLEY.

He states that in the Menominee district there appears to be no quartzite at the base of the Upper Huronian corresponding to the Ishpeming quartzite in the Marquette district, nor is there in the former district any great volcanic formation corresponding to the Clarksburg formation of the Marquette area. The Lower Huronian formations in the three districts are practically parallel, except for the volcanic deposits in the Crystal Falls district.

The distribution of the formations in the three districts indicates that the transgression of the Huronian sea was from the southeast toward the northwest; the Menominee area having been submerged before the central portion of the Crystal Falls district and the western part of the Marquette district. Practically the same view is expressed by Smyth in Chapter V of the report (pp. 140–145), as the result of magnetic observations west of Republic.

CLEMENTS, J. MORGAN, and SMYTH, HENRY LLOYD. The Crystal Falls iron-bearing district of Michigan, with a chapter on the Sturgeon River tongue, by Wm. Shirley Bayley, and an introduction by Charles Richard Van Hise: Mon. U. S. Geol. Survey, vol. 36. With 13 maps, 36 plates, and 24 figures in the text. 1899.

This report contains a more detailed account of the geology of the Crystal Falls district than that referred to in the immediately preceding paragraphs. So far as the Menominee district is concerned, it contains practically the same statements as the preceding article.

NEWETT, GEORGE A. Mines and Mineral Statistics of Michigan. 1899.

The annual statistical and mine report of the commissioner of mineral statistics for Michigan contains the usual statistics of the Menominee and other ore districts and items of interest concerning the mines.

1900.

VAN HISE, C. R., and BAYLEY, W. S. Description of Menominee district: Geologic Atlas U. S., folio 62, U. S. Geol. Survey. With geologic and topographic maps. 1900.

This is a preliminary report on the geology of the Menominee district. Its conclusions are practically the same as those embodied in the present monograph, of which it is actually a summary. The geological map is less complete than that accompanying the present volume, since several areas on the former were left without the color of any of the formations of the district because of lack of evidence as to the nature of the underlying rock.

The correlation of the various formations in the different iron-ore districts on the south side of Lake Superior is given as follows:

Descending succession in the Penokee, Marquette, Crystal Falls, and Menominee districts.

Penokee District.	Marquette District.	Crystal Falls District.	Menominee District.
Lake Superior sandstone.	Lake Superior sandstone.	Lake Superior sandstone.	Lake Superior sandstone.
(Unconformity.) Keweenaw series. (Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Upper Huronian.	*Upper Huronian.*	*Upper Huronian.*	*Upper Huronian.*
1. Upper slate member.	1. Michigamme formation (locally replaced by Clarksburg volcanic formation). One might divide the Michigamme sedimentary formation into three members: (*a*) Upper slate member.	1. Michigamme formation (consists of three members equivalent to those of the Marquette district, but 2 and 3 given below can be separated in mapping only in the southern part of the district).	1. Hanbury slate, bearing in lower portion calcareous slates, etc., containing siderite.
2. Iron-bearing member. (In east part of the district volcanic fragmentals are associated with 1 and 2.)	(*b*) Iron-bearing member.	2. Groveland iron-bearing formation in southern part of district.	2. Vulcan formation consisting in descending order of— (*a*) Curry iron-bearing member.
3. Quartz-slate member, having— (*a*) A thin belt of quartzite at its top; (*b*) A main belt of slate below; and (*c*) A thin belt of quartzite at its bottom at various localities.	(*c*) Lower slate member. 2. Ishpeming formation of quartzites and detrital ores, and the Bijiki schists in western part of district.	3. Mansfield slate.	(*b*) Brier slate. (*c*) Traders iron-bearing member.
(Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Lower Huronian.	*Lower Huronian.*	*Lower Huronian.*	*Lower Huronian.*
(Evidence of the former existence of an iron-bearing member above the cherty limestones is seen in the presence of ore and jaspilite grains in basal portion of quartz-slate member. 1. Cherty limestone member.	1. Negaunee iron-bearing formation.	1. Negaunee iron-bearing formation in northeastern part of district.	1. Negaunee iron-bearing formation.
	2. Siamo slates, containing interstratified amygdaloids. 3. Ajibik quartzite. 4. Wewe slate. 5. Kona dolomite.	2. Hemlock volcanic formation. 3. Randville dolomite.	2. Randville dolomite.
	6. Mesnard quartzite.	4. Sturgeon quartzite.	3. Sturgeon quartzite.
(Unconformity.)	(Unconformity.)	(Unconformity.)	(Unconformity.)
Archean.	*Archean.*	*Archean.*	*Archean.*

In the table it will be noted, by comparing the column given for the Crystal Falls district with that contained in Monograph XXXVI of the United States Geological Survey, that the succession has been somewhat changed. When the monograph was published, it was supposed that the Groveland iron formation and the Mansfield slate of the southern part of the district belong in the Lower

Huronian; but the work in the Menominee district shows beyond reasonable question that these formations, which have a comparatively small areal extent in the Crystal Falls district, really belong in the Upper Huronian.

Discrepancies in columns.—In the four districts the correlation of the series placed opposite one another and separated by the unconformities, and the correlation of the unconformities, may be regarded as practically certain; also the correlation of individual members within the parallel series has in many cases a very high degree of probability. However, an examination of the table shows various discrepancies. These discrepancies are due in a given case to one or more of the following causes:

During the time a series or formation was being deposited throughout all or a part of one district, all or a part of another district was still undergoing erosion. As the sea advanced overlap resulted. * * *

The inter-Huronian erosion cut to different depths in the different districts, as a consequence of which formations of the Lower Huronian may have been largely removed in one district and may have been comparatively untouched in another. * * *

A formation may have a greater vertical range in one district than in another; the conditions may have remained uniform in one district, and therefore deposits of the same kind continued, while the conditions changed in another district, and therefore more than one formation was deposited. * * * The order of formations in the Upper Huronian might at first thought be regarded as very different in the various districts. However, if one reduces the order of succession to a general statement, it is as follows: (1) An upper fragmental slate member; (2) an iron-bearing member, largely nondetrital; and (3) a lower fragmental member, which consists of quartzites, slates, and, at its base in some districts, large quantities of fragmental iron-formation material.

* * * * * * *

The attempt to correlate the various formations of the two Huronian series in the four different iron-bearing districts south of Lake Superior shows very significantly that the geologic history of pre-Cambrian time was extraordinarily complex. From Archean to Cambrian time, in the Marquette, Crystal Falls, and Menominee districts, the areas three times emerged from the sea and were three times overridden by the sea. In the Penokee district there was a fourth emergence and transgression of the sea. The epeirogenic or land-making movements were accompanied by orogenic movements, or mountain growths, of varying power, but some of them exceedingly intense. In Huronian time, in all the districts except the Menominee, there were important and long-continued periods of volcanism. The great events of Keweenawan time are only mentioned, since they do not particularly concern the Menominee district. The erosive forces at periods when the districts were land areas found rocks of very different characters. Here they were resistant; there easily denuded. As a consequence, when the sea encroached at the close of Archean, Lower Huronian, and Upper Huronian times, the country in detail was very irregular—was, in fact, bluffy, but not mountainous. Therefore certain areas were covered by the sea, while other immediately adjacent areas were above the water and were being actively eroded. As a consequence of all these complex conditions we have unconformity, overlap, changes in the characters of contemporaneous sediments along the strike and across the strike, disturbances in the successions due to volcanism, close folding and attendant metamorphism, and all of these phenomena in a region which is largely covered by glacial drift.

Van Hise, C. R. The iron-ore deposits of the Lake Superior region: Twenty-first Annual Rept. U. S. Geol. Survey, pt. 3, with maps and other illustrations. The Menominee district, pp. 388–400. 1901.

In this paper Van Hise gives a summary of the facts known concerning the geology of the various iron-ore producing districts in the Lake Superior region, and a brief discussion of the processes that resulted in the deposition of the ores.

The account of the Menominee district is, in the main, abstracted from the preliminary report on the district by Van Hise and Bayley (see p. 121). The development of the Menominee ores is said to combine the features that characterize the development of the ore deposits that occur in the Penokee-Gogebic and the Marquette districts. The occurrence of the ore bodies is declared to be in practically every case on the lower portions of slopes; that is, at the places where descending waters have been converged from a wide variety of sources. The time of the concentration must have been after the folding which produced the troughs in the district and after the period of erosion which removed the Hanbury slates that once covered the ore formations; that is, in the interval between Upper Huronian and Upper Cambrian times.

The map of the Menominee district accompanying the paper is a reproduction of that published in folio 62 of the Geologic Atlas of the United States.

CHAPTER III.

PHYSIOGRAPHY.

TOPOGRAPHY.

The Menominee district is but a small portion of a large area, which lies between Green Bay and Lake Superior and the margin of the valley of the Mississippi River, and which may be characterized physiographically as a southeasterly inclined peneplain. In that portion of the area discussed in the following pages the relief is strong, though in no sense mountainous. The highest elevation is in Hughitt Bluff, at Iron Mountain, the top of which is between 1,560 feet and 1,580 feet above sea level. The banks of the Menominee River, where this stream leaves the area, have an altitude of 800 feet. While this difference in height is only 760 or 780 feet the slopes of the elevations are comparatively steep. The heights of the hills are thus emphasized and the surface of the area appears to the eye much more rugged than it actually is (see map, Pl. VIII).

The Huronian trough, or the Menominee district proper, as has been explained, lies between the Menominee River on the south and an area of granite and schist knobs on the north. Its surface comprises two plains sloping gradually toward the southeast. The lower one, which has an elevation of about 1,000 feet in the center of the district, gradually rises to 1,200 feet in its extreme northwestern portion and descends to about 900 feet in its extreme southeast corner. It also inclines southward toward the Menominee River at the rate of about 25 feet to the mile. This plain forms the valleys between the residuals of the higher plain which constitute the hills.

The higher plain, like the lower one, slopes to the southeast. In the western portion of the area its surface is at an elevation of about 1,500 feet, while in the eastern portion, near the Sturgeon River, it recedes to 1,200 feet. Only a few remnants of the higher plain remain. They are arranged in two series, constituting two well-defined ranges of hills trending a little south of east, or in the direction of the prevailing strike of the Huronian rocks composing them. In nearly every instance the hills consist very largely, if not exclusively, of the hard, vertical, or nearly vertical, Randville dolomite, and of the even more resistant jaspilites of the Vulcan formation, and are topped by the horizontal beds of the Lake Superior sandstone. The intervening valleys between the hills are underlain mainly by the soft slates of the Hanbury formation, although along the northern border of the trough the valley floor may extend across a narrow belt of the Randville dolomite.

The plan of the topography thus corresponds very closely with the geological structure of the district. The ridges follow the strike of the more resistant rocks and end where these pitch beneath the overlying softer slates. The valleys occupy the synclines of slate between the anticlines of the harder rocks and open out toward the west to correspond with the widening out of westward-pitching synclines of the softer rocks. Glacial deposits have modified to some extent the perfection of the plan, but they have not affected the topography greatly, except in the northwest corner of the area, where high and irregularly shaped sand hills constitute all the elevations.

DRAINAGE.

The area is drained by two longitudinal streams, the Menominee River, where it borders the area on the south, and Pine Creek, and by two cross streams. The latter are the Menominee River, where it borders the area on the west, and the Sturgeon River near its eastern side.

The major streams traversing the district—the Menominee and the Sturgeon rivers—are both apparently antecedent. They both cross the hard rock beds transversely to their strike and flow through gorges over cataracts and rapids. The Menominee River shows its disregard of the geological structure by cutting indifferently through crystalline greenstones and soft sand and clay deposits. Along the southern side of the district its meanders wind in and out of the green schist area, always keeping near the boundary between the schists and the Hanbury slates. Where the stream enters and leaves the schist area there are falls, and within the area its channel is marked by many small cascades and rapids (see pp. 132–133).

The Sturgeon River enters the district near its northeast corner and flows across it for a distance of 6 miles. Where its channel traverses the quartzite bordering the north side of the trough is one of the most picturesque and wildest gorges in the Upper Peninsula of Michigan. This gorge is only a few hundred feet in length, but its walls, cut in snow-white quartzite, rise almost perpendicularly above the bed of the stream, confining the water to a narrow channel, through which it rushes with great rapidity over several little cascades.

The principal drainage of the district is through Pine Creek, which, though small in volume, extends nearly the entire length of the trough. It has been referred to above as a longitudinal stream; and, within the limits of the Menominee district, as defined in the preceding chapter, its course is longitudinal. Just beyond the boundary of the area, however, it crosses the quartzite belt in a narrow gorge, known as the "rock dam" (see pp. 189–192), where it is transverse.

The stream rises some distance north of the Menominee area and enters the district from the north. It flows south for a few miles after entering the district and then turns to the southeast, keeping very close to the base of the quartzite bluffs forming the northern side of the Huronian synclinorium. In its southeast course it follows a belt of dolomite lying south of the quartzite until within a few miles of its mouth. Here it crosses a slate valley to its center and then turns abruptly eastward and follows along the north side of a more southerly belt of dolomite to the Loretto mine, where it empties into the Sturgeon River. Through most of its course its bed is composed of sand and gravel, and nowhere within the confines of the district mapped does it reach the underlying rocks.

ORIGIN OF THE TOPOGRAPHY.

It appears quite evident that Pine Creek, with its present small volume of water, could not have carved the large valley in which it flows. It is also plain that the wide valley floors with the residuals of a higher plain rising above them could not have been the result of the action of the present Menominee River. The higher ridges are much nearer the channel of this river than they are to the channel of Pine Creek. Moreover, there is no distinct valley on both sides of the river which is at all commensurate in size with the magnitude of the river. The country to the south of the river has not been mapped, but the impression gained while traveling across it is to the effect that a distinct valley is lacking. This is in accord with the view that the Menominee is in its present position a new stream that has been turned from its old course by recent events.

The major features of the topography of the district not only antedate the Glacial epoch, but they were determined before Upper Cambrian time. Not only are the hills of the region capped by the horizontal Upper Cambrian sandstone, but remnants of this formation have been found in the cross gorges at Iron Mountain, Quinnesec, and Norway, and in the longitudinal valleys at several places. At Iron Hill a miniature sandstone mesa, with perpendicular sides 10 feet high, stands near the banks of the little stream near the quarter post between secs. 32 and 33, T. 40 N., R. 29 W. It is entirely isolated from the surrounding rocks and is plainly a remnant of a bed that once completely occupied the lowlands.

Although very resistant to weathering agencies, the sandstone has, nevertheless, been almost completely removed from the valleys, while it has escaped erosion mainly on the tops of the ridges. The topography which has resulted from the removal of this covering is therefore very similar to that which characterized the surface at the beginning of Upper Cambrian time. The present valleys correspond to the pre-Cambrian valleys and the present hills to elevations that existed on the pre-Cambrian[a] surface. The floors of the valleys may have been lowered somewhat since the sandstone disappeared, but since the bases of sandstone remnants are in several widely separated localities either at the present valley surfaces or only a few score feet above them, the differences in elevation between the pre-Cambrian valley floors and those of the present valleys can not be great.

The present topography of the district is thus mainly resurrected pre-Cambrian topography. It had its origin in the interval between Huronian and Upper Cambrian times, and was protected until very recently by the blanket of sand laid down upon it by the Upper Cambrian sea. If erosion was no more rapid in early Cambrian time than in later time, the interval between Huronian time and Upper Cambrian time must have been extremely long.

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[a] The term "pre-Cambrian" is here used to cover that portion of time antecedent to the time represented by the Lake Superior sandstone, which belongs in an Upper Cambrian horizon. Rocks of Lower and of Middle Cambrian age have not yet been identified in the Lake Superior region.

PRE-CAMBRIAN TOPOGRAPHY.

The pre-Cambrian topography, though in the main similar to that of the present, nevertheless differed from it in some minor respects. The hills of the earlier period were not so lofty as those now existing, but they were sharper and more rugged. Moreover, both hills and valleys were cut by deep and narrow gorges, which have been preserved to us by sandstone fillings. The Cuff mine, for example, is situated at the top of an ancient north-facing bluff, for the sandstone, which forms a thin covering over the surface at the shaft, is found again at considerable depths at the north ends of the mine levels. Prospect Bluff was narrower in these earlier times. Its north side sloped steeply and its apex was sharp. A deep gorge crossed Hughitt Bluff on the property of the Pewabic mine. North of the Quinnesec mine, well up on the slope of a high hill, was formerly a deep basin in which were accumulated bowlders of ore and hematite sand worn from shores carved in Huronian rocks. Finally, drill borings have shown that a deep and narrow channel crossed the plain east of the Norway mine.

The surface upon which the sandstone was laid down was then, apparently, rougher than that of the present time, although in their major features the topography of the pre-Cambrian land surface and that of the present land surface were similar. The presence of gorges and valleys in the pre-Cambrian land surface at places where they do not now exist may explain the occurrence of ore deposits in certain positions within the Menominee area where the present topographic conditions are not especially favorable to their development (see p. 401).

CHAPTER IV.

THE ARCHEAN SYSTEM.

The sediments composing the Menominee trough are bordered on the north for nearly their entire extent by a complex of granites, gneisses, hornblende-schists, and a few greenstone-schists that are cut by dikes of diabase and dikes and veins of granite. This has been designated the Northern Complex.

On the south, along the Menominee River, the trough is bordered by a series of dark-green or black basic schists and light-colored acid schists, designated hereafter as the Quinnesec schists. These are cut by large dikes of gabbro, diorite, and diabase; by smaller dikes of granite, quartz-porphyry, and felsite; and by veins of quartz. The porphyries and many of the granite dikes are apophyses of a large mass of granite which intrudes the schists and constitutes a boss whose surface occupies hundreds of square miles in Wisconsin. No portion of this boss falls within the limits of the Menominee district. Its northern boundary approaches within one-half or three-quarters of a mile of the Menominee River at the Big Quinnesec Falls, but only a few of its apophyses cross the river into Michigan. It is this granite which Brooks regarded as Huronian in age (see p. 61). It undoubtedly intrudes the Quinnesec schists and is younger than these; but that it is as young as Brooks supposed is doubtful, since none of its apophyses intrude the Lower Huronian sediments. It is to this complex of acid and basic schists, cut by dikes, that the name Quinnesec schists is applied. A second area of Quinnesec schists occurs in the central part of the west end of the trough. Only its east end comes within the limits of the map. It appears as a narrow wedge-shaped area widening toward the west. It is surrounded on the north, east, and west sides by the Menominee sediments. To the west it crosses the Menominee River into Wisconsin, where it has not yet been studied in detail. The rocks are greenstone-schists and ellipsoidal greenstones, cut here and there by basic dikes. The area bordering the Menominee River to the south of the trough is referred to in the following pages as the southern area of Quinnesec schists, and that within the west portion of the trough as the western area.

SECTION 1. QUINNESEC SCHISTS.

RELATIONS TO OVERLYING FORMATIONS.

In neither the southern nor the western areas have contacts of the Quinnesec schists with the sedimentary rocks of the Huronian series been seen. There is no positive proof that the green schists are older than the Huronian rocks. There can be little doubt, however, that the schists belong in the Archean. They have all the complex lithological and structural features that are recognized as characteristic of typical Archean greenstone-schists elsewhere. They are mainly volcanic or intrusive rocks which have been subjected to intense metamorphism and which, in consequence of this, have acquired a marked schistosity. No ordinary sediments have been discovered among them. Moreover, the schists are in every respect identical with similar schists in the Marquette district of Michigan that have been demonstrated to be unconformably beneath the Lower Huronian sediments[a] of that district, and they are also identical with greenstone-schists in the Vermilion district of Minnesota that possess similar relations to the oldest Huronian sediments of that district.

Exposures of the two series are found in closest proximity on the Menominee River near the Fourfoot Falls. The Chicago and Northwestern Railway bridge crossing the river at this place is built on ledges of the schist. Below the bridge is a long exposure of black slate belonging to the Hanbury formation of the Upper Menominee. The schists and the slates are separated by a distance of about 150 paces, and this interval is occupied by sand and glacial drift (see also p. 289).

THE SOUTHERN AREA.

DISTRIBUTION.

The southern area of Quinnesec schists borders the south side of the Menominee trough. Its northern boundary extends along the Menominee River from a point a short distance below the mouth of Pine Creek to the eastern limit of the area mapped. The line enters Michigan at the south town line of T. 40 N., R. 31 W., runs a little south of east to the

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[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 152–168.

Big Quinnesec Falls, where it crosses to the Wisconsin side and continues its course in a nearly straight line to the Little Quinnesec Falls. Here it recrosses the river into Michigan, where it remains. From the Little Quinnesec Falls it runs approximately parallel to the stream as far as the mouth of the Sturgeon River. At this point it leaves the river, runs nearly southeast to the southeast corner of T. 39 N., R. 28 W., and then a little south of east to the southeast corner of sec. 4, T. 38 N., R. 28 W., where it is lost beneath a covering of sand. The southern boundary of the schists has not been definitely determined. It is somewhere in Wisconsin, a considerable distance south of the Menominee River, which is practically the limit of the area discussed in this report.

TOPOGRAPHY.

The topography of the southern area underlain by Quinnesec schists is rough and broken, at least it is so over most of the valley of the Menominee River, where the area has been most carefully studied. In the bed of the river, where the channel is cut through the schists, are great ledges of rocks forming rapids and falls, and along its banks are often craggy precipices and shelving rock walls. Three noted falls exist within that portion of the district here described. These are the Big and the Little Quinnesec Falls and Sturgeon Falls (Pl. X, *A*), all of which are over the harder and more massive ledges of the schists or of the intrusives associated with them. The most famous rapids are the Horserace Rapids (Pl. XI, *A*), the head of which is situated a few hundred yards below the bridge of the Chicago, Milwaukee and St. Paul Railway. At this place the river dashes through a narrow rock-walled gorge, over a rough and rugged channel in a series of plunging falls and seething caldrons. The schists here have been greatly metamorphosed by the intrusion through them of enormous dikes of granite and porphyry. These harder portions produce the falls and the softer, less metamorphosed portions between the intrusions give rise to the caldrons. Although less than half a mile long, the Horserace is dreaded by the lumberman more than any other stretch in the river, since here are formed every year great jams of logs that are extremely expensive to break. In Pl. XI, *B*, is shown the rock-bound channel filled with logs. Between the various falls and rapids are comparatively long stretches of quiet water (Pl. X, *B*). The general character of the stream may be judged from the fact that the fall

A. VIEW FROM BRINK OF STURGEON FALLS, LOOKING DOWNSTREAM.

The barrier rock is a saussuritized gabbro, seen to the left. The rocks to the right, limiting the basin below the falls, are gabbros and schists derived from gabbros and diabases.

B. MENOMINEE RIVER ABOVE STURGEON FALLS.

One of the quiet basins in the Quinnesec schist area produced by the backwater above the falls.

of the river is about 260 feet in the 20 miles of its course between the point west of Iron Mountain, where it enters the southern area of schists, to the point where it crosses the east range line of T. 38 N., R. 29 W., near the southeast limit of the map. When it is realized that only about 14 miles of this course is in the schists, and that in this distance nearly all the fall is made, some idea may be gained as to the roughness of the stream. The fact that more than half of this fall is made at Sturgeon Falls and at the Big and Little Quinnesec Falls, affords abundant opportunity for the development of immense power at these localities when economic conditions for its utilization are more favorable than they are at present. At the Little Quinnesec Falls, where about 10,000 horsepower is available for use, there is now a paper mill which employs less than half of this power, and at the Big Quinnesec Falls is an air-compressor plant. The greater portion of the power of the stream in this area is, however, not used for any purpose.

Away from the river the country underlain by the schists is very rough, though lofty eminences and deep valleys are not noticeable. The topography is made up of many ridges and elongated hills having steep slopes covered with thin layers of soil, or precipitous sides of bare rock. On the tops of the hills bare flat ledges are met with, here and there covered with patches of soil an inch or so thick.

On the Michigan side of the river a thick mantle of sand and glacial drift lies upon the schists and obliterates their characteristic topography, but very close to the river bank, where recent erosion has removed the sand, and along the Wisconsin shore, for a few miles from the bank, the rugged nature of their surface is well shown.

COMPOSITION AND STRUCTURE OF THE ROCK SERIES.

The Quinnesec schists of the southern area consist mainly of schistose basic and acid igneous rocks and a few basic tuffs.[a] The former comprise

[a] Although tuffs are only rarely found in the area included in this study, they are by no means rare in the extension of the schist area south of the Menominee River. About midway between this river south of Norway and the "Soo" Railroad in Wisconsin, there are great hillocks and bare bluffs that are composed exclusively of coarse greenstone conglomerates like those so abundant in the northern Archean complex in the Marquette district, and interlaminated beds of fairly well-banded greenstone tuffs. The area has not been studied, but from the great magnitude of these deposits at the locality referred to, it appears probable that volcanic fragmentals play a much greater part in the constitution of the Quinnesec-schist complex than would be inferred from studies confined to that portion of the schist area in the neighborhood of the Menominee River.

chlorite-schists, amphibolites, schistose diabases, schistose diorites, and schistose gabbros. With these are large, almost massive layers of gabbro and diorite that are supposed to be interbedded sills or flows, and dikes of gabbro, diorite, diabase, and granite. The basic schists constitute by far the greater part of the schists of the area, but in the vicinity of the Horse-race Rapids and of the the Big Quinnesec Falls, the basic rocks are associated with large quantities of acid ones. The acid rocks are in some places nearly massive granites, in other places they are gneisses, and in still other places they are finely banded and schistose rocks like the Saxon granulites. The last-named rocks occur in bands of different widths, nearly always striking conformably with the strike of the foliation of the basic schists with which they are associated. The schistosity of the bands is parallel to the schistosity of the adjoining schists, irrespective of the direction of the band itself. Although rather irregular in their distribution, the different schists may be observed to occur in more or less well-defined belts extending for comparatively short distances in approximately straight lines. These belts strike a little north of west at the Sturgeon Falls, a little south of west at the Little Quinnesec Falls, and about northwest at the Big Quinnesec Falls. Their schistosity strikes approximately parallel to the trend of the belts, but not always exactly so. The dip varies slightly in different ledges, but is never far from perpendicular. On the northern and eastern peripheries of the granite boss in Wisconsin the foliation of the schists is very well developed. Here the schistosity is nearly parallel to the contacts with the granite, changing with the trend of this boundary and following in a general way its sinuosities. This fact suggests that the schistosity of these rocks is due to pressure and that its direction is determined by the directions of the lines along which the stresses acted, i. e., along lines at right angles to the boundary of the granite boss.

LITHOLOGY.

There is very little to add to the account of the lithological features of the Quinnesec schists given by Williams[a] in his bulletin on the Marquette and Menominee greenstone-schists. In this report the author presents excellent descriptions of all the various forms of schists met with along the

[a] Williams, George Huntington, The greenstone schist areas of the Menominee and Marquette regions of Michigan, with an introduction by Roland Duer Irving: Bull. U. S. Geol. Survey No. 62. 1890.

Menominee River and describes in detail the character of the intrusion traversing them. There seems to be no need of duplicating these descriptions in the present volume. In the following pages a brief summary of Williams's discussion will, however, be given, and a few additions will be made to his descriptions in order that the great similarity between the Archean in this and other districts may be clearly perceived, and that the great contrast always existing between the Archean and the Huronian rocks of the Lake Superior region may again be emphasized.

For purposes of description the Quinnesec schists may be divided into greenstone-schists, chlorite-schists, amphibolites, gneisses, and sericite-schists. The massive rocks associated with them may be classed as greenstones and granite. The greenstones include gabbros, diorites, diabases and basalts; the granites include granite and granite-porphyry. Because of the close genetic relationship existing between the greenstones and the greenstone-schists on the one hand and between the granites and the acid schists on the other hand, the former will be described together, as will also be the latter.

GREENSTONE-SCHISTS AND ASSOCIATED GREENSTONES.

The term greenstone-schists is applied to those basic schists which show clearly by their composition and structure that they were derived from basic igneous rocks. They grade on the one side into massive gabbros, diorites, diabases, basalts, and basic tuffs, and on the other side into the chlorite-schists and amphibolites. Specifically they might be termed gabbro-gneisses, diorite-gneisses, etc., but their present mineralogical and chemical composition is so different from that of the corresponding massive rocks that it is thought best to refer to them under the generic term greenstone-schists. The term is a convenient one, partly because it is so comprehensive, and partly because some such term is absolutely necessary to the prosecution of field work in regions of ancient schist complexes. The term comprehends all dark-colored schistose feldspathic rocks derived from massive igneous rocks and their tuffs. In the Menominee district the greenstone-schists comprise schistose gabbros, diabases, diorites, basalts, diabase tuffs, and basalt tuffs. They vary in color from greenish gray to greenish black, in texture from coarse grained to aphanitic, and in structure from almost massive to perfectly schistose. The more massive phases are sometimes poikilitic. The finer-grained rocks are usually more schistose than the coarse-grained ones, though not always so. The most perfect schistosity, amounting almost to perfect fibrosity, is met with only in the aphanitic phases. The rock of nearly every exposure, or at least of every group of exposures, possesses a characteristic appearance which differs from that of corresponding rocks of other ledges, so that a detailed description of the macroscopic features of all the different greenstone-schists of the district would be nothing more or less than a description of individual specimens. The same statement applies to the description of the massive greenstones. A detailed description of this kind does not seem necessary in this place, especially since Williams has so well described nearly all the several phases of the greenstones and their schists in the bulletin referred to above. Only the principal and predominating types of the schists will be described in the following pages, the unusual types being referred to only in the descriptions of interesting localities.

COARSE-GRAINED VARIETIES.

The material of the coarse-grained schists, which may represent dikes, or flows of coarse lavas in a series of finer-grained lavas, differs very little from the material of the coarse-grained, massive greenstone dikes cutting through the schist series. Most of these rocks are light-gray diabasic aggregates of a white feldspathic mineral and a greenish-gray hornblendic one, with occasionally here and there an irregular grain of magnetite or ilmenite. Others are darker in color and greener in tinge. In these the hornblendic mineral predominates and the feldspar is often epidotized. In most specimens the feldspar is in diabasic forms, in others it is in the irregular grains characteristic of gabbro, and in still others it is in rounded phenocrysts. Near slickensided surfaces the characteristic gabbro or diabasic structure disappears, and the rock becomes a typical chlorite-schist or amphibole-schist.

Gabbros and their derived schists.—The barrier rock of Sturgeon Falls (see Pl. X, *A*) is an excellent example of one of the most massive phases of the coarse-grained rocks. It is not known whether it is a dike or an immense flow. It exhibits many lithological features of the massive dikes, and at the same time it possesses phases that are identical in character with those of many of the coarser-grained schists.[a] The most massive phase of the rock is light gray in color. On a fresh fracture it is mottled in white

[a] Cf. Williams, op. cit., p. 68.

and dark-greenish gray, the consequence of the presence of a greenish-white feldspar and a brownish, lustrous amphiboloid. The texture is moderately fine, but is subject to sudden local variations which develop comparatively coarse-grained patches in the main mass. Under the microscope the rock is discovered to be a gabbro in which there still remain remnants of colorless diallage, but in which the plagioclase has been almost wholly altered to a gray and opaque saussurite. Most of the original diallage has been changed to a compact brown amphibole, which, together with calcite, albite, chlorite, and quartz, are the principal secondary products present. All specimens exhibit the action of dynamic forces that have more or less profoundly affected the different constituents.

The rock seems in places to have been crushed and a mosaic of the component minerals to have been formed. Hornblende, generally colorless, is unusually abundant. Colorless chlorite and zoisite are also developed, and all are mixed indiscriminately. In one part of the section a vein is seen to traverse the rock. This is filled with limpid quartz in long, wedge-shaped areas, which extend from one side of the small fissure to the other. This quartz is traversed by long, colorless fibers of the greatest delicacy, and it also contains a good deal of the colorless chlorite, both in solid masses and in those peculiar vermicular groups to which Volger has given the name helminth. These curious groups, which resemble piles of little coins, are sometimes straight, sometimes curved. They are so minute as to be visible only with a high magnifying power.[a]

In the more schistose phases of the rock the constituent minerals, while the same as those in its less schistose phases, have suffered much greater changes.

The feldspar is remarkably fresh and its twinning lamellæ are quite distinct, but it is everywhere crushed, broken, and faulted. The crystals are often plainly seen to be separated into a number of fragments which are removed a considerable distance from one another. Frequently a fine-grained mosaic has been formed by the crushing of the larger feldspar crystals. In other cases * * * the feldspar is not so much broken, but it is altered around its edge to an opaque gray saussuritic mass, while its interior is hardly changed. * * * The diallage is more altered than in the rocks last described. * * * The crystals are very much bent and twisted and frequently so changed to the light-colored chlorite that only a few minute remnants of the brightly polarizing mineral remain in this nearly isotropic base. * * * Fibrous hornblende now becomes more abundant than the compact, and leucoxene patches are seen at intervals.[b]

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[a] Williams, op. cit., p. 71.

[b] Ibid., p. 72.

The compact massive or slightly schistose rock passes gradually into softer, more schistose, ones, that have lost all traces of their original structure and of their original mineral composition as well. The schists are now composed of broken pieces of feldspar which has been almost completely changed—

to an aggregate of calcite and minute brightly polarizing needles or plates of a colorless micaceous mineral (probably sericite) along with occasional areas of secondary quartz. What was once the pyroxene or hornblende is now a colorless or extremely pale-green, scaly mineral, which an examination shows to be chlorite.[a]

The most schistose phases of the rock are examples of fissile, silky, chloritic schists, composed of a fine-grained schistose aggregate of colorless chlorite, quartz, and calcite.

These rocks are schists, indeed, of the most characteristic type, but in the light of their field relations, and still more from the evidence which a microscopical study of the whole series has afforded, it is evident that they represent the most altered form of the massive gabbro, between two areas of which they are included.[b]

The chemical changes undergone by the gabbro in its transition to a schist are shown by the following three analyses made for Dr. Williams by Dr. R. B. Riggs:

Analyses of gabbro and schist from Sturgeon Falls.

	I.	II.	III.
SiO_2	51.46	38.05	45.70
Al_2O_3	14.35	24.73	16.53
Fe_2O_3	3.90	5.65	4.63
FeO	5.28	6.08	3.89
CaO	9.08	1.25	4.28
MgO	9.54	11.58	9.57
Na_2O	2.92	2.54	.55
K_2O	.24	1.94	3.82
H_2O	3.30	7.53	4.70
CO_2	.20	.93	5.95
Total	100.27	100.28	99.62

Rock powder dried at 105° C.

I. Freshest gabbro from barrier rock of Sturgeon Falls,

II. Schistose gabbro from south side of I.

III. Silvery chlorite-schist from band between two bands of saussuritized gabbro.

[a] Williams, op. cit., p. 73.

[b] Ibid., p. 75.

The most marked variations noted in the composition of the three rocks is with reference to the lime, alumina, soda, potash, and carbon dioxide. Williams explains the fact that the intermediate rock (II) differs more from the original type (I) than does the most schistose phase (III) by supposing that the processes of alteration have been different in the two altered phases. In the first case the main product of the alteration has been chlorite; in the second case it is sericite and calcite. It is difficult to conceive a process which, acting upon two portions of the same rock close together, will cause chloritization in one part and sericitization in the other. The production of sericite in a rock of the composition of a gabbro necessitates the addition of potash and alumina from some extraneous source, through the transporting agency of solutions. It is very difficult to understand how such solutions might be confined to a certain definite band in an altering basic rock and be practically excluded from other portions of the same rock. It is more probable that the three rocks whose analyses are given above originally possessed different compositions, and that this accounts for their differences in composition at present.

Diabases and their derived schists.—The coarse diabases and their derived schists are in all essential respects, except structure, like the gabbro and the gabbro-schists.

Diorites and their derived schists.—The diorites and the schists derived from them are slightly different from the gabbros and their associated schists, but the processes which changed the massive rocks into schistose phases were practically the same in both cases. The rock forming the high bluff skirting the east side of the river below the Little Quinnesec Falls is the best example of the massive diorite met with in the district. It is described by Williams as being in all probability a great dike. Though for the most part quite massive, the rock presents frequent and instructive evidence of the effect of great pressure upon it.

It is seamed and gashed, broken and torn, and contains schistose bands of varying width. Since the continuity of these bands with the massive rock is established, their study is calculated to throw light on the subject of dynamical metamorphism.

Major Brooks designated the rock which composes this ridge as a "massive gabbro," and correlated it with the above-described saussurite-gabbro of Sturgeon Falls. My studies have, however, failed to disclose in this rock any trace of pyroxene. In addition to its feldspathic constituent, which is generally altered to saussurite, it contains in abundance that peculiar pale-green and more or less fibrous variety of hornblende which is quite universally conceded to be of secondary origin. What the primary form of all this green hornblende was, it is now impossible to ascertain with certainty. It is of a kind well known to originate from the alteration of pyroxene. The rock as a whole also bears decidedly the character of a diabase or pyroxene rock; and yet, not a trace of pyroxene has been discovered in any of the Menominee River greenstones, if we except the light-colored diallage of the Sturgeon Falls gabbro. Whenever the pale-green hornblende can be traced back to an original form, it is seen to be derived from a compact brown or basaltic hornblende.

* * * * * * *

It is, of course, impossible to prove that some of the secondary fibrous hornblende has not been derived from pyroxene. Indeed, it seems very probable that both augite and compact brown hornblende may have existed side by side as original constituents of the rock, and that both finally succumbed to the same process of alteration, although the hornblende resisted this much longer than the augite. * * * Inasmuch, however, as the rocks here under discussion afford no trace of pyroxene, it hardly seems justifiable to call them anything but diorite.[a]

Some of the phases of the rock are porphyritic. These contain large crystals of saussuritized feldspar in a matrix composed wholly of hornblende in compact, brown and green, or colorless grains, and in light-green fibers, in which are embedded small laths of plagioclase. The hornblende by alteration passes into chlorite and tremolite.

The schists derived from the diorite are largely chlorite-schists. They present no peculiar features distinguishing them from the schists derived from the gabbro, except in those phases where the structure of the original rock is still retained. At one place toward the west end of the diorite ridge a well-marked band of schist traverses the massive rock. The latter is—

composed of stout rectangular feldspars, with a somewhat rounded outline, and internally changed to saussurite, though their periphery is mostly clear. Between these are the remains of former hornblende (possibly pyroxene) individuals now represented only by amphibole fibers and chlorite. Beautiful skeleton forms of leucoxene, composed of three sets of parallel bands reproducing the rhombohedral parting of the original ilmenite, are abundant.[b]

The rock of the schist band is much more altered. Its feldspar is mostly changed to calcite, and the hornblende to chlorite. The original structure has wholly disappeared, and there is now a fine mosaic of quartz and secondary albite between the calcite and chlorite masses. The same skeleton forms of leucoxene remain, however, and "there is no doubt

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[a] Williams, op. cit., pp. 77–78.
[b] Ibid., p. 83.

that the two specimens represent the same rock in different stages of alteration, the more changed form having become decidedly schistose."[a]

FINE-GRAINED VARIETIES.

The finer-grained greenstones and greenstone-schists were originally diabases, basalts, and basic tuffs. In composition they are similar to the coarser-grained varieties described. Their structure is less well defined, and in some cases the original rock appears to have been essentially a glass. One of the best preserved of the fine-grained rocks is that on the Michigan side of the Little Quinnesec Falls. It is a massive, dark-green rock which, according to Williams—

> was originally a diabase, although its present constituents are for the most part secondary. The shapes of the original minerals are indistinctly outlined, and so the structure of the rock is preserved. There is now present a pale-green hornblende, probably secondary to pyroxene, although no traces of this mineral are preserved; epidote, chlorite, saussurite, and leucoxene in zones around the titanic iron. The feldspar has rarely changed to the opaque, gray saussurite, but is replaced for the most part by a mass of sharply defined epidote crystals. Where the feldspar and hornblende have jointly contributed to the formation of secondary products, we have the chlorite-epidote aggregate as a result. A little secondary quartz is also observable.[b]

These massive or almost massive rocks, as has been said, grade in many places into schists. Where they do not actually pass into schistose phases they are often associated with basic schists in which traces of the original structure of eruptives can be detected or which can be traced into rocks exhibiting this structure. In other cases, as stated by Wadsworth[c] in connection with the discussion of the origin of these rocks at the Little and the Big Quinnesec Falls, the basic schists may have been derived from volcanic tuffs or, as Wadsworth calls them, porodites. The predominant rock on the Michigan side of the lower falls, for instance, is plainly conglomeratic. It is either an old eruptive ash or an agglomerate. "Of the fragmental and conglomeratic nature of the rock," Wadsworth declares, "no one can possibly doubt after studying it on the Michigan side, below the falls, and then tracing it back into the finer grained and more compact part near the bridge."

[a] Williams, op. cit., p. 83.

[b] Ibid., p. 94.

[c] Wadsworth, M. E., Report of State Board of Geological Survey for 1891 and 1892, Lansing, 1890, p. 125.

Origin of the schistosity.—The least-altered phases of the fine-grained greenstones are characterized by a rhomboidal parting. As the rocks depart more and more from their original character the rhombs produced by the parting become more and more elongated until finally their sides are approximately parallel and a well-developed schistosity results. At the same time the original components of the rock mass undergo change. In many of the less-altered schists that have been derived from massive eruptives the structure of the originals can still be recognized, though their mineral composition can only be surmised, since they consist of secondary products exclusively.

Basic lavas and their derived schists.—In the field, dark- and light-colored schists are readily distinguished, and both are closely associated with nearly massive phases. On the east side of the basin, below the Little Quinnesec Falls, the dark schists are so intimately associated with massive greenstones that there can be little doubt as to the original identity of the two. In the hand specimen the least schistose rock is a compact, aphanitic mass of a dark-green color.

Under the microscope the original diabasic nature of the rock is at once apparent, although the extensive mineralogical changes which have gone on have greatly obscured its former structure. The components now present are almost wholly secondary. These are hornblende, chlorite containing epidote, quartz, and leucoxene. Ilmenite and occasional traces of feldspar are the only original constituents which remain. Still, the disposition of the secondary minerals is such as to outline a diabasic or ophitic structure often with great distinctness. The feldspar is rarely well preserved; but a narrow zone of the unaltered substance of this mineral often outlines a stoutly lath-shaped crystal, even when its interior is wholly changed to an aggregate of quartz, chlorite, and epidote. The hornblende has a curious appearance. Its crystals are brownish and nonpleochroic with a somewhat granulated surface, so that it externally resembles diallage. Its cleavage and optical properties prove it to be undoubtedly hornblende, although this superficial likeness to diallage is so strong as to almost compel the conviction that it has originated by paramorphism from a pyroxene. This brown hornblende is seen with a high power to be gradually changing to a green variety, in which a pleochroism for the first time becomes apparent. This also frequently passes over into a fibrous hornblende. The chlorite-epidote aggregate in these rocks is very finely developed. The chlorite is of an emerald-green color and distinctly pleochroic. It appears between crossed nicols as isotropic or polarizes with a maroon tint. The epidote is in sharp, light-yellow crystals, with the characteristic shape and optical properties of this species. * * * This chlorite-epidote aggregate covers considerable areas and occupies the place of both the feldspathic and the pyroxenic constituents. In addition to the minerals already named, ilmenite with its leucoxene border, pyrite, and secondary quartz are quite abundant in these rocks.[a]

Through this rock passes a schistose band so intimately related to the massive rock in both sides of it that there can not be the least doubt as to the continuity of the two. The hand specimen taken from the band is decidedly schistose.

Under the microscope it shows the effects of mechanical crushing and attendant mineralogical changes with great distinctness. The whole rock, with the exception of certain remains of the larger feldspar crystals, has been reduced to a fine-grained mass, showing an aggregate polarization. Light-green chlorite has been largely developed and has completely replaced all the bisilicate elements. The parallel arrangement of the scales of this mineral is what produces the schistose structure.[b]

The chlorite together with clear grains of quartz and probably of unstriated feldspar are embedded in a quartz-albite mosaic. Calcite is also abundant as little nests in the mosaic, and rutile either in stout yellow grains, or in minute sharp crystals traverse it in long sinuous lines. This rutile represents the ilmenite of the original rock.

The mechanical action which produced this schistose band has therefore resulted in the crushing of the rock, and the almost total disappearance of all of the original components. The comparatively slight change in the chemical composition of the rock as a whole may be seen from the two following analyses * * * made by Mr. R. B. Riggs:

Analyses of greenstone from Little Quinnesec Falls.

	I.	II.		I.	II.
SiO_2	43.80	44.49	Na_2O	1.96	2.59
Al_2O_3	16.08	16.37	K_2O	0.34	0.56
Fe_2O_3	9.47	5.07	H_2O	3.99	4.99
FeO	10.50	5.50	CO_2	0.08	5.38
CaO	7.81	7.94	Total	100.57	100.39
MgO	6.54	7.50			

TiO_2 not determined. Powder dried at 105° C.

I. Dark, massive greenstone, Lower [Little] Quinnesec Falls.

II. Dark, schistose greenstone, forming a band in the last.

[a] Williams, op. cit., p. 90.

[b] Ibid., p. 90.

The changes here are at once seen to be due (1) to the total removal of the iron ores (loss of iron); (2) to the production of carbonates (gain of CO_2, carbonatization); and (3) to the increase in the amount of chlorite (increase of H_2O, hydration).[a]

These darker schists pass into lighter ones that are more typical chlorite-schists, composed of extremely pale chlorite and quartz grains, with a little calcite and occasional sericite shreds, and numerous minute sharp crystals of rutile. Whether these lighter schists are actually phases of the darker ones, or whether the two are schistose phases of rocks that were originally different, can not now be told, since the true nature of the contact between them has been obliterated by the changes through which the rocks on both sides of it have passed. Even if the latter be the case the two originals were not very different, both in all probability being basic lavas or tuff beds.

Basic tuffs and their derived schists.—The schists derived from tuffs generally exhibit their origin in their structure when this has not been completely destroyed. Usually, however, the tuffaceous structure disappears so rapidly with the assumption of schistosity that nothing remains to distinguish the schists derived from tuffs from those derived from fine-grained eruptives.

In a few instances sections made from the schists at the Little Quinnesec Falls possess characteristics that point to a tuffaceous origin. In natural light these sections show irregular granular areas and black dots in a colorless, transparent, almost amorphous matrix. Between crossed nicols plagioclase, saussurite, kaolin, calcite, colorless or light-green chlorite, and bleached hornblende are noticeable. The plagioclase is largely altered into chlorite, saussurite, and kaolin. The greater portion of the mineral is often fresh enough to exhibit clearly its twinning striations, though not fresh enough to yield accurate measurements of extinction angles. This feldspar occurs in lath-shaped crystals, in rounded and irregular-shaped grains, in sharp-edged fragments, and in some instances it appears as though it were a secondary deposit filling triangular spaces between the other components. Some of the crystals are fairly well formed, others are broken, and still others are castellated at their ends. A large number of skeleton crystals are also noticed scattered through the matrix.

[a] Williams, op. cit., p. 91.

Only a few indications of the original structures can be detected. In a few small areas of some of the sections the structure appears to have been ophitic, the plagioclase laths occurring as radial groups in a matrix of chlorite, calcite, and bleached amphibole. In most of the sections, however, no traces of diabasic structure can be detected. The rocks, though much decomposed, look as though they were composed of crystals, fragments, and small, almost dust-like grains of feldspar in a groundmass that yielded on decomposition new plagioclase, light-green amphibole, chlorite, and calcite. Most of the fragments are certainly portions of crystals that were crushed when the rock was made schistose, but there are many others which do not seem to be due to mashing. Some of these have concave outlines, like the outlines of splinters of minerals often found in volcanic dust. The structure thus appears to resemble more closely that of tuffs than that of lavas.

CHLORITE-SCHISTS.

The chlorite-schists differ from the very schistose greenstones mainly in the fact that they contain no original plagioclase nor any saussurite derived from this. They are finely schistose, sometimes fissile, dark-green or light-gray rocks containing abundant quartz The darker varieties are often so dark and so very fine grained that they look very much like greenish-black slates. The lighter-colored varieties resemble very soft, fine-grained sericite-schists or talcose schists.

Under the microscope the dark-green chlorite-schists are seen to be aggregates of green chlorite, calcite, and an occasional flake of a sericitic mineral, in a mosaic of quartz and secondary albite.

In the light-colored schists the sericitic mineral and calcite are more prominent than in the darker phases. At the same time the chlorite has been replaced by an almost colorless variety.

An analysis of a specimen of one of the lightest colored of these rocks, taken from "the western corner of the little cove just below the Lower [Little] Quinnesec Falls,"[a] resulted as follows:

Analysis of schist from Little Quinnesec Falls.

[Analyst, R. B. Riggs.]

SiO_2	46.21
Al_2O_3	18.38
Fe_2O_3	3.30
FeO	3.90
CaO	6.28
MgO	7.03
Na_2O	2.14
K_2O	.35
H_2O	3.82
CO_2	8.32
Total	99.73

TiO_2 not determined.

The small proportion of K_2O present in the rock would seem to indicate that the sericitic mineral is paragonite rather than sericite.

Between the dark and the light varieties of the schists all gradations are met with, the color depending upon the relative proportions of the dark chlorite and the colorless sericitic mineral developed.

Many of the chlorite-schists of all kinds occur as definite bands in the schist series. They are not so related to the massive rocks as to present undoubted evidence that they are derived from these. In composition and structure, however, they are identical with the most schistose phases of the greenstone-schists described in preceding pages (pp. 136–139) as the end products of the alteration of gabbros, diorites, diabases, and their tuffs, so that little doubt can be felt as to their origin from similar rocks.

AMPHIBOLITES.

The amphibolites are limited in their distribution to the neighborhood of the great granite mass in Wisconsin. They nearly always occur near the contact of the granite with the greenstone-schists, though they are occasionally met with as narrow selvages along the side of granite or granite-porphyry dikes where these cut through the green schists.

The only careful examination of any part of the contact between the

[a] Williams, op. cit., p. 89.

granite and the surrounding greenstones was made in 1894 by A. T. Lincoln. Lincoln followed this contact about three-quarters of a mile in secs. 15 and 16, T. 38 N., R. 20 E., Wisconsin, a short distance southwest of the Little Quinnesec Falls. In an unpublished thesis[a] he states that "near the granite the greenstone becomes quite schistose, and in some places becomes a typical hornblende-schist. Fragments of the greenstone were broken off and included in the granite mass at the time of its intrusion. In some parts the greenstone is very intricately ramified by apophyses of granite."

The hornblende-schists are described as fine-grained, lustrous, black rocks, traversed by small veins of feldspar, as well as by cracks ramifying in various directions. They all contain more or less altered plagioclase in considerable quantities. Some are porphyritic, others are devoid of phenocrysts.

The porphyritic schists, when examined in thin section, are found—

to consist chiefly of actinolite crystals so arranged as to give the rock a decided schistose structure. Distributed throughout the hornblende are phenocrysts of much-altered feldspar. These have quite the appearance of amygdules. They have altered almost completely to zoisite, with which is found also some calcite. * * * Sphene is quite abundant, some of which still retains small cores of ilmenite.

The nonporphyritic schists differ from the porphyritic ones merely in the absence of the phenocrysts. They are aggregates of hornblende and comparatively fresh plagioclase.

Since all of these schists contain large quantities of plagioclase they are more properly designated amphibolites than hornblende-schists. The latter are characterized by the possession of much quartz and but little feldspar. Typical hornblende-schists have not yet been recognized among the Quinnesec schists, though they are found in fair abundance in the gneiss-schist complex north of the Menominee trough.

From the nature of the amphibolites and their intimate association with the ordinary types of the greenstone-schists, it may fairly be concluded that they were derived from the same kinds of basic igneous rocks as were the greenstone-schists and the chlorite-schists. Their exclusive occurrence

[a] Lincoln, A. T., On the greenstone area in the vicinity of the Lower Quinnesec Falls, Wisconsin side; a thesis submitted for the degree of B. S. in the group course in mineralogy, University of Wisconsin, 1894. (Not published.)

near granite contacts would indicate that they owe their peculiar character to their proximity to the intrusive. In other words, they are greenstones that have been subjected not only to dynamic metamorphism, but to contact alteration as well.

Types of rocks intermediate in character between the amphibolites and the greenstone-schists are found in profusion along the banks of the Menominee River at the rapids known as the Horserace. Here the basic schists are intruded by acid rocks, to which fact their peculiar features may be ascribed (see pp. 158–159).

ORIGIN OF THE BASIC SCHISTS.

From the field and laboratory study of the basic schists, one must conclude with Williams that they are squeezed igneous rocks, and their tuffs, which, on account of the squeezing to which they have been subjected, have lost in many instances all traces of their original structure and nearly all of their original mineral components. From the nature of the products that have arisen from the alteration of these components we are led to believe that the original rocks were basic. In a few cases the original composition and the original structure of the schists can be reconstructed from the evidences still remaining, and in these cases it may be safely asserted that the original rocks were gabbros, diorites, diabases, and perhaps basalts among the crystalline varieties and diabase tuff among the fragmental varieties. Many of the schists that are without a distinct igneous structure are so closely associated with basic rocks which are almost massive, and are connected with these by such intimate gradational phases, that no doubt can be felt as to their origin. These schists are unquestionably squeezed gabbros, diorites, diabases, and other basic rocks. They are identical in every respect with many of the schists whose field relations do not directly connect them with massive eruptives, and thus lend force to the view that these latter schists are likewise squeezed igneous rocks.

The conditions under which the igneous rocks consolidated are not plain in all cases. Some of the more massive greenstones were certainly originally dikes. Many of the others and most of the schists were probably lavas or sheets, or tuffs. Dr. Williams thinks that there is considerable evidence to show that the Menominee greenstones solidified at the surface under subaerial or subaqueous conditions.

In the Menominee Valley this evidence consists (1) of the fine texture of the rocks; and (2) of the alternation of bands of different types, which probably in their original position represented successive flows. Fineness of grain is universal in the Menominee greenstones, and we may be certain that it was a primary feature in spite of the extensive alteration of these rocks. It is especially noticeable in the case of the gabbro, which is almost always a coarse-grained rock when it has solidified at any depth. The succession of massive beds, like the pale gabbros and the dark diabases seen at Lower [Little] Quinnesec Falls, are difficult to account for except by supposing that they were once horizontal sheets which flowed one over another, and which were subsequently elevated into their present nearly vertical position. Traces of tuff material are not as distinct here as in the Marquette region, although indications of their existence are by no means wanting. We might reasonably expect that any original scoriaceous or amygdaloidal structure would have disappeared in the course of the profound chemical changes through which these greenstones have passed.[a]

Since the above was written undoubted tuffs have been discovered in the Menominee district in the vicinity of the Little and the Big Quinnesec Falls, and in Wisconsin about a mile southwest of the lower falls, and over a large area in the latter State several miles south of the river, opposite the city of Norway. This discovery adds additional strength to Williams's view, which must therefore be accepted as probably true.

ACID INTRUSIVES AND THEIR DERIVED SCHISTS.

The acid rocks associated with the basic schists in Michigan are limited principally to the neighborhood of the Horserace Rapids and the Big Quinnesec Falls. They include gneissoid granites, porphyritic gneisses or porphyroids, felsite-schists, sericite-schists, and probably paragonite-schists. The sericite-schists and paragonite-schists are found also associated with the greenstone-schists in other portions of the southern area.

The gneisses, porphyroids, and felsite-schists are so similar in composition to the Wisconsin granite, which is only about three-quarters of a mile from the Menominee River at the Little Quinnesec Falls, that they may be regarded as its apophyses. Some of the larger of the gneiss bands may be traced practically continuously into the granite mass. The sericite-schists and the paragonite-schists in many places pass by a continuous series of gradational phases into the felsite-schists. Hence it seems probable that these are also extensions of the granite.

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[a] Williams, op. cit., pp. 200–201.

Structurally the acid rocks are in the form of dikes or sheets. Some of them cut across the bands of basic schists in any direction. These are unquestionably dikes. The greater portion, however, occur in bands that trend parallel to the direction of the bands of basic schists surrounding them. These may be either intrusive sheets or they may be dikes which at the present surface happen to follow the bedding planes of the schist bands. Below the surface they may all cut across the schist bands, as some are known to do. The rocks of these two classes comprise gneisses, porphyroids, felsite-schists, and some of the sericitic schists. The finer-grained rocks are always associated with coarser-grained gneisses or gneissoid porphyries. A third class of acid schists may have been volcanic flows These comprise some of the sericite-schists and paragonite-schists. They occur in definite bands running parallel to the bands of the basic schists. They occur sporadically in the midst of the greenstone-schists, and are not associated with any forms of rocks regarded as apophyses of the granite.

All of the acid members of the Quinnesec schists are more or less schistose. The most massive granite-like dikes, and even the peripheral portion of the granite boss, exhibit distinct foliation. In the porphyritic varieties the finer-grained groundmass is very strongly schistose, while the phenocrysts are elongated into lenticular masses. The felsites and, in general, the fine-grained rocks are much more distinctly schistose than the coarser-grained ones, and many of them are fissile.

The schistosity of all the acid rocks, like that of the basic schists, is clearly the result of pressure acting after the intrusive masses assumed their present position, since in some cases, at least, the direction of the schistosity is inclined to the direction of the walls inclosing the intrusion.

Gneissoid granite and granite-gneisses.—The mass of the rock constituting the boss in Wisconsin is—

a typical coarse-grained granitite, with a decided tendency to a porphyritic structure. * * * When examined under the microscope the macroscopic diagnosis is found to be correct, and several additional points of interest are brought to light. The oldest constituents are zircon and apatite; both quite abundant in the form usual in granitic rocks. Iron oxide seems to be almost absent as an original constituent, though it is found in some of the altered micas. The biotite, the only mica present, is not abundant. It is invariably bleached to a green color by the reduction of its iron to the ferrous state. It contains abundant inclusions of apatite, zircon (around which are pleochroic aureoles), and some secondary magnetite. No trace of either hornblende or pyroxene was observed. Sphene, however, is present, as are also a few sharp crystals of a dark grayish-blue tourmaline. The principal interest of this rock attaches to its feldspar and quartz. They, together, make up nearly the whole mass, and exhibit in a remarkable degree the effects of pressure. The feldspar is of three kinds—normal plagioclase (oligoclase), unstriated orthoclase, and microcline. The relationship of these species of feldspar is a suggestive one. Both the oligoclase and the orthoclase are always altered to a fine micaceous or kaolinitic product which is particularly abundant in the center of the crystals, a zone of the unaltered mineral being often preserved around the edge. The microcline, on the other hand, almost never shows any indication of alteration.

It is always clear and fresh in appearance, but its twinning lamellæ are bent or curved and bear every sign of having been secondarily developed. * * * The large original feldspar crystals show a peripheral granulation. * * * and where they have been fissured their cracks are filled with a new crystallization of plagioclase, orthoclase, and quartz. None of these minerals shows any signs of chemical alteration and microcline is never to be found among them. Thus is produced a good example of what Törnebohm has called a mortar structure ("Mörtel-Structur"). In this secondary cement-like aggregate a micropegmatitic intergrowth of quartz and feldspar is quite common, and calcite, in good-sized individuals, is by no means rare.

The original quartz of this granite also shows many indications of having been squeezed. The crystals or grains often have an undulatory extinction, while larger grains are broken and the fragments are more or less displaced.[a]

The coarser-grained gneissic granites, augen-gneisses, and porphyries incorporated with the green schists are identical in composition with portions of the great granite mass. The rocks have in many cases undergone considerable chemical change, and have been subjected to a great deal of crushing. Nevertheless they can all be recognized as having differed originally from the granite only in structure. Nearly all appear to have been porphyritic. Many of them have lost their porphyritic character by the crushing of their original components and the crystallization of new material between the crushed fragments. The mashing, together with recrystallization, has changed the phenocrysts of feldspar into the augen of the augen-gneisses; it has produced well-characterized gneisses from quartz porphyries; and has changed the quartz phenocrysts of the latter into granular, lenticular aggregates of this mineral.

Williams describes a band of granite-porphyry cutting the greenstone-schists on the south side of the basin, just below the Horserace Rapids. The

[a] Williams, op. cit., pp. 111–112.

center of the band is a massive gray porphyritic rock. This grades on both sides into a well-characterized fine-grained gneiss, resembling a granulite. The central portion of the band consists of large crystals of a zonal plagioclase embedded in a granular mosaic of clear, colorless, untwinned, and probably newly crystallized grains of andesine, associated with brown leaflets of biotite. Apatite, zircon, and a reddish pleochroic sphene are also present in small crystals. Calcite is also abundant. Though the rock is fresh and appears to be unaltered, the presence of calcite indicates that it has suffered a change from its original character. The andesine is probably one of the new products formed.[a]

The gneissic portion of the band resembles the groundmass of the central, porphyritic phase. The chief difference is the banded appearance of the gneiss, produced by the parallel arrangement of the biotite and the alternation of layers of different-sized grains. Tourmaline and rutile are present in some sections. Remains of plagioclase phenocrysts are observed in others, but the porphyritic crystals have been nearly destroyed by granulation.

An analysis of the most massive portion of the band was made by Mr. R. B. Riggs. It disclosed the fact, already intimated above, that the rock is more nearly a diorite than a granite in composition.[a]

Analysis of massive portion of band of granite-porphyry near Horserace Rapids.

SiO_2	54.83
Al_2O_3	25.49
Fe_2O_3	1.61
FeO	1.65
CaO	6.08
MgO	1.96
Na_2O	5.69
K_2O	1.87
H_2O	1.18
CO_2	.18
Total	100.54

Other specimens of the granite-porphyry are more like granite than the one just described. In these quartz and orthoclase both occur as phenocrysts. Biotite and muscovite are present in the groundmass, the latter being derived partly, at any rate, from orthoclase. The quartz phen-

[a] Williams, op. cit., p. 113.

ocrysts are usually granulated—sometimes throughout their entire masses, often only peripherally.

The augen-gneisses differ from the porphyritic gneissic granite mainly in the extent of the mashing which they have suffered. They are well banded or gneissic through the arrangement of the constituents of the groundmass, notably biotite and muscovite, in parallel directions. Phenocrysts have disappeared by granulation, and have been deformed into flattened bodies, and new crystallizations of feldspar or quartz have been deposited in masses with triangular cross sections at the ends of the long axes of the flattened grains. The crystal forms of the phenocrysts have thus disappeared, and lenticular bodies have resulted.

One of these rocks from a dike at the upper end of the Horserace Rapids, on the Michigan side of the river, was also analyzed by Mr. Riggs. Its composition is that of a granitite.[a]

Analysis of granitite from upper end of Horserace Rapids.

SiO_2	67.77
Al_2O_3	16.61
Fe_2O_3	2.06
FeO	1.96
CaO	1.87
MgO	1.26
Na_2O	4.35
K_2O	2.35
H_2O	1.69
CO_2	.19
Total	100.11

Porphyries and felsites and their schistose phases.—The quartz-porphyries are now to all intents and purposes like the groundmass of the augen-gneisses, with the addition of rounded or dihexhedral quartz grains and an occasional phenocryst of plagioclase. They are yellowish-gray or reddish schists, with a greasy feeling. The components are the same as those of the augen-gneisses, but muscovite is much more abundant in them than in the latter rocks. The mineral that was originally biotite is often now represented by chlorite. All the larger grains are fractured or granulated, and the smaller ones are flattened. Nests of calcite are often abundant. An analysis of one of these rocks by Riggs showed it to belong unquestionably with the granite magmas.[b]

[a] Williams, op. cit., p. 119.

[b] Ibid., p. 121.

Analysis of quartz-porphyry from Big Quinnessec Falls.

SiO_2	66.69
Al_2O_3	16.69
Fe_2O_3	2.06
FeO	.93
CaO	1.40
MgO	1.15
Na_2O	2.46
K_2O	5.23
H_2O	1.70
CO_2	1.42
Total	99.73

The schistose felsites differ from the schistose quartz-porphyries only in texture. They are very fine-grained aggregates of the same minerals that characterize the matrix of the porphyries. Originally they may have been felsitic apophyses of the granite mass, or possible porphyritic microgranites, that were later so thoroughly crushed that their constituents have been completely granulated into minute flattened particles which are now cemented together by newly deposited material. The felsites as they now exist are very schistose. Muscovite is abundant in them and this is always so arranged in the thin section that the long axes of its shreds are parallel to the plane of flattening of the other components.

SERICITE-SCHISTS.

All the acid rocks thus far discussed are plainly younger than the greenstone-schists which they intrude. From their nature and the relations of some of them to the granite mass south of the Menominee River we are led to conclude that they are apophyses of this mass. A few other schists may also be acid rocks. These are so intimately incorporated with the green schists that they appear to be integral portions of the schist series. They always occur in bands parallel to the bands of basic schists, and never cross the latter. These rocks are the light-colored white or gray micaceous schists called by Williams "silvery schists." In composition they are mainly sericite-schists. Williams regarded them as specially metamorphosed basic schists. Some of the light schists associated with the dark-green ones may be of this character, but these are light-colored chlorite-schists. The sericite-schists are of a different character. Under the microscope they are seen to be composed of quartz grains, sericite scales, and chlorite shreds arranged in a parallel manner. No feldspar is noticeable in them, but calcite is abundant. As at present constituted the rocks are unquestionably acid. Though no analyses are at hand to substantiate this statement, the abundance of quartz and sericite noted in the slides leaves no doubt as to its correctness.

These acid schists probably represent acid flows contemporaneous with the basic flows with which they are associated. Their source is not yet known. They are so rare that they constitute but a small fraction of the Quinnesec schist series, which is essentially a set of schists produced by mashing from a succession of layers of basic lavas and tuffs.

INTERESTING LOCALITIES.

Good exposures of the Quinnesec schist series and their intrusions may be seen at the Sturgeon Falls, the Big and the Little Quinnesec Falls, and along the Horserace Rapids. At the various falls only the basic members of the series are present, and a few minor bands of sericite-schists, except that at the Big Quinnesec Falls there are a few bands of gneiss. At the Horserace Rapids the basic schists are also mainly in evidence, but acid intrusions are also common. Moreover the basic schists are of a different character from those at the several falls. In appearance they are more crystalline than the latter. In composition they are more hornblendic and less chloritic. The peculiar character of the schists along this stretch of the river he been ascribed in previous pages (pp. 146–148) to the effect of the granitic intrusions.

Sturgeon Falls.—The most abundant rock at the Sturgeon Falls is a coarse-grained, light-gray massive saussurite-gabbro. It forms the first barrier over which the water plunges in the series of cascades that constitute the falls (see Pl. X, *A*), and again it occurs at the lower end of the basin below the falls. The falls proper occupy a stretch of several hundred feet along the river. The stream here is narrow and its channel is gorge-like. Precipitous walls of the gabbro form the banks and these are practically continuous. At the lower end of the narrows the rocks are slightly schistose, but still retain the gabbroitic texture. About midway between the upper and the lower portions of the exposure several narrow bands of fissile, silky sericite-schist penetrate the gabbro and appear midway of the east wall. Between two of these is a narrow band of the massive rock exactly like the gabbro of the barrier. Intimate gradations exist between the schists and the massive gabbro. Although the gradation is much more rapid in some places than in others, no sharp line of demarcation can be drawn between the schistose and the massive rocks. From the field relations of the two phases it is evident that the schists represent mashed and altered forms of the gabbro.

Little Quinnesec Falls.—At the Little Quinnesec Falls a great width of basic schists and massive rocks, best seen in the west or Wisconsin side of the river, stretch up and down the stream for a distance of about 1,500 feet. The succession is made up of dark-green chlorite-schists, light-colored sericite-schists, light-gray schistose diabases, and several beds of fairly massive dark-green diabase. The light schists grade into the lighter-colored diabases, and the darker ones into the dark diabases So gradual is the transition between the massive and the schistose phases of the rocks and so intimate is the relation of the two varieties that there is no escape from the conviction that the former are but schistose portions of the latter. At the immediate foot of the falls on the east side is an exposure of sericite-schist of the kind that is supposed to have been derived from an acid bed. It is a little more distinctly separable from the bands of diabase between which it lies than are the light-colored schists farther downstream, but nevertheless it apparently grades into them.

On the Michigan side of the river, near the water's edge, much of the rock is essentially like that on the Wisconsin side, but in addition there is present just below the falls and extending from this point to the bridge over the falls the thick band of conglomeratic greenstone referred to by Wadsworth (p. 102). This is doubtless a tuff bed. Sericite-schists and bands of fairly massive basic rocks traverse the tuff. The former were regarded by Wadsworth as dikes and by Williams as special phases of the green schists. The bands of basic rock were described by Williams as dikes. By Wadsworth it was thought that they might be finer-grained and more massive phases of the tuff beds. On both sides of the river the strike of the schistosity of the schists and of the trend of the more massive bands associated with them is a little south of west. The dip is about vertical. All the massive or nearly massive bands of this series consist of some form of diabase, which is usually saussuritized. On the Michigan side of the river, however, and a little distance back from its bank is a high, abrupt ridge composed of a dark coarse-grained gabbroitic rock, which is uniform in composition and structure throughout the entire length of the ridge. Near the western end of the ridge the rock is composed of a light-greenish gray matrix in which lie porphyritic crystals of white feldspar and black hornblende. This is the type called by Williams "diorite." At its southeast end the rock is green and fine grained. It contains no phenocrysts.

This is compact and massive in structure, but everywhere profoundly seamed and jointed. It is cut by cross gashes and parted joints, and gives every indication of having been pulled or crushed—at all events, of having been subjected to enormous mechanical strains. The joints and seams often run in many different directions, producing a regular breccia without cement. The rock is also much slickensided, frequently so much so as to produce a schistose structure. The layers thus formed sometimes bend around more massive cores, which seem to have resisted the rubbing action.

The formation of what are above described as "cross-gashes" is very curious. At times the entire face of the rock wall is scarred with approximately parallel gaping seams, closely resembling the rents formed in moderately dry clay or putty when this is stretched. A single opening does not extend for any great distance, but a great number of them of all dimensions, closely crowded together, may produce an irregular sort of foliation. * * * These gashes seem to have been produced by a stretching of the rock or, what amounts to the same thing, by a bulging perpendicular to the action of some great pressure. They resemble the "klaffende Risse," described by Heim, in the Alps. * * * The edges of the seams are ragged, as though they had been formed by a forcible tearing asunder of the rock after it was solid. They are often filled with subsequent infiltrations of secondary minerals like calcite or quartz, but more frequently they are open.[a]

Big Quinnesec Falls.—At the Big Quinnesec Falls and the Horserace Rapids there is about a mile of continuous exposure on both sides of the river. The barrier rock of the falls is a medium-grained, gray, saussuritized gabbro, which is in places almost massive. On the Wisconsin side of the river the pale gabbro can be seen grading into a light-green schist; and again, just below the engine house, on the Michigan side of the falls, it can be traced into the silvery hydro-micaceous or sericite-schists and into green chlorite-schists. At the lower extremity of the basin, below the falls, is an exposure that juts into the river from the Wisconsin side. The main portion of the exposure is composed of a green massive rock, which is a good illustration of a diabase that has suffered epidotization and chloritization. In places it is crossed by bands of schist, that grade imperceptibly

[a] Williams, op. cit., p. 80.

into the massive rock. Farther up, on the Michigan side, is a series of exposures of practically the same rocks. Schistose phases are more common in these exposures than in the one on the Wisconsin side. It is in these rocks that the fine intergrowths of magnetite and rutile described by Williams[a] occur

Horserace Rapids.—At the Horserace Rapids the rocks are markedly different from any others occurring in the Michigan area of the Quinnesec schists. They are, however, like many of those near the granite mass in Wisconsin. During times of high water the Horserace is a foaming, dashing cataract, rushing between two low but steep walls of dark-green rocks, crossed here and there by dark pink bands. When the water is low, shelving banks extend streamward from the bases of the cliffs, and along these the relations of the various rocks to one another may easily be studied.

Between the Big Quinnesec Falls and the lower portion of the rapids is a short stretch of comparatively quiet water bordered by dark-green massive and schistose greenstones like those in the basin below the falls. In places these are cut by bands of pink gneiss.

The rapids have excavated their channel through rocks of an entirely different character. Here the greater portion of the river's banks consists of a coarse, gray diorite, speckled by large, and often glistening, crystal faces of dark-green hornblende, which sometimes measure 1 or 2 inches in diameter. Occasionally biotite flakes are discernible in the hand specimen, and minute silvery glistening scales of talc. This mineral coats the walls of all cracks and fissures in the rock and dots the faces of the hornblende crystals. In many places the basic rocks have a distinctly gneissic structure. The schistose rock is darker than the more massive phase and presents a more crystalline appearance. Other exposures consist of fibrous dark amphibolite and others of dark-green chlorite-schists. The latter often traverse the massive diorites and grade into them on both sides. In general the basic rocks along the Horserace are coarser grained, darker colored, and more crystalline than elsewhere along the river.

Another respect in which the Horserace exposures differ from those elsewhere is in the presence of numerous acid rocks. These occur in bands

[a] Williams, G. H., The greenstone-schist areas of the Menominee and Marquette regions of Michigan: Bull. U. S. Geol. Survey No. 62, 1890, pp. 99–101; and Neues Jahrbuch für Min., etc., 1887, vol. 2, p. 263. Cf. also A. Cathrein, ibid., 1888, vol. 2, p. 151.

A. HORSERACE RAPIDS DURING HIGH WATER.

Looking downstream from Chicago, Milwaukee and St. Paul Railway bridge.

B. LOG JAM IN HORSERACE RAPIDS.

Looking downstream from Chicago, Milwaukee and St. Paul Railway bridge.

of varying width, generally conforming to the foliation of the greenstones. The bands are sometimes composed of a massive pink granite. Usually, however, they are gneissic or schistose, and the rocks are gneisses, augen-gneisses, felsites, or other acid types already referred to in previous pages. In texture these rocks are usually coarse grained, but some of them are very fine grained. In color they vary between gray and red, pink shades predominating. Although, as has been stated, the acid bands usually trend conformably with the foliation of the greenstones, there are enough exceptions to this rule to prove conclusively that many of the bands are intrusive. On the shore of the little cove in the Michigan side of the river at the head of the Horserace, the intrusive character of one of these bands is plainly shown. Two bands of gneiss cut the greenstones. One traverses the schists. At another point farther downstream a band of gneiss ends abruptly in the green schists and sends out short apophyses into them. A few other instances of similar character may be seen at several places on the Michigan side of the rapids, but the general tendency seems to have been for the acid intrusions to follow the planes of foliation of the schists.

THE WESTERN AREA.

DISTRIBUTION.

The western Quinnesec schists occupy a triangular area of about 5 square miles, in Michigan, extending from about the center of sec. 15, T. 40 N., R. 30 W., Michigan, westward to the Menominee River. Where it crosses the river the belt is about 3 miles wide. After crossing the strean into Wisconsin, it gradually widens into a broad expanse, the boundaries of which are at present unknown. The Fourfoot Falls are at the southern side of the area where it crosses the Menominee River, and the old Indian village of Badwater is at its northern limit. The portion of the area away from the river is outlined by a few small, scattered exposures rising as little knobs above the soil and glacial sands.

TOPOGRAPHY.

The topography of the area underlain by the schists possesses no distinctive peculiarities. At its east end are several small rugged knobs with exposures of greenstones on their slopes, and at the western edge along the river are other knobs, some of which are rough and bare. The rest of the area is covered with glacial deposits that are so thick as to produce the usual assemblage of hills and hollows characteristic of drift topography. In the river channel, however, stretches of dead water are interspersed between rapids and falls in the manner described as characteristic of the channel through the Quinnesec schists of the southern area. Smooth water is more common than in the southern area, and rapids are less common, probably partly because of the thicker covering of drift, and partly because of the fact that the rocks are more uniform in character than in the southern district. The Upper and the Lower Twin Falls, situated in sec. 12, T. 40 N., R. 31 W., are about one-half mile apart. Each is a single cascade, with a plunge of about 20 feet (Pl. XII, *B*). Between them is a stretch of quiet water (see Pl. XII, *A*) flowing gently for the most of this distance between banks of gravel, sand, and clay. Below the Lower Twin Falls the stream is fairly rapid, but its banks are free from exposures for a distance of about a mile. Here the river leaves the schist area at a little falls and rapids known as the Fourfoot Falls. The final plunge is not above 1 or 2 feet in height, but back of this the stream flows over a rapids for a distance of 100 yards or more, and in this distance it makes a fall of about 6 feet.

LITHOLOGY.

The rocks of this area are grayish green in color, and so fine grained that in many instances no texture can be discovered in their hand specimens. Most of them are schistose, but their schistosity is not particularly noticeable until an attempt is made to break them, when they tend to split easily along approximately parallel planes like slates, and only with difficulty can they be made to break in any other direction. In some instances, however, the schistosity is so perfect that the rocks cleave exactly like slates. On many of the exposures, especially of the more massive phases, 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 cases 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.

In a few exposures in the northern and eastern portions of the area the rock is a little coarser grained. It possesses a structure that suggests

A. BASIN BELOW UPPER TWIN FALLS.

The water surface is smooth and the current sluggish. The rocks are dense, fine-grained, and ellipsoidal greenstones. The bridge is on the highway between Iron Mountain and Florence, Wis.

B. BARRIER ROCK AT UPPER TWIN FALLS.

The basin below the falls into which the water plunges is about 20 feet below the crest of the cascade. The rock is a dense, jointed greenstone.

the diabasic structure. It is, moreover, distinctly schistose, but its schistosity is more like that of the gneisses than like that of the slates. The rock probably represents a dike or a series of dikes in the fine-grained greenstone. At the Fourfoot Falls the exposures consist of alternating bands of massive, schistose, and slaty rocks striking about N. 80° W., almost at right angles to the course of the river, and yet these exposures are usually schistose on the Wisconsin side of the stream and massive on the Michigan side. At many places, both at this point and elsewhere in the area, the more massive phases alternate with schistose phases in the same manner as in the southern area. The schists grade into the massive rocks, and often no break of any kind can be discovered between them. This relation suggests the origin of the former from the latter. One peculiar rock of the Upper Twin Falls remains to be mentioned. It is observed in the smooth face of the exposure extending a little south of east from the barrier over which the water plunges. It is apparently a bed of conglomerate or breccia in the schists. At its extreme eastern end, where first met with, it is a band 6 feet wide composed of irregularly shaped and sharp-edged fragments of an aphanitic green rock in a matrix composed of small angular fragments of chlorite-schist cemented together by a mixture of quartz, calcite, and chlorite (Pl. XIII, *A*). The large fragments often match together in such a way as to indicate clearly that they were originally portions of the same mass. This was crushed into fragments and these were thrust apart, and at the same time the matrix was forced between them. To the west this bed splits up into several smaller ones, the largest of which passes over the brink of the falls. This peculiar conglomerate or breccia band strikes approximately parallel to the schistosity of the rocks in its vicinity. It appears to be a breccia zone, produced in all probability by the crushing of the rocks which it traverses.

Unlike the schists in the Menominee River, those of the western area are rarely cut by dikes. A few intrusions of diabase are met with in the area, but granitic intrusives are entirely absent.

The microscopical features of most of the finer-grained rocks of this area do not afford much evidence as to their original character. The rocks have suffered so much alteration that in many cases all traces of the original structures by which their nature might have been identified have disappeared. The composition of the alteration products, however, and the gradation of the dense rocks into coarser-grained varieties which still possess traces of structure, admit of no interpretation other than that the original rocks were basic igneous rocks. Their fine grain and ellipsoidal structure proclaim them lavas.

Fine-grained greenstones and their derived schists.—A few of the fine-grained greenstones still retain their original structure, and this is in accord with the character ascribed to them above. One of the more massive homogeneous light-green rocks from the Fourfoot Falls is described by Williams as follows:

Mineralogically there is hardly a trace of the original rock left. Almost colorless hornblende, pale-green chlorite, zoisite, leucoxene, and a little calcite (all of secondary origin) are the present constituents; and yet the original structure of the rock is strikingly well preserved. When viewed with a comparatively low power, in ordinary light, the outlines of long, almost acicular, feldspar crystals are very apparent, in spite of the fact that the substance of the feldspar itself is changed to chlorite or zoisite. These outlines of former crystals make a confused aggregate, but each individual preserves its own proper form (idiomorphic in the sense of Rosenbusch). The angular spaces between the feldspars produce a typical example of the ophitic or diabase structure, although no trace of a diabase mineral remains.[a]

This rock is traversed by "schistose bands, which show indications of having been much crushed and rubbed. Slickensides are abundant, and lenticular fragments fit into one another so as to produce an imperfect sort of foliation." Under the microscope this schistose rock exhibits the effects of great mechanical stresses.

Curving and interlacing areas of pale-green chlorite and of a grayish substance (perhaps the remains of titanic iron) form the main mass of this rock. Thickly scattered through these are patches of a dark-brown substance, often showing concentric zones of a clear, transparent character. These look like opal, but their optical character shows them to be single individuals of crystalline quartz. Imbedded in this material of such pronounced secondary character are fragments of feldspar, which have been crushed or broken. These * * * are less changed chemically than those in the massive rock from which this schistose band has been derived.[b]

Other schists of this vicinity are composed of hornblende, chlorite, feldspar, quartz, and leucoxene. Most of the hornblende is a pale-green variety, surrounding compact cores of a brown variety of the same mineral, from which the lighter-colored phase is believed to have been derived by

[a] Williams, op. cit., pp. 124–125.

[b] Ibid., p. 125.

A. BRECCIATED BAND OF MASSIVE FINE-GRAINED GREENSTONE AT UPPER TWIN FALLS.

The fragments are mainly dense, light-colored greenstone. The matrix is a schistose, chloritized greenstone containing streaks of chlorite.

B. RIDGE OF DOLOMITE SOUTH OF LAKE ANTOINE.

One of the typical hills of the dolomite formation. View taken from north side of the Clifford open pit, Traders mine. The crest of the hill is about two miles south.

bleaching. In these rocks no diabasic texture was observed. This fact, together with the presence of the brown hornblende, seems to indicate that the original rock from which the schist was derived may have been a diorite.

At the Twin Falls the rocks are so much altered that no trace of their original structure can be detected. They are usually dense, homogeneous, dark-green rocks, composed of a confused aggregate of pale-green fibrous hornblende, shreds of biotite, remnants of plagioclase, and grains of ilmenite. Around the feldspar remnants, and occupying the space originally occupied by this mineral, is now a mass of actinolite, zoisite, and epidote.

These rocks are crossed by bands of chlorite-schists, consisting of bright-green chlorite, finely granular quartz, and perhaps some secondary albite. In addition to these components the schists also often contain grains of ilmenite and leucoxene, flakes of biotite, and occasionally crystals of tourmaline.

The contacts between the schists and the massive phases are often very indefinite. The rocks grade into each other by infinitesimal variations. As described by Williams,[a] the first step in the production of the schistose structure is the division of the massive rock by two systems of joints intersecting at acute angles. These joints divide the mass into rhomboidal prisms, whose cross sections are well displayed on the smooth glaciated surfaces of many of the ledges. As the schistose phases of the rock are approached, the joints become more and more nearly parallel, with the result that the rhombs are all lengthened in a corresponding direction. The elongated prisms finally, by a more severe action of the lengthening process, become very thin and much extended lenses, which produce a well-developed wavy schistosity. The process is plainly dynamic, the schistosity being produced by pressure acting at right angles to the final direction of the foliation.

Coarse-grained greenstones and their derived schists.—Although most of the rocks in the western Quinnesec schist area are of the indeterminable character described above, a few of them possess more definite characteristics. A few exposures are plainly porphyritic. The phenocrysts were originally plagioclase, and the groundmass was a fine-grained ophitic aggregate that may have contained some glass. These rocks must be classed

[a] Williams, op. cit., p. 128–129.

with the basalts. Their relations to the fine-grained homogeneous greenstones can not be seen, so that it can not be determined whether they are dikes or flows.

In a few instances coarser-grained rocks have retained enough of their original structure to leave no doubt as to their character. Of course they are much altered, but they show plainly the divergent radial structure of diabases. Moreover, some of them still possess remnants of augite grains, surrounded by light-green hornblende in the triangular areas between the plagioclase laths. Through the hornblende are scattered little grains of magnetite, ilmenite, leucoxene, a few crystals of rutile, and nests of calcite. The plagioclase is partly fresh, partly changed to zoisite, and partly changed to chlorite.

These rocks are nearly massive, only traces of foliation being occasionally observed in them. Their constituents are much fresher than those of the schists and the dense greenstones. Although their relations to the latter rocks can not be seen it is probable that they are younger than these, and that they are dike masses intruding them.

Fragmental schists.—The only rocks in the area that appear to be fragmental are several narrow bands at the Upper Twin Falls, just below the Cascade. The bands are only an inch or two in width. In the field they were supposed to be stringers from the breccia already referred to (p. 161) as occurring at this place. Under the microscope the rock is seen to be very different from anything else found among the western Quinnesec schists. It is plainly a very fine-grained aggregate of quartz and tiny grains and specks of some black, opaque substance. From the fact that the bands run irregularly through the greenstones, it is believed that they represent cracks that were filled from above by material from some of the Huronian beds that must once have overspread the greenstones.

A somewhat similar rock is described by Williams from the same place. It constitutes one of the schist bands alternating with the more massive greenstones. The thin section—

> contains irregular and angular fragments of quartz and a slightly altered feldspar of considerable size. These are imbedded in a matrix of irregular grain, composed of chlorite, calcite, quartz, and opaque iron oxide, which is accompanied by leucoxene. The chlorite scales often have a radially divergent arrangement around the larger included fragments of quartz and feldspar.[a]

[a] Williams, op. cit., p. 133.

The particular schist band from which this specimen was taken differs from most of the schists of the area in the fact that its contact with the massive rocks is very sharp and distinct. This leads Williams to the conclusion that it is not simply a schistose phase of the massive rock, but that it represents a distinct bed in a volcanic series, the massive rocks and the schists derived from them being old lava flows and the schist just described being a tuff bed.

ORIGIN OF THE ROCKS.

The fine-grained texture of most of the rocks of the western area of Quinnesec schists, when considered in connection with their composition, indicates that they are old lava flows of the general character of basalts. Their ellipsoidal structure points to the same conclusion. In the Crystal Falls district, a few miles west of the Menominee district, the greenstones associated with the Huronian deposits exhibit this structure in a peculiarly fine manner. These rocks are plainly volcanic flows, since they occur in well-defined beds, many of which are amygdaloidal. The Quinnesec schists seem to have originated in the same kinds of rocks. They have, however, suffered so much more metamorphism than the Crystal Falls volcanics that their distinctive volcanic characteristics have disappeared.[a]

Tuff beds may have been associated with the old lava flows, but if so, they seem to have been in very subordinate quantity. At any rate, there is no certain evidence that they ever exisited in the area, though they may have done so.

The volcanic beds were cut by basic intrusions, and then the whole complex was folded. Where the folding was severe the finer-grained lavas and tuffs were changed into fissile schists, and the coarse-grained beds into schistose greenstones. Where the folding was less severe all the rocks were rendered schistose, but the resulting schists still retained traces of their original structures. After the folding other basic intrusions took place. These are represented by a few massive diabases met with in the area.

INTERESTING LOCALITIES.

The best exposures of the rocks of this area are found at the Twin Falls and the Fourfoot Falls. Both the Twin Falls are easily reached by the wagon road from Iron Mountain to Florence, Wis. The two falls are

[a] Clements, J. M., Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 113–135.

about half a mile apart, but it is only in the vicinity of the cascades that rock exposures are abundant.

Upper Twin Falls.—At the Upper Twin Falls (Pl. XII, *A* and *B*), low flat exposures occur practically all the way from the highway bridge around the basin below the falls to a point a little above the cascade. The ledges here are fine examples of the dense, dark-colored massive greenstones exhibiting the ellipsoidal structure. This structure is best seen on the flat rocks near the water's edge on the Michigan side of the river just above the bridge. The rock is dense and presents a smooth, almost featureless surface. On it, however, by close inspection, can be detected round and oval areas separated from interstitial areas by fine lines. The rock within the lines and that without them is practially alike, except that the former is sometimes slightly different in tinge from the latter. The round and oval areas are cross sections of ellipsoids which, in this ledge, vary in size from those having a diameter of 6 or 7 inches to those having a similar dimension of a little over 2 feet. None of them have amygdaloidal peripheries.

Near the falls, on both sides of the river, and at the lower end of the basin below the falls, on the Wisconsin side, several bands of chlorite-schist traverse the massive rocks, but they are rare. At the cascade, and on its east side, is the narrow band of fragmental greenstone referred to in a previous page (p. 161).

Lower Twin Falls.—At the Lower Twin Falls the ledges are larger and rougher than at the more northerly fall. The rocks are practically the same at both places, but at the lower falls the schistose phases are rather more common. Here can be well seen the transition between the massive-jointed greenstones and the chlorite-schists, and here also, on a small scale, can be seen the actual passage of massive into schistose phases along shearing zones. Just below the falls, on the Michigan side, the dense rock is traversed by a seam of quartz occupying a crack along which there has been movement. The rock, at the distance of a few inches from the vein, is quite massive; nearer the vein it becomes schistose, with a foliation inclined about 45° to the direction of the vein, and very near the vein it is a typical chlorite-schist. Similar chlorite-schists may also be seen in this ledge coating surfaces of joint planes.

Fourfoot Falls.—At the Fourfoot Falls the rocks exhibit greater variety.

The falls themselves are not much more than a rapids over ledges of greenstone-schists. The Chicago and Northwestern Railway bridge, on the line between Iron Mountain and Commonwealth, crosses the river at the foot of the rapids. For a few hundred yards above the bridge instructive exposures can be seen on both sides of the stream. Alternating bands of massive and schistose greenstones, striking about N. 80° W., outcrop on bare banks and form the rapids and several small islands in the river. On the Michigan side the prevailing rocks are massive. On the Wisconsin side schists predominate.

At the western end of the railroad bridge the rock is a light-green aphanitic, massive greenstone, traversed here and there by wavy bands of schistose greenstone, characterized by abundant slickensides. Beyond this to the north is a narrow band of a black graphitic-looking schist, and north of this another band of schistose greenstone best exposed near the water's edge. Immediately north of this exposure rises a high, sheer cliff, undermined at the base by hollows produced artificially. This consists of a soft, black, slaty-looking, very schistose, and quite fissile rock. In the hand specimen and in the ledge it bears a strong resemblance to a black slate, but under the microscope it is seen to be a chlorite-schist. At the water's edge, beyond the cliff, the schist again appears, and north of this follow ledges of schistose greenstone.

On the Michigan side the rock is fairly uniform in character. The southernmost ledge just under the bridge is a massive, dense, light-green rock. The northernmost ledge is a dark greenstone-schist. The intervening low ledges that dot the bank are massive and schistose greenstones that are a little coarser in grain than the rock under the bridge. In the rocks of some of these ledges the diabasic structure is plainly discernable, but in most ledges the grain is so fine that no well-characterized structure is observable except in thin section under the microscope.

SECTION 2. NORTHERN COMPLEX.

The rocks constituting the Northern Complex are gneissoid granites, banded gneisses, hornblende-schists, and a few feldspathic green schists, identical with some of the squeezed basic schists among the Quinnesec schists. Mica-schists also occur in the complex, but they are rare. They have been found only in a few exposures in the interior of the Archean area north of the limits of the map. The granites, gneisses, and schists are cut by dikes of coarse-grained and fine-grained basic rocks, by small dikes and veins of aplite and pegmatite, and by numerous quartz veins.

DISTRIBUTION.

These rocks occupy an elliptical area north of the Menominee trough of fragmentals, separating it from the Calumet trough farther north. The complex is separated from the Huronian beds by unconformities and by basal conglomerates which will be referred to later. Only those rocks occurring along the southern edge of the area have been studied in detail. The rest of the area has been examined sufficiently closely, however, to warrant the statement that it does not differ in any essential respect from its southern periphery.

TOPOGRAPHY.

The topography of the country underlain by the crystalline rocks is not unlike that of Basement Complex areas elsewhere. In the western portion of the area small and large, rounded, glaciated hummocks of rock, often with precipitous sides to the south, rise above the gravels and sands of the glacial deposits. In the eastern part of the district, where these deposits are thinner, the hills protrude higher above the drift, appearing as groups of knolls with bare, fairly smooth upper surfaces, but with ragged and precipitous sides.

SEQUENCE OF ROCKS.

The study of the relations of the rocks of the complex to one another has not afforded any more data for determining their exact sequence than studies in other Archean areas. In general it appears that some of the gneisses and some of the hornblende-schists are older than most of the granites. Others of the schists are plainly mashed intrusives that are younger than most of the granites. All of the greenstone-schists are of this nature. The aplites, pegmatites, and some of the basic intrusives are the youngest rocks belonging in the complex, but even these, since they are not known to cut through the Huronian beds, are thought to have taken their present position before the sediments were deposited. The latest of all the intrusives are certain coarse-grained massive diabases and gabbros. These rocks not only occur as intrusives in the complex, but they are found also in the lower member of the Huronian series overlying the Archean rocks. There is no reason to believe that any of the rocks of the complex are metamorphosed sediments. Most of them are clearly igneous in origin.

LITHOLOGY.

GNEISSOID GRANITES.

The most abundant rocks of the complex are gneissoid granites and granitic gneisses. These rocks differ from one another in no essential respect. The former are merely less schistose than the latter. Both embrace a series of medium-grained to fine-grained gray and pink rocks with a granitic texture that sometimes approaches in appearance the texture of fine-grained quartzites. The pink or red granites are usually a little coarser grained than the gray ones. In the hand specimen red orthoclase is seen to be the principal constituent. In addition to this there can also be detected a few grains of white feldspar, a large number of quartz grains, and an occasional flake of mica. The gray granites appear to be almost homogeneous. Here and there through them are stringers and patches of pink granite, but most of the hand specimens are of a nearly uniform dark-gray tint. The gray rock passes into the pink rock by almost imperceptible stages, the differences in the tints of the two end members of the gradation series being due mainly to the color of their feldspathic component.

In some instances the pink stringers are very coarse-grained aggregates of feldspar and quartz, like pegmatites. The material of these pegmatitic veins, like that of the finer-grained ones, grades into the mass of the gray rock. There is nowhere any sharp contact between the two. The red granite does not seem to be of the nature of an ordinary intrusive, but it appears rather to have the character of an impregnation, which saturated the gray granite and crystallized in certain places as patches or irregularly shaped stringers, and in other places, probably along cleavage planes, as more regular and definite veins. In the banded gneisses, to be referred to later, the pegmatitization followed approximately parallel planes, but in the gray and pink gneissoid granites it took place irregularly through the rock mass.

Under the microscope all the granites and granitoid gneisses of this area, whether of the pink or the gray variety, are found to consist of quartz, orthoclase, plagioclase, and biotite, and large quantities of the decomposition products of the last-named mineral, and of the feldspars. The most abundant of the decomposition products are kaolin and chlorite, but sericite, calcite, epidote, and ocher are nearly always present in small quantity. Rutile, zircon, and apatite are also present as accessories. In some sections a little microcline is also to be found among the feldspars. It appears in all cases to be an original component and not a new product as in the Marquette granites.

All the feldspars are altered. Small flakes of sericite and spicules of kaolin are scattered through them somewhat uniformly. The microcline and the plagioclase have undergone less alteration than the orthoclase, which in many sections is so completely decomposed that no trace of the original material can now be detected.

The biotite is a green variety with a pleochroism in yellowish-green and emerald-green tints. It is present as small flakes and in aggregate of flakes between the feldspars and the quartz. The secondary chlorite and epidote are found mainly in the vicinity of the biotite, from which they seem to have been derived. At all events, when these products are abundant the biotite appears to be more or less bleached.

The red granites differ from the gray varieties mainly in the fact that the feldspars of the former inclose large numbers of inclusions of hematite and reddish-brown ocher. They also contain but little biotite and almost no microcline. In other respects the two rocks are essentially the same. The red granite appears to be a little more decomposed than the gray rock and is apparently more crushed, but otherwise there is little besides difference in color to distinguish the two.

All specimens of the gneissoid granites show plainly the effects of mashing. Many of their components are broken and squeezed out into lenticular masses, which give the rocks their schistosity. The peripheral portions of many of the grains are granulated and in these granulated portions is found the greater portion of the secondary sericite.

BANDED GNEISSES.

The banded gneisses are composed of the same components as are the gneissoid granites. Secondary products are, however, more abundant than in the granites, and the primary constituents are usually less fresh looking. At first glance these banded gneisses appear to be made up of alternate parallel bands of gray and pink schistose granitic material like that of the gray and pink gneissoid granite described above. A close inspection of the ledges, however, shows that while these bands are approximately parallel for short distances, they nevertheless wedge out when traced for distances of 18 or 24 inches, split up into several narrower bands, or coalesce with other bands, forming broader ones. Often, also, narrow bands of one color cut across broader bands of the other color, so that the rocks are actually made up of an interlacing network of veins with meshes of very unequal dimension. The long dimensions are parallel to the apparent banding of the rocks, which is also the direction of their schistosity, and the short dimensions are perpendicular thereto.

The banded gneisses are thus like the mottled red and gray gneissoid granites in the fact that they consist of granitic impregnations in a granitic rock The impregnations in the banded rock, however, followed approximately parallel courses, while in the mottled rocks they occurred irregularly. The source of the impregnating material may very well be the rock in which the impregnations took place. This may have been partially dissolved, yielding solutions which transported the dissolved material to situations where the conditions were favorable to its crystallization.

HORNBLENDE-SCHISTS.

The hornblende-schists 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 hornblendic 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 intrusives. They differ from the schists of the first kind in being duller in luster and in having a greener tinge.

In their petrographical character the hornblende-schists vary between normal phases composed of hornblende, quartz, epidote, and perhaps occasionally a little feldspar, and greenstone-schists composed of amphibole, plagioclase and its decomposition products, quartz, epidote, kaolin, calcite, and sericite. As the proportion of quartz present increases, sericite, calcite, and kaolin gradually disappear, and the rocks approach more and more nearly the normal hornblende-schists in appearance and composition. This gradation from rocks that are unquestionably altered basic rocks to true hornblende-schists may not often be observed in a single outcrop, but the two end members of the series are united by so many gradational phases that there can be little question that they are genetically connected. It is very evident from the microscopical study of their thin sections that the feldspathic hornblende-schists are squeezed and altered basic eruptives. It is very probable that the nonfeldspathic hornblende-schists have the same origin and that they differ from the feldspathic schists only in the amount of mashing to which they have been subjected and the consequent amount of alteration they have suffered.

INTRUSIVES.

The granites, gneisses, and schists are cut by veins of granite, pegmatite, aplite, and quartz, and by well-defined dikes of basic rocks.

Acid intrusives.—The granite veins are of all sizes, from a few feet to a few inches in width. Their material is identical with that of the red granites referred to a few pages back.

The pegmatites are coarse-grained red rocks composed of red orthoclases and white quartz. The feldspar is in grains that occasionally have rudely outlined crystal forms and the quartz in irregular areas between these. While the rock bears some resemblance to a graphic granite, the pegmatitic structure is not very pronounced.

The aplite is a fine-grained purplish rock, in which can plainly be seen small lath-shaped crystals of red feldspar lying in a fine-grained matrix composed of irregular grains of red orthoclase and irregular dark-gray areas of a black micaceous mineral and white quartz. The rock is quite massive, not the slightest evidences of schistosity being observed in it. Under the microscope the lath-shaped crystals are found to be andesine. In addition to the lath-shaped crystals there are present also many quadrangular sections of a feldspar that extinguishes differently in the four quadrants. These apparently consist of orthoclase twinned according to the Manebach and the Carlsbad laws. These feldspars are embedded in a groundmass made up of orthoclase, quartz, epidote, green chlorite, calcite, a little brown biotite, and some rutile.

The orthoclase and the quartz compose the greater part of the groundmass. They are mainly in micropegmatitic intergrowths, the quartz apparently saturating the feldspar. Untwinned orthoclase is also often found surrounding the quadrangular feldspar phenocrysts above referred to, while the quartz occupies the same position with respect to areas of micropegmatite in which the quartzose constituent predominates over the feldspathic one. Between the phenocrysts and the areas of micropegmatite is an aggregate of quartz, orthoclase, and the other minerals mentioned above. In this aggregate quartz and feldspar are in small grains, the former with rounded contours and the latter with very irregular ones. The other constituents are also in the aggregate, the chlorite as fairly large green flakes that look as though they may have been derived from biotite, the epidote as colorless irregularly shaped grains, the rutile as tiny crystals, and the calcite as nests in the interstices between the quartz and feldspar grains.

The orthoclase of the phenocrysts and also of the groundmass is always more or less altered into kaolin-like decomposition products, the porphyritic crystals, however, being much less decomposed than the grains of the matrix.

Basic intrusives.—The basic dikes consist of rocks that are known comprehensively as "greenstones," dark-green rocks produced by the alteration of basalts, diabases, or gabbros. The dikes vary widely in size. Some are only a foot or two in width, while others measure as much as 300 feet. The smaller intrusions are usually dike-like in form, while the larger ones are more boss-like in character. Their intrusions follow the same general courses for short distances, but they vary in width and have irregular contacts with the rocks through which they intrude.

A few of the basic intrusives may be limited to the Basement Complex. The majority of them, however, cut both the rocks of this series and those of the Huronian. In several instances the large dikes may be traced step by step across the contact of the granite-schists series into the quartzites of the Lower Huronian without any break in their continuity, so that in these cases there is no question but that they are younger than the quartzites of the iron-bearing series.

The macroscopic aspects of these rocks are those of the ancient basic dike rocks so common in Archean areas everywhere. Some of them are fine-grained green rocks without any peculiarly characteristic structure, others are darker-colored, medium-grained rocks with a distinct diabasic structure, and others are coarse-grained varieties with a granular structure.

These last mentioned are gabbros, the others are diabases, some of which are very fresh, while many are much altered.

Under the microscope the diabases are identical in every respect with the diabases cutting the Quinnesec schists, and the gabbros with corresponding phases of the basic intrusives in the Huronian beds (see pp. 185–186).

INTERESTING LOCALITIES.

The rocks of this series are well exposed along the entire northern side of the Menominee trough. They may be seen at almost any place north of the quartzite belt in a number of small exposures separated from each other by stretches of glacial drift. The best and largest exposures are in secs. 29, 31, and 32, T. 41 N., R. 29 W., and secs. 1, 2, and 12, T. 40 N., R. 30 W., where the rocks forms huge bare cliffs that are almost in contact with equally large cliffs of quartzite (see Pl. XIV). These exposures are easy of access from Iron Mountain by the road that leads from this city to the so-called gold mine that has been opened in the quartzite in their vicinity. They present the usual features characteristic of Archean complexes.

CHAPTER V.

THE ALGONKIAN SYSTEM.

General character and definition.—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 usually being plainly apparent in them. The iron formations are 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 dolomites are principally chemical or organic sediments, but in their lower portions there is an abundant admixture of mechanical débris. The sedimentary rocks have been intruded by a few coarse-grained and some fine-grained basic igneous rocks. The latter are now usually schistose.

The lowest member 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 north border of the trough. Their best-known exposures are those at the Falls of the Sturgeon River, made classic by Credner, Brooks, and Irving. Hence the Algonkian rocks are younger than the underlying schists.

The members of the system are likewise separated from the overlying Cambrian sandstone by a profound unconformity. The Algonkian rocks are folded; the sandstone is practically horizontal. The latter thus lies across the truncated ends of the eroded folds. Its lower layers are 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 sandstones.

Unconformity within the system.—Within the Algonkian system there is an unconformity corresponding to that in the Marquette district between the Upper Marquette and the Lower Marquette series. This unconformity is not so plainly marked in the Menominee as it is in the Marquette district, but it is similar in all essential respects to the unconformity between the Lower Huronian cherty limestone formation in the Penokee district and the overlying quartz-slate member of the Upper Huronian. In the Marquette district the unconformity is indicated by a marked discordance between the upper members of the lower series and the lowest members of the upper series, and by the presence of a widespread basal conglomerate in the upper series. In the Penokee district it is indicated by an erosion contact between the limestone and the quartz-slate without discordance of bedding, and by the presence of fragments of the lower formation in the lowermost beds of the overlying slates.[a] In the Menominee district the direct evidence of the unconformity is the presence of a conglomerate or of a coarse quartzite at the base of the upper series containing undoubted fragments of some of the rocks of the lower series, and the presence near the base of this series of an iron formation made up in part of the detritus of an older iron formation. There is also, in addition, indirect evidence of the unconformity in the absence from parts of the district of the lowest and most resistant members of the Algonkian series—the Sturgeon quartzite and the Randville dolomite. The nonexistence of the iron-bearing Vulcan formation in parts of the district adjacent to the Randville dolomite and the overlapping of the Vulcan formation by the Hanbury slate at some of these places give further evidence of unconformity. The Algonkian system is therefore divided into a Lower Menominee and an Upper Menominee series, equivalent to the Lower Huronian and the Upper Huronian elsewhere in the Lake Superior region.

The data upon which the foregoing conclusions are based are discussed in detail in connection with the descriptions of the several formations comprising the different systems under the heading "Relations to adjacent formations."

SECTION 1. LOWER MENOMINEE SERIES.

Succession and distribution.—The Lower Menominee series is divided into three formations. These are, in the order of upward succession, the Sturgeon quartzite, the Randville dolomite, and the Negaunee formation.

[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 171, 443–444, 454–455, and 472.

The formations belonging to the Lower Menominee are observed only in the center and on the northern side of the Menominee trough. On the southern side of the trough and around the borders of the western area of Quinnesec schists no evidence of the existence of these formations is obtainable. This may possibly be due to the thick covering of drift that blankets the rocks in these portions of the district, but since ledges of the soft Hanbury slate are found at no great distance from the borders of the schist areas, it is probable that the two formations are actually absent. For it is hardly credible that two such resistant formations as the quartzite and dolomite could have been so completely planed down in these particular portions of the area as to leave no projecting ledges above the drift, while soft slate formations nearby resisted planation sufficiently successfully to yield ledges, especially since in the central and northern portions of the trough the quartzite and dolomite constitute the prominent elevations and the slates the valleys between these.

STURGEON QUARTZITE.

The Sturgeon quartzite is so called because the principal rock of the formation is a quartzite which is in the same position with respect to the Archean complex and the dolomite formation of the Menominee district as is the Sturgeon quartzite of the Felch Mountain district with respect to the Archean series and the dolomite of that district.[a]

DISTRIBUTION AND TOPOGRAPHY.

The Sturgeon quartzite forms an almost continuous belt on the north side of the Menominee trough immediately south of the northern Archean complex, with which it is in contact. Its most easterly known exposures are in the center of sec. 9, T. 38 N., R. 28 W. From this point the belt continues in a general northwesterly direction to sec. 2, T. 40 N., R. 30 W., with an average width of a little less than one-fourth of a mile. In its eastern portion the belt is narrow, rarely reaching a breadth of one-fifth of a mile. As it passes west, however, it gradually widens out, and in sec. 2, T. 40 N., R. 30 W., it has a width of a mile. Here the belt turns north and the rock is folded into many pitching folds which cause repetitions of the same beds and a great increase in the apparent thickness and conse-

[a] Mon. U. S. Geol. Survey, vol. 36, 1899, pp. 398–405.

quently in the width of the formation. For 2 miles northward exposures of the quartzite are very abundant, but near the north line of sec. 29, T. 41 N., R. 29 W., it disappears under a covering of the characteristic micaceous quartzite of the Calumet trough, believed to belong in the Upper Menominee series.

Throughout the distance of 16 miles between the eastern end of the quartzite belt and the north line of sec. 29, T. 41 N., R. 29 W., where it suddenly ends, the belt is marked by an almost unbroken succession of great, bare, rugged bluffs with smooth tops and almost precipitous sides, especially to the south, cut here and there by deep, narrow gorges, or by a series of small, low ledges separated from one another by stretches of glacial sands. In only one place is there a notable gap between neighboring exposures. The belt should extend through secs. 34 and 35, T. 40 N., R. 30 W., and sec. 2, T. 39 N., R. 30 W. Ledges of quartzite are found in the northeast quarter of sec. 2 and in the northwest quarter of sec. 34, but in the intervening mile and a half no exposures have been found. To the north are the usual knolls of the Archean gneisses and schists. The absence of exposure may be due to the erosion that occurred between the Lower and the Upper Menominee times and the consequent cutting out of the quartzite at this place, or it may be that the formation exists deeply buried beneath the sands. There is a marked contrast between the topography of this portion of the belt and the remaining portions. Instead of the southward-facing cliffs that are so prominent a feature of the area underlain by the quartzite elsewhere we see here a stretch of sand plain whose surface is 100 feet or more below the level of the surrounding gneiss and quartzite hills. It is true that two small streams cross the area at right angles to the strike of the belt, and these may have lowered the surface to its present position. When we consider, however, that the Sturgeon River, where it crosses the quartzite, has produced no such effect, and, furthermore, when we note that the gneiss and granite still exist as rugged hills, whose elevation is practically that of the neighboring gneiss and granite hills at some distance from these streams, the conclusion that the quartzite did not exist at this place when the present topography was produced seems to be the more reasonable of the two alternatives. There is no direct evidence as to the presence of the quartzite under the sand.

LITHOLOGY.

The Sturgeon quartzite comprises conglomerates, quartzites, quartz-schists, arkoses, graywackes, and dolomitic sandstones or quartzites. It is cut by a few basic dikes and by veins of quartz.

CONGLOMERATES.

The conglomerates occur only in a few places very near the granite-schist complex. They are well exposed on the flanks of this complex near the north quarter post of sec. 32, T. 41 N., R. 29 W., near the south quarter post of sec. 6, T. 39 N., R. 28 W., near the west quarter post of sec. 1, T. 39 N., R. 29 W., and in the north half of sec. 8, T. 39 N., R. 28 W., in which is the famous locality at the Falls of the Sturgeon. In all these places the rock is composed of gneiss, granite, and quartz pebbles and bowlders in a groundmass that is sometimes an arkose, sometimes a graywacke, and occasionally a quartzite. The fragments vary in size from a few inches to a foot and a half in diameter. Some of them are well rounded, while others are sharp edged. The matrix in which they are embedded is sometimes a white quartzite, but usually it is dark colored, being either dark red or dark gray, according to the predominance in it of red feldspar grains or of chloritic or micaceous particles derived from the decomposition of this mineral. The darker-colored matrices are also schistose, the schistosity being generally parallel to their contacts with the granite-gneiss complex.

The character of the conglomerates varies mainly with respect to the groundmass. This may have the composition of a quartzite, an arkose, or a graywacke, and it may either be massive or schistose. The conglomerates with a quartzitic matrix are usually massive in structure, while those with an arkose or graywacke matrix are always more or less schistose. The included pebbles are in all instances fragments of gneiss, granite, basic schists, and vein quartz, identical with the corresponding rocks in the Archean complex.

The quartzitic conglomerates are simply quartzites, like the normal rock of the formation described below, containing pebbles and bowlders of granite, vein quartz, and crystalline schists, together with irregular grains of the individual components of the first-named rock.

The greater number of conglomerate specimens contain a large quantity of feldspar in their groundmass. Sometimes, as has been stated, the matrix has the composition of a recomposed granite or arkose, and at other times its composition is more nearly that of a graywacke.[a] Whether the matrix is arkose-like or graywacke-like appears to depend upon the character of the Archean shore line against which it was deposited. Where the Archean rocks in contact with the conglomerates are mainly granites and gneisses, the matrix of the fragmental rock contains large quantities of orthoclase—is an arkose. On the other hand, where the Archean rocks are largely greenstones, the matrix contains chlorite and the decomposition products of plagioclase—is a graywacke. In both cases the structure is usually schistose.

The larger pebbles in these conglomerates possess their original character. The smaller ones, however, show plainly the effects of mashing. The quartz pebbles are crushed into fragments, which are sometimes separated from one another by portions of the groundmass, but which are as frequently aggregated into groups of variously oriented grains, differing in outline from the original pebbles in being much elongated, often to the extent of becoming almost vein-like. The particles of the aggregates are crossed by strain shadows, and the whole appearance of the quartz suggests pressure phenomena.

The smaller granite and gneiss pebbles are likewise shattered. Their individual components occur as sharp-edged fragments scattered through the matrix at intervals. The plagioclase and the microcline are still fresh, but the orthoclase has been changed to a micaceous aggregate of secondary products, in which particles of muscovite, kaolin, chlorite, and quartz may be detected.

The matrix surrounding the pebbles is composed of isolated grains of quartz, microcline, and plagioclase in an extremely fine-grained groundmass that has nearly the composition of an altered feldspar. In the darker-colored phases of the rocks there is in addition to the usual decomposition products of feldspar, quite a little chlorite, and other greenish alteration products of biotite. All these components are arranged in a rudely parallel

[a] The term graywacke is here used in the sense in which it has been defined by Geikie and J. Roth, and in the sense in which it has been used in the description of the Survey's "Educational series of rock specimens," i. e., as a fragramental rock, the cement of which is dark colored and of the composition of a clay-slate. See Bull. U. S. Geol. Survey No. 150, 1898, pp. 84–87.

direction, which is approximately parallel to the direction of the elongation of the crushed quartz fragments derived from the quartz pebbles.

The coarser grains of the matrix evidently represent sand grains in a sediment that consisted largely of the material from which the finer portion of the groundmass was produced. This must have been a mud or silt which was made up of the finer detritus of the Archean rocks, and which was therefore comparatively rich in ferromagnesian components.

ARKOSES AND GRAYWACKES.

The conglomerates pass rapidly into nonconglomeratic beds, whose composition is like that of the conglomerate groundmass. In some places the nonconglomeratic rock is a red massive or schistose arkose; in other places it is a dark-gray schistose graywacke; and in still other places, it is a massive or schistose light-gray quartzite, according as the matrix of the conglomerate associated with it is coarse or fine, feldspathic or quartzitic, massive or schistose. These rocks are interbedded with the conglomerates in comparatively thin layers. They are more common in the upper portion of the conglomerate beds than at lower horizons and constitute gradation phases between the conglomerates and the typical quartzites.

The gradations can be best seen at the Falls of the Sturgeon River, where there is a fairly continuous exposure from the conglomerate into the quartzite, through transition phases that are rocks like the matrix of the conglomerate. The rock immediately above the conglomerate is a bright red arkose; above this is a fairly massive gray graywacke containing here and there little nests of pink calcite; and above this again a schistose phase of the same rock. The next layer above the schistose graywacke is a bright red arkose, which grades through a light-gray schistose quartzite into the normal vitreous rock.

There are very few of the arkoses that are not schistose. Their feldspathic constituent furnished abundant material for the production of micaceous products, and these, under the influence of shearing stresses, readily took on the parallel arrangement which gave rise to the schistose structure. In their present condition they are feldspathic sericite-schists. The few massive arkoses met with appear as thin beds of fairly coarse-grained pink rocks lying between thicker beds of quartzite. The more purely quartzitic phases contained but little feldspar; consequently there was less solution of their constituents and therefore a smaller production of mica. These rocks are therefore only rarely schistose, except along their shearing zones bounding joint cracks along which readjustment took place during folding.

In thin section the arkoses are seen to be composed of quartz grains and fragments of orthoclase, various plagioclases, microcline, and microperthite, in a matrix of finer grains of the same substances colored red by iron oxides. Magnetite crystals, clumps of rutile, an occasional crystal of zircon, and a few grains of epidote are the only other constituents noticeable, except certain micaceous decomposition products of the feldspars. These are especially abundant in the finest-grained portions of the matrix, which in many places is composed almost exclusively of kaolin, sericite, and quartz. The larger feldspar grains are often quite fresh, the plagioclases and the microcline being almost devoid of alteration products of any kind. The orthoclase, on the contrary, is usually much altered, even in the largest grains. None of the grains are as completely waterworn as those in the typical quartzite. They are usually much more angular than the latter, like grains of sand that have not traveled far from the coast along which they were formed.

The graywackes are darker than the arkoses. They are always schistose and fine grained. The schistosity can be seen to arise from the parallel arrangement of tiny shreds and plates of chlorite and some light-colored mica, and in all cases where it has been carefully examined it is parallel to the bedding. The graywackes are always finer grained than the arkoses. A few large quartz grains are scattered through them, but the main portion of the rocks consists of small grains of quartz and decomposed feldspars, spicules of muscovite, chlorite, and green biotite, crystals and grains of magnetite, little nests of calcite, and occasionally a small prism of tourmaline. Much of the quartz of the groundmass seems to be secondary, as it is in the form of interlocking areas traversed by the micaceous spicules.

The schistose structure is produced in part by the parallel arrangement of the chloritic and micaceous minerals and in part by original sedimentation, for there is often noticeable in the sections alternating layers of finer- and coarser-grained components and layers containing more or less of the quartz and feldspathic constituents.

QUARTZITE.

The major portion of the Sturgeon formation consists of massive beds of a very compact quartzite. As a rule the quartzite is entirely massive; but in a few places it is schistose. Usually the schistose phases are feldspathic and sericitic, and they are nearly always associated with the conglomerates. In a sense they appear to be gradation phases between those rocks which are always feldspathic and the vitreous massive quartzites. Hence they are found only in the lower portion of the formation. One of the best illustrations of the schistose quartzite is the ledge separating the upper from the lower basin below the Falls of the Sturgeon River. This schist is a very fine-grained, saccharoidal dark-gray rock with a silky luster on its indistinct cleavage planes, due to the presence of some sericitic mineral in plates lying parallel to the cleavage. Above, the quartzites pass into dolomitic sandstones by the gradual replacement of their siliceous cement by dolomitic material.

The normal rock is a very pure quartzite, composed almost exclusively of quartz grains cemented by quartz. Its material appears to have been well sorted, practically all the feldspar grains and easily decomposable substance having been removed from the sands before they were deposited in their present position.

The rock is either vitreous or saccharoidal. It is usually white or light gray in color, but many beds are tinged with a faint-pink shade, and occasionally a bed is observed that is distinctly green. One such bed is interleaved with ripple-marked beds of snow-white phases of the rock in the small knob 1,250 paces north, 250 paces west of the southeast corner of sec. 2, T. 39 N., R. 29 W.

As a rule the quartzites exhibit little evidence of mashing. Their components are large and small rounded quartz grains cemented together by quartz material that is optically continuous with the grains it surrounds. Many of the grains are beautifully enlarged, the added quartz often building them out into well-proportioned crystals. In the pink and white varieties of the rock no other constituents are present except here and there a grain of pyrite or a small spicule of chlorite.

The green quartzite referred to in a previous paragraph contains, in addition to the quartz, a considerable quantity of light-green sericite, forming a very sparse interstitial filling between the quartz grains Under high powers of the microscope this mineral appears as a thick felt of spicules traversing the cementing quartz and penetrating for short distances into the quartz grains. In those cases where two grains are contiguous with no recognizable intervening cement, the line of junction between them is marked by a very thin film of needles which, to all appearances, have been formed by corrosion of the quartz. The needles penetrate the quartz on both sides of the junction line, destroying the rounded outlines of the grains and producing very ragged ones. The phenomenon looks very much as though produced by corrosive processes—as though decomposition of the quartz had been brought about through solutions passing between the grains and reacting on the walls of the tiny canals through which they flowed. Single flakes of the sericite are occasionally included within the grains, and little clumps of rutile are found in the midst of the felt in the large interstices.

In the schistose quartzites the proportion of sericite is very large, and the crushing of the quartz grains is very noticeable. The rocks consist essentially of sharp-edged fragments of quartz embedded in a groundmass of sericite and very fine quartz grains. The larger quartzes are evidently fragments that have been rubbed together, producing by their attrition the finer grains that are mingled with the mica in the groundmass. This mica, in all probability muscovite, is in exceedingly large quantities. It occurs as tiny colorless spicules and fair-sized plates, forming a matted felt, in whose meshes are tiny grains of quartz. The mica fibres penetrate the borders of the larger quartz grains like those in the green quartzite described above, so that the outlines of all grains are exceedingly ragged.

A very noticeable feature in the schistose quartzites at the Falls of the Sturgeon River is the presence of large pieces of a brown-blue tourmaline, idiomorphic in cross section. These are found only in the mica-quartz matrix. They are much larger than the components of this matrix and were evidently formed after them. They possess the characteristic sponge-like or cellular structure of contact minerals, and are distributed indiscriminately in the rock without respect to its schistosity.

The schistosity, which is so noticeable in some hand specimens of these rocks, is not a marked feature of the thin sections. It is produced by the arrangement of a small majority of the mica flakes in parallel positions and the elongation of a few of the quartz grains in the same direction.

DOLOMITIC QUARTZITE.

The dolomitic quartzites are intermediate in character, as they are intermediate in position, between the normal quartzites below them and the dolomite of the Randville formation above them.

In its upper portions the cement between the quartz grains of the quartzites is often dolomitic. This carbonate constituent increases in quantity as the overlying dolomite is approached, until the rock becomes a dolomitic quartzite and finally a quartzose dolomite. In the hand specimen the carbonate phases may usually be easily distinguished from the normal quartzites by their porosity. Where the rock has not been exposed to the weather for any great time it is quite compact, but on its exposed surface may be detected numerous little pits that have resulted from the solution of the carbonate cement from between the quartz grains. When the weathering has been more profound the rock has lost its compactness and is now a friable mass of loosely cohering sand grains.

In thin sections the dolomitic quartzites consist of quartz grains lying in a dolomitic cement. They present no specially noticeable features. The presence of these rocks at the top of the Sturgeon formation points to a gradual deepening of the waters in preparation for the succeeding deposition of the Randville dolomite.

VEINS AND DIKES IN THE QUARTZITE.

In general the Sturgeon quartzite is devoid of intersecting rock masses. However, in the close folds already referred to as existing in the northeast portion of T. 40 N., R. 30 W., and southwest portion of T. 41 N., R. 29 W., the quartzite is much fissured by quartz veins of various widths, which in some places are so numerous and close together as to form a breccia of quartzite fragments in a quartz cement. Some of these quartz veins contain small quantities of free gold, as does also the quartzite in their vicinity. An attempt was made a few years ago to work them, but the venture was not profitable and was therefore abandoned.

In this portion of the quartzite area intrusions of a dark-colored diabase are also very prominent. They occur as narrow dikes traversing the quartzite and the underlying gneiss, and also as boss-like masses partially surrounded by the quartzite, or as small isolated knobs separated from one another and from neighboring quartzite ledges by stretches of surface free from exposures.

At one other place, near the south quarter post of sec. 6, T. 39 N., R. 28 W., the conglomerates and quartzites are cut by a very large dike of coarse-grained, black gabbro that extends across the contact between the two rocks nearly at right angles to the strike of the quartzite and traverses nearly the entire breadth of this formation.

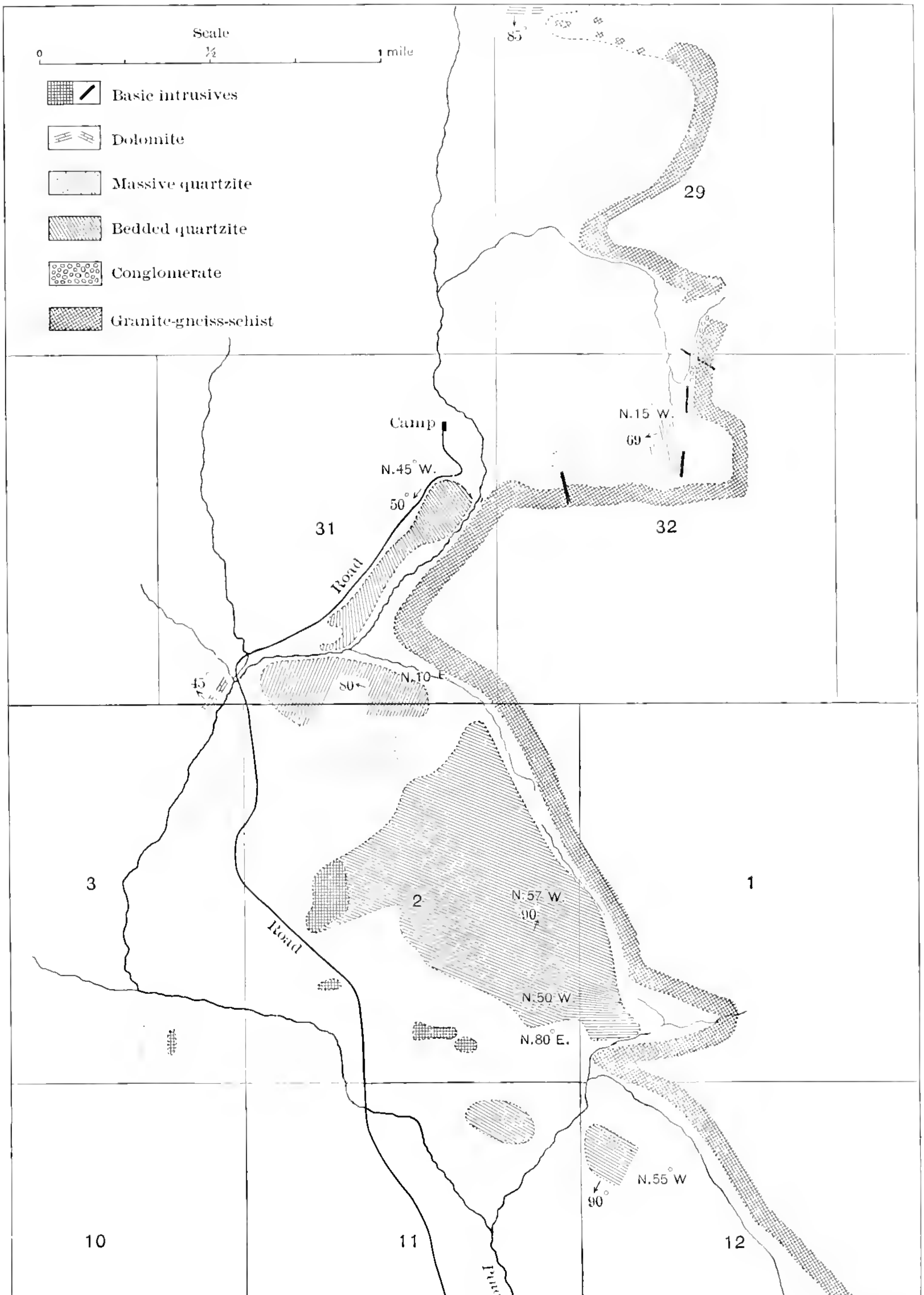
At no other places were intrusives noted in the quartzite.

FOLDING.

Except for a slight divergence of strike in the quartzite beds outcropping in sec. 7, T. 39 N., R. 28 W., there is no certain indication of folding in the entire quartzite belt from its eastern end in sec. 9, T. 39 N., R. 28 W., to the point in the southeast quarter of sec. 2, T 40 N., R. 30 W., where it turns north into the Calumet trough. In all this distance the beds are practically monoclinal, with dips varying between 65° and 90°. Moreover, there are nearly as many dips northward toward the granite-gneiss complex as there are southern dips away from it. In the northeast quarter of sec. 7, T. 39 N., R. 28 W., however, there is a large, bare knob of quartzite showing a slight divergence in the beds, which indicates that cross folding has taken place to some extent. The general strike of the bedding is N. 65° W. (25° N. of W.), but in the southeast portion of the knob the strike is N. 75° E. (15° S. of W.), a variation of 40° from the general strike. Furthermore, the general dip of the rock is 75° to 90° N., while the dip of the beds striking S. of W. is 70° S. These observations are not sufficient to establish the nature of the fold at this place, but they are significant in that they point to the possible existence of close folds in the series.

So far as can be inferred from the distribution of the quartzite, the formation constitutes the north limb of a synclinal fold pitching westward. Its southern limb would normally appear adjacent to the Quinnesec schists along the Menominee River, but this was apparently removed by erosion in the interval between Lower Menominee and Upper Menominee times.

At the western end of the district, in the southeast quarter of sec. 2, T. 40 N., R. 30 W., the quartzite turns northward, wrapping around the Archean complex and then passing eastward into the area of the Calumet trough (see Pl. XIV). In the 3 miles occupied in the turn from the



SKETCH MAP OF EXPOSURES NEAR THE CONTACT BETWEEN THE STURGEON QUARTZITE AND THE ARCHEAN COMPLEX, IN T. 40 N., R. 30 W., AND T. 41 N., R. 29 W.

Menominee trough into the Calumet trough the margin of the quartzite is made up of three salients and four reentrants. The salients extend eastward into a corresponding number of embayments in the gneiss-schist complex. The quartzite is evidently closely folded, the salients consisting of synclines and the reentrants of anticlines, but the rock is so massive that dips and strikes are not easily recognized. It is plain, however, from a consideration of those observed, that the synclines pitch steeply to the west, for the points from which the platted strikes diverge—i. e., the apexes of the folds—are at some distance east of the western limits of the Archean rocks and necessarily above their present surfaces.

THICKNESS.

In the attempt to calculate the thickness of the quartzite we are met by two difficulties. The first is the impossibility of deciding how much of its apparent thickness is due to the duplication of beds. At one place we have seen that duplication is probable. Whether there is a repetition of the same beds in other portions of the belt or not we can not be certain. A second difficulty arises from the fact that we are unable to fix definitely the upper limit of the formation.

If we assume that the southward-facing cliffs which so frequently 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 thickness of the quartzite may be easily calculated at a number of places. At the gorge below the Falls of the Sturgeon River in the northeast quarter of sec. 8, T. 39 N., R. 28 W., is a continuous exposure of conglomerate and quartzite beds about 350 paces in width. For 300 paces the walls of the gorge are in even-bedded quartzite, striking N. 57° W. and dipping 75° to 83° N. An inspection of these beds reveals no indication of folding. The formation in its entire width appears to consist of consecutive beds. The thickness corresponding to this width, calculated at an average dip of 80°, is 915 feet. Approximately the same result is reached from measurements made on the east side of the river a few hundred feet from the river bank. Here the breadth of the formation is 400 paces and its dip 70° N. The corresponding thickness is about 1,050 feet.

A third estimate is based on a series of fine exposures in the south half of sec. 1, T. 39 N., R. 29 W. At this place the quartzite has a very regular bedding, striking N. 65° W. and dipping 87° S. The beds are beautifully ripple marked and this ripple marking is so perfectly preserved that it is very difficult to believe that the beds have ever been subjected to such close folding as would be necessary to produce in them a uniform dip throughout their entire breadth. The width of the belt measured across the strike of the quartzite from the edge of the granite-gneiss, about 150 paces north of the most northerly ledge of quartzite, to the cliff bordering the quartzite on the south, is about 500 paces. The equivalent thickness would be about 1,250 feet.

These are the only places at which the conditions are favorable for the measurement of the thickness of the formation. It is probable that its thickness, like that of sedimentary formations elsewhere, varies in different places, but it seems safe to presume that the above figures represent a fair average and that its maximum thickness is between 1,000 and 1,250 feet.

RELATIONS TO UNDERLYING FORMATIONS.

The fact that conglomerates occur at and near the base of the Sturgeon quartzite has already been mentioned, and the locations at which some of them occur have also been referred to. These basal conglomerates contain almost every variety of fragment derivable from the rocks of the Northern Complex. Moreover, the material of the fragments exhibits the same secondary structures as are noticed in the Archean rocks. Plainly, then, the Archean had reached its present condition before the conglomerates were laid down. Furthermore, some of the Archean rocks must have been formed at great depths in the earth. Therefore the Archean area must have suffered deep-seated denudation before the deposition of the quartzite. The presence of the conglomerates, then, is evidence of the existence of a great time interval between the production of the granite-schists complex and the overlying Sturgeon quartzite. A consideration of the character of the matrix of the conglomerates points to the same conclusions. The matrix consists largely of the débris of granites, gneisses, and basic schists; or, in other words, of sand and silt such as would be produced by denudation of the Archean complex.

Contacts of the Sturgeon quartzite with the underlying rocks are very rare. They are found only where the conglomerates are present. In these cases the schistosity of the conglomerates is discordant with that of the subjacent gneisses and schists. At most places there is a topographic depression between the two formations, due, no doubt, to the relative ease with which the conglomerates, arkoses, and graywackes are eroded as compared with the adjacent granites and schists on the one side of them and the pure quartzites on the other. The quartzites on the south of the break, however, sometimes strike directly toward the boundary of the granite-gneiss complex. This may indicate an unconformity between the two series.

INTERESTING LOCALITIES.

Although the quartzite formation is well exposed throughout nearly its entire extent, there are several localities where the exposures are of special interest, either because of the relations shown in them or because of the fine expanse of rock surface they exhibit.

The "rock dam" on Pine Creek.—One of the best places at which to study the quartzitic phase of the formation is in sec. 2, T. 40 N., R. 30 W., and secs. 31 and 32, T. 41 N., R. 29 W. (Pl. XIV). Here is found the greatest expanse of quartzite occurring anywhere in the Menominee district, and the wildest and most picturesque scenery. Precipices, crags, and gorges abound everywhere. The precipices are so steep and the gorges so narrow that the snow-white bluffs appear much loftier than they actually are. Moreover, the effect of the roughness of the country on the observer is much heightened because of the great contrast between it and the flat sand plains and rounded sand hills over which he must travel to reach the quartzite area.

The quartzite forms a few high, bare bluffs, with precipitous sides and broad, flat tops, and numerous lower and smaller hills, often with uneven tops. From their eastern limits bare bluffs of black, pink, and gray Archean rocks extend eastward for long distances. To the west the bluffs end abruptly, and a comparatively level sand plain, dotted with low, rounded sand hills, stretches from their bases and gradually rises into a series of smoothly rounded elevations in the distant west.

The boundary line between the quartzite and the Archean rocks, unlike this boundary elsewhere, consists of curves with broad crests turned eastward toward the Archean complex, and sharp crests turned westward toward the quartzite. The former have already been explained as due to synclines and the latter to anticlines in the quartzites.

The principal rock of the bluffs, as has been intimated, is a white saccharoidal or vitreous quartzite. This is so heavily bedded that only occasionally can strikes and dips be observed in it. Where they can be measured they are found to vary in such a way as to prove the existence of folds with westward-pitching axes. The dips vary between 50° and 90°, and are always directed to the south or west, or to some point of the compass between west and south. The strikes vary greatly. Near the southeast corner of sec. 2, T. 40 N., R. 30 W., the strike of a definitely bedded quartzite is N. 50° W. Near the east quarter post, sec. 31, T. 41 N., R. 29 W., it is N. 45° W. Near the south quarter post of the same section it is N. 10° E., and about one-fourth mile south of the north quarter post, sec. 32, T. 41 N., R. 29 W., it is N. 15° W. However irregular these dips and strikes may seem at first thought, they are nevertheless distributed in accordance with the view suggested as to the structure of the formation at this place.

One of the most striking of the quartzite bluffs is that in sec. 2, T. 40 N., R. 30 W. It is a bare, rough knoll whose southern face is an almost vertical cliff rising about 40 feet above the bed of a small stream that separates the quartzite from the adjacent gneisses and schists. Farther west the cliff is less nearly vertical, but it rises to greater heights. As at this place, so nearly everywhere else in this portion of the district, the quartzite and the granite-gneiss complex are separated from one another by topographic breaks in the shape of narrow valleys. These are often but 20 to 100 paces wide, have precipitous sides, and are usually occupied by the channel of Pine Creek or some one of its tributaries. At several places the streams turn abruptly from the contact valleys and cross the quartzite bluffs, producing in them likewise narrow gorges. The best example of one of these cross gorges is about 300 paces north of the south quarter post, sec. 31, T. 41 N., R. 29 W., where the main stream of Pine Creek runs for a short distance across the strike of the quartzite between walls that rise nearly 100 feet precipitously from the stream's banks. This place is known locally as the "rock dam." The rock on the weathered surface of the bluffs through which the gorge is cut is brilliantly grayish white and very massive, only here and there exhibiting any signs of bedding. When the bedding is noticeable the beds are seen to be nearly on end. Two dominant sets of joints traverse them, both of which are vertical. One set runs parallel to the creek, i. e., about east and west, and the other is at right angles to this, in places apparently following the bedding. It is the opening up of one of the former by the stream that produced the gorge at the rock dam. Besides these two vertical systems of joints there is a marked sheeting or schistose structure to the quartzite which dips to the west at low angles (8° to 10°). The structure produces layers from 1 to 2 feet across, separated from one another at intervals by joints. They are so distinct that they might easily be mistaken for beds. This apparent bedding is no doubt due to differential movement parallel to the axis of a large fold. The rock at this place is near the top of an anticline plunging to the west. Accommodation must have taken place parallel to this direction with resulting schistosity along the zones of rock movement. This structure must have been produced at a time when the rock was heavily loaded. The joints may have been formed later.

The quartzite is cut by many white quartz veins of all sizes up to 20 feet in width. Some of them follow the jointing systems in direction, while others cut the rock irregularly. In some of these gold has been discovered.

Although the quartzite phase of the formation is so well developed in this vicinity, its feldspathic phases, characteristic of the lower horizons, are notably absent except at one place. They were no doubt originally present in the interval now occupied by the little valleys between the quartzite and the Archean schists. The only remnants of these beds still remaining are to be found near the north quarter post of sec. 32, T. 41 N., R. 29 W. Here a well-defined conglomerate composed of rounded fragments of granite and gneiss, with diameters ranging from the fraction of an inch to 1½ feet, lying in a dark-gray schistose matrix, occurs in patches adhering to the almost vertical face of a cliff of Archean gneiss. The strike of the schistosity and banding of the gneiss is N. 15° E. That of the corresponding structures in the conglomerate is parallel to the trend of the cliff, which varies from due north–south to nearly east–west. (See Pl. XIV and fig. 13.) While the variation in the strike of the schistosity of the two rocks may not in itself necessarily prove the existence of an unconformity between them, the presence of large bowlders of the gneisses in the conglomerate is undoubted evidence that the former rocks had been subjected to wave action before the conglomerate was formed.

The conglomerate and the gneiss are cut by a dike of dark, almost black, diabase trending about northwest. Across a little valley the same dike can be traced into a ledge of quartzite, where the contrast in color between the two rocks is very strikingly brought out. Again, farther south, there is a large dike of the same rock trending nearly north–south. This dike is just west of the one of the larger exposures of conglomerate, which

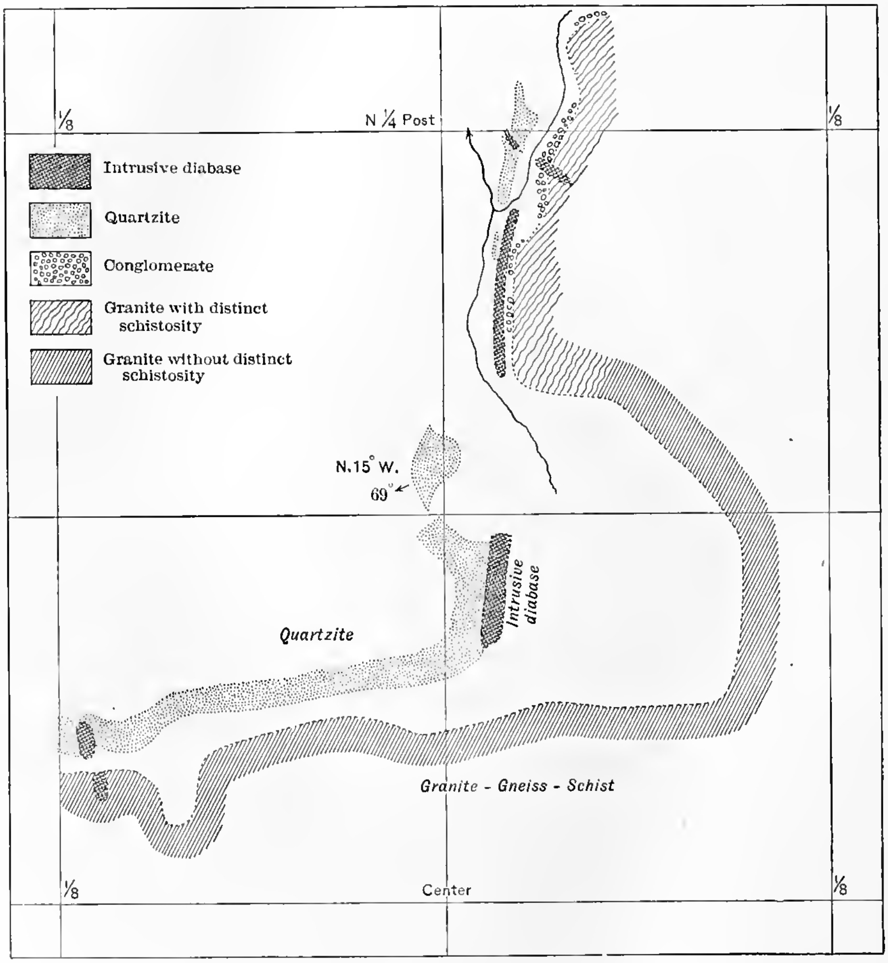


Fig. 13.—Sketch map of exposure in north half of sec. 32, T. 41 N., R. 29 W., showing relation between conglomerates and gneisses. Scale: 1 inch = 660 feet.

thus lies between the igneous rock on the one side and the gneiss on the other, a position which has protected it from rapid erosion.

Farther south, especially in sec. 2, T. 40 N., R. 30 W., several other masses of the diabase occur. These, however, do not possess the dike form of the more northerly masses. They appear as small, isolated knolls rising above the sands, except in one instance, where the rock forms a huge black boss-like mass in contact on the east with beds of snow-white quartzite. The parti-colored knob formed of the two rocks can easily be seen from the road leading to the "rock dam." It is a prominent object in the landscape viewed from the south and southwest, even at distances of several miles.

Before leaving this portion of the district it might be well also to refer to one other exposure which may be considered as representing the upper members of the Sturgeon formation, though more properly belonging among the outcrops of the next higher formation, the Randville dolomite. The ledges are near the northeast corner of sec. 3, T. 40 N., R. 30 W., and near the southwest corner of sec. 31, T. 41 N., R. 29 W., about 300 paces west of the nearest exposure of the normal quartzite. They constitute a little cliff overhanging the flood plain of Pine Creek. The top of the elevation of which the cliff forms the eastern escarpment is covered with sand, and both ends of the cliff face also disappear under deposits of sand and bowlders. On the face of the cliff, however, the rocks are well exposed for a distance of about 200 paces. They are noticeably different from the normal quartzite, even when viewed from the road. They weather with a rough sandy surface and rounded edges, whereas the quartzite weathers with smooth surfaces and sharp edges. Moreover, they are distinctly bedded and plainly folded. When examined closely the cliff is seen to be made up of a calcareous quartzite containing a few thin cherty layers and in the upper horizons a few layers of red slate. The lowermost exposed layers are comparatively flat lying, but the upper layers are in a series of westward-pitching folds, some of which are completely recumbent. The strikes and dips are therefore very different in different parts of the ledge. Opposite the bridge over Pine Creek, for instance, the strike is N. 55° E. and the dip 45° northwest. About 50 paces south of this point the strike is N. 20° E. and the dip 20° west, and about 100 paces farther south the strike is N. 40° W., and the dip 45° southeast. The weathered surface is ridgy with alternate elevations and depressions about one-half inch to 1 inch in width, produced by differential weathering of alternate layers that are usually inclined to the bedding. Along these layers differential movement has taken place, the alternate laminæ thus becoming more or less schistose. The more schistose layers representing zones of weakness were weathered more rapidly than the others and determined the position of the depressions in the surface. These laminæ, like the bedding layers, are likewise folded into minor plications, some of which are clearly recumbent folds.

Black Creek.—About 250 paces north of the south quarter post of sec. 6, T. 39 N., R. 28 W., a small stream known locally as Black Creek, falls in a little cascade over a ledge composed partly of granitoid gneiss and partly of conglomerate (see map, fig. 14). The gneiss is of the usual character. The conglomerate is made up of round and angular fragments of the gneiss strewn thickly through a matrix composed of the fine detritus of the same rock. So nearly alike are they in general appearance that at a casual glance it is difficult to distinguish between the original rock and the recomposed phase.

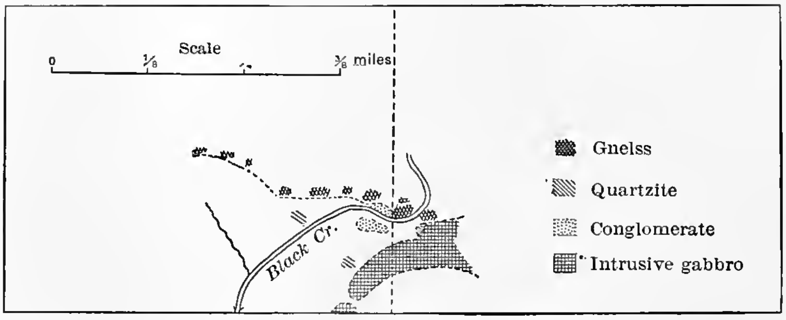


FIG. 14.—Sketch map of exposures on Black Creek, in S. ½ sec. 6, T. 39 N., R. 28 W., showing relation of conglomerate to gneisses.

Associated with the conglomerate are a few beds of a banded rock that strike N. 55° W. and dip nearly vertical. This is plainly fragmental and is like the groundmass of the conglomerate. A few hundred paces west is a small ledge of white vitreous quartzite and about the same distance southwest is another of the same rock. Neither show any special peculiarity.

The contact between the gneiss and the conglomerate is not well enough exposed to give any very clear idea of the structural relations existing between, but of course there can be no doubt that the latter is much younger than the former.

Cutting through gneiss, conglomerate, and quartzite is a great dike of medium- to coarse-grained black gabbro. In the gneiss it appears as an ordinary dike whose upper surface is flush with the surface of the surrounding rock. As it crosses the conglomerate it forms a prominent knob. From this point it continues southwestward as a ridge of knobs, with occasional quartzite exposures on their flanks.

It is to be noted here, as at the rock dam, that the conglomerate which remains is in a position where it was protected by a mass of igneous rock.

North half of sec. 7, T. 39 N., R. 28 W.—Southeast of the exposures described in the foregoing paragraph the quartzite forms a belt of cliffs and bluffs that extends for over a mile and a half through secs. 6 and 7 without interruption except at one place where it is trenched by the Sturgeon River (fig. 15). Near the north quarter post of sec. 7 the quartzite is intruded by the great dike of gabbro already referred to in connection

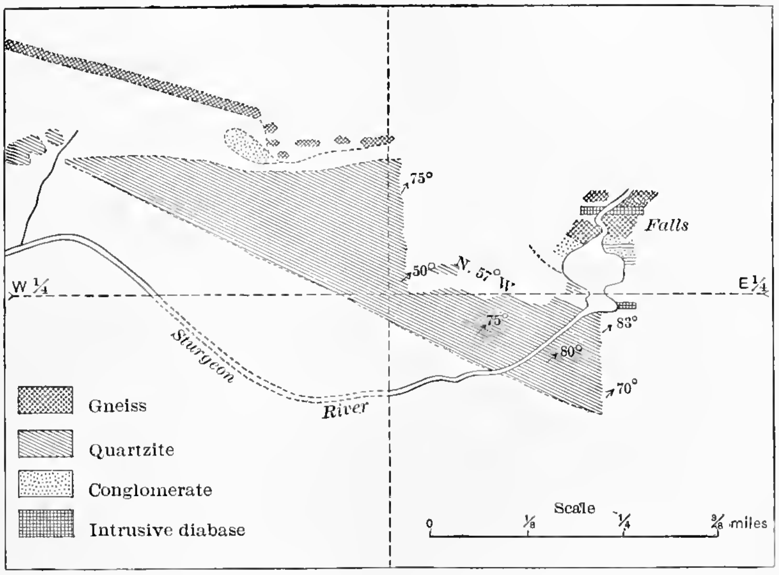


Fig. 15.—Sketch map of exposures at and near the Falls of the Sturgeon River, sec. 8, T. 39 N., R. 28 W.

with the conglomerate of Black Creek. East of this the quartzite constitutes a long, narrow hill with a very steep south side overhanging the swampy flood plain of the Sturgeon. On the north the declivity is less steep but very rugged. The rock is the typical white vitreous quartzite. It is nowhere in contact with the granite, a space of about 200 paces devoid of exposures usually separating the two rocks. The bluff is interesting from the fact that it exhibits strikes and dips so distributed as to suggest close folding in the beds of which it is composed. Northwest of the main bluff are several ledges near the gabbro, in which the bedding strikes N. 55° W. and dips 87° north The main bluff is roughly triangular in outline, the western end being about 300 paces wide and the eastern end, where the east line of the section crosses it, measuring only about 100 paces in width. On the south side of the hill, in its eastern part, the rock in the cliff overlooking the river strikes N. 75° E. and dips 75° south, whereas the beds on the north side strike N. 60° W. and dip about vertically. Thus at the eastern or narrow portion of the bluff the variation in strike between the beds on its north and south sides is about 45°. Toward the west the strike of the southern beds turns gradually to the north, and at the west end of the hill its entire width is made up of a series of parallel beds striking uniformly about N. 35° W.

West half of sec. 8, T. 39 N., R. 28 W.—In a hill east of the one just described quartzite is again beautifully exposed in well-bedded, though massive, layers striking about N. 60° W. and dipping 50° to 75° north. (See map, fig. 15.) This hill, like the northwesterly one, is precipitous on both north and south sides. To the north of it is the granite-gneiss complex forming an assemblage of hillocks which in some places terminates in a southward-facing cliff and in others ends in a series of isolated hillocks of comparatively slight elevation. In two or three places the schist formation and the quartzite formation are practically in contact, being separated by a distance of only a few inches. The rock on the south side of the contact plane is a well-characterized conglomerate. It is exposed in a small knoll about 125 paces long and 50 paces wide at 1,400 paces north and 1,350 paces west of the southeast corner of the section. The knoll is practically isolated from the ledge of white quartzite to the south and the gneissoid-granite ledges to the north. At one place the conglomerate and granite are in contact, but the contact line is so short and the relations between the two rocks are so obscure that nothing can be learned from it. The composition of the conglomerate, however, is such that no doubt can arise as to its meaning. It consists largely of granite and gneiss bowlders in a matrix composed of the débris of the same rocks.

Falls of the Sturgeon.—The granites and quartzites so well exposed in the western half of sec. 8, T. 39 N., R. 28 W., continue eastward in almost unbroken ledges to the Sturgeon River and a short distance beyond. Where the river crosses them occur the falls and the gorge, made classic by the discussions of Credner, Brooks, Rominger, Irving, and others. The falls are over granitoid gneisses (fig. 15). Below the rapids at the foot of the falls is an open basin of comparatively smooth water flanked on both sides by conglomerates and arkoses, and below this, again, is a narrow rapids about one-eighth mile long, in a gorge bordered by an almost unbroken ledge of heavily bedded white quartzite, striking N. 65° to 67° W., and dipping about 70° to 80° northeast. There is a fairly good trail on the east side of the river that runs along the side of the cliff at about 20 feet above the water's edge. The way is rough and broken, but the trip over the trail gives an excellent opportunity for examining the walls of the gorge on both sides of the river. Throughout the entire length of the gorge the quartzite is of the same general character, except at its north end. Here the rock is schistose and has developed in it a considerable quantity of sericite, in this respect being like the matrix of the conglomerates on the contact with the granite. Everywhere in both cliffs the quartzite beds are conformably stratified, no indications of folding being observed anywhere.

It will be remembered that Credner described the conglomerates as occurring interbedded with micaceous and hornblendic rocks. He mentions the existence, in the midst of the granite-gneiss series, of several hundred feet of a complex consisting of thin-bedded talcose and sandy schists, the latter being ripple marked, a thin layer of protogine-gneiss, and three beds of conglomerate, each 30 feet in thickness, in which were found pebbles of gneiss, granite, and quartzite embedded in a talcose sandy groundmass. The conglomerate was thought to be overlain by gneiss. All these rocks he regarded as Laurentian (see pp. 51–53).

Brooks, in his first report, described the same conglomerates and the rocks associated with them as a series of soft, light-gray, talcose slates, underlain by four beds of conglomerate, which in turn are underlain by two beds of protogine-gneiss separated by a bed of chlorite-schist. Their precise age he was not able to make out, though he declared that the conglomerates separate unquestionably Laurentian beds from those that are certainly Huronian (see p. 58).

In his second report he described the sequence at the falls and concluded that "the structural facts, in connection with the strong lithological affinities which the schist-conglomerate series bear to the Huronian, and the still more important fact that the pebbles contained in the conglomerate are unmistakably Laurentian, leave no question in my own mind but that the rocks under consideration are Huronian and form the base of the series at this point." (See pp. 66–67.)

Next Rominger described the succession of beds in the vicinity of the falls with great care. The conglomerate he described as having a sericitic schistose matrix, identical with certain sericitic schists that are interbedded with ripple-marked feldspathic beds. These he thought to be in "conformable contiguity" with the granites to the north. The author's explanation of the phenomena is given in the following words: "We have here, evidently, a series of sedimentary beds deposited on a granitic substratum, which during the upheaval became wedged in between the plastic granite mass, tilting and overlapping them locally so as to appear the lower beds" (see p. 75).

Irving corroborated Brooks's observations concerning the nature of the conglomerate and agreed with him as to its signification. He found the conglomerates to consist of granite fragments in a fine-grained sericitic slaty rock which at times looks like a crystalline schist. The granite sheet described by Rominger as interleaved with the conglomerates could not be found. The character of the rock was clear evidence to Irving that "we have here to do with a detritus derived by water action from the granitic and gneissic area immediately to the north. The slight inclination from the vertical toward the granite which these conglomerate schists sometimes show is, of course, no argument against their having been deposited upon the granite as a substratum" (see p. 94).

A careful examination of the rocks exposed along both sides of the gorge below the falls will show clearly that Brooks and Irving are correct in their conclusions. Beginning at the falls and passing southward on the west side of the stream we find at the falls themselves the usual granite-gneiss complex cut by a great greenstone dike, which forms a southward-facing cliff, at the base of which is a small patch of conglomerate. South of this, across a valley about 80 paces wide, we next find a schistose sericitic quartzite which passes gradually to the south into the normal white vitreous quartzite striking N. 57° W. and dipping 80° to 83° north.

On the east side the sequence is much fuller. We have again at the falls a mass of gneissoid granite, cut by greenstone, forming a small cliff at whose base is conglomerate. The banding of the gneiss strikes N. 80° W., forming an acute angle at its contact with the conglomerate. This is filled with fragments and bowlders identical in character to the gneiss at the falls.

South of the conglomerate is a narrow bed of quartzite followed in succession by conglomerate, fairly massive pink arkose, a gray micaceous quartzite traversed by veins of red feldspar, and another bed of pink arkose, the whole having a width of about 50 steps. The last of these is well exposed on the north side of the wide basin below the contact. For the next 100 steps, along the east side of the basin, there are no exposures, but on its south side is the eastward extension of the light-gray sericitic quartzite already mentioned as occurring on the west side of the river. This rock forms a little point separating the larger basin below the falls from a smaller one still farther south. On the east side of this southern basin is a ledge of massive greenstone, and on its south side is the northern edge of the great exposure of quartzite which stretches about 300 paces southward. The strike of the quartzite is N. 65° W. and its dip 70° N. The interbedded quartzites and conglomerates to the north strike N. 70° W., and dip 80° N. Their schistosity, on the other hand, strikes N. 55° E.

There can nowhere be discovered on either side of the river any evidence of the existence of granite beds south of the northernmost exposure of conglomerate. All of the rocks south of this point are unquestionably fragmental, except, of course, the intrusive greenstone, and all of them appear, without doubt, to have been derived from rocks like those in the granite-gneiss complex. In the ledge some of the arkoses interstratified with the conglomerates look quite like fine-grained gneisses, but in thin section under the microscope their fragmental character is very plain in spite of their schistose structure. It is these beds, very likely, that Credner regarded as gneisses and talcose schists.

The conglomerate grades upward through the arkoses and graywackes into schistose quartzite and through these into the massive vitreous quartzite of the gorge. During the folding of the series readjustments took place along a zone bordering the contact with the underlying granites and as a result of the consequent shearing we find the conglomerates and other rocks near the base of the series schistose, while the quartzites at a greater distance from this contact are practically massive. Moreover, at the lower horizon the series consists of several kinds of beds varying in hardness and rigidity, whereas the quartzites comprise a set of beds of the same kind. It is a well-recognized fact that readjustments during the process of folding are much more apt to take place between beds of different characters than in a series of uniform character.

RANDVILLE DOLOMITE.

Next in order above the Sturgeon quartzite is a thick series of beds among which dolomitic layers predominate. This series is identical in character with a similar series in the Felch Mountain district known as the Randville dolomite. It is, morever, in the same geological position as the latter, and hence is regarded as its continuation into the Menominee district. It has therefore been designated by the same name.

DISTRIBUTION AND TOPOGRAPHY.

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.

The northern belt lies immediately south of the belt of Sturgeon quartzite, and presumably along nearly its entire extent from sec. 3, T. 40 N., R. 30 W., to sec. 8, T. 39 N., R. 28 W. Only a few exposures have been seen, but they are widely distributed through the area. The easternmost one is a calcareous or dolomitic quartzite outcropping on the south bank of the Sturgeon River a few hundred paces south of the center of sec. 8, T. 39 N., R. 28 W. It is an obscure ledge, almost hidden by the sandy detritus produced by its disintegration. The next western exposures discovered are located in a swamp, about 400 paces south, 200 paces east of the north quarter post, sec. 33, T. 40 N., R. 29 W. This location is 5½ miles distant from the first ledge. The exposures are two in number, but they are so close together that they may be considered as parts of a single one. The rock is a friable quartzite with a carbonate cement, interbanded with a few cherty layers. The third group of ledges is in the southeast quarter of sec. 11 and the northeast quarter of sec. 14, in T. 40 N., R. 30 W. It comprises five independent exposures outcropping from the sides of the valley of the little stream that empties into Pine Creek at Hamilton and Merryman's camp No. 6, near the line between secs. 11 and 14, T. 40 N., R. 30 W. They extend in a line running about southeast for 800 feet, thus giving a good section across the formation. A dolomitic marble and dolomitic quartzite constitute the northern ledges, crystalline dolomites the intermediate ones, and cherts the southernmost one. The fourth and last exposure belonging in this belt is that already referred to as occurring in the northeast quarter sec. 3, T. 40 N., R. 30 W. (see p. 193).

In the country between these groups of exposures no ledges of any kind have been discovered, but a pit in the northeast quarter of the southwest quarter of sec. 7, T. 39 N., R. 28 W., and several drill holes farther west (see p. 405) encountered cherty quartzites and dolomites belonging to the formation north of the jaspers and ores of the Appleton location. It is probable that the formation continues uninterruptedly between its known occurrences, except for a possible break in sec. 34, T. 40 N., R. 29 W., The whole belt with this exception has therefore been colored for the formation on the map (Pl. IX). It is quite possible, however, that in the intervals between the ledges erosion has carried away the dolomite and that the Upper Huronian rests immediately upon the Sturgeon quartzite. The mapping of sec. 34, T. 40 N., R. 29 W., is in accordance with this view.

The country underlain by the northern belt of dolomite is now the valley of Pine Creek. It is a low plain, covered by sand, which has been partly deposited by the creek and partly by glaciers. It was a valley long before the advent of the glaciers, and there is some evidence indicating that there was a valley in this place even before the deposition of the Cambrian sandstone. The long-continued erosion produced by Pine Creek and its ancestors has reduced the area to one of low relief. The topography is very different in character from that of the other dolomite areas in the district, which correspond to divides, and thus are elevations rather than depressions.

THE CENTRAL BELT.

The central belt of dolomite borders the north side of Lake Antoine for a portion of its length, passes eastward between the Cuff and the Indiana mines and north of the Forest mine, and terminates at the bluff known as Iron Hill in the northeast quarter of sec. 32, T. 40 N., R. 29 W. The belt is well marked in places by numerous and often large exposures, but, as in the area just described, the exposures are not continuous. The intervals between them are sometimes covered by deep deposits of soil, but more frequently they are occupied by the Lake Superior sandstone, which completely blankets the underlying rocks. Fortunately, however, there has been some exploratory work done along the belt, and this has shown in several places the existence of the dolomite beneath the surface. Consequently on the map the color of the dolomite formation is made to cover a continuous belt from the known westernmost occurrence of the rocks belonging in it to the easternmost known occurrence at Iron Hill.

The known occurrences of the dolomite and other rocks belonging to the formation along this belt are as follows: A tunnel and drill hole near the quarter post between secs. 20 and 21, T. 40 N., R. 30 W., which runs north into the hill for a distance of about 800 feet all in dolomite; a group of bluffs stretching for about one-half mile through the southeast quarter of sec. 21 and the southwest quarter of sec. 22, T. 40 N., R. 30 W., and a test pit in chert just south of these; a "horse" of white dolomite in the first level of the Cuff mine; a small ledge of the same rock on the south side of the track of the Escanaba and Iron Mountain Railroad (Chicago and Northwestern) about 1,000 feet east of the north quarter post of sec. 27, T. 40 N., R. 30 W.; dolomites and red slates in the shaft of the Federal exploration near the southeast corner of sec. 22 in the same town; dolomites and red slates in the drill holes near the Indiana mine, and in the workings of this mine; red calcareous slates in the dump piles of two test pits on the north side of the Escanaba and Iron Mountain Railroad track near the line between secs. 26 and 27, T. 40 N., R. 30 W.; two ledges of dolomite a short distance west of the Forest mine near the center of sec. 25, T. 40 N., R. 30 W.; one ledge and a pit exposing the same rock near the center of the southeast quarter of this section; and, finally, the numerous large exposures running through the east half of sec. 32, T. 40 N., R. 29 W.

The only stretches of any considerable length over which the formation is shown on the map without direct evidence of its existence beneath the surface are: (1) The three-fourths of a mile between the west line of sec. 21, T. 40 N., R. 30 W., and the road to Hamilton and Merryman's camp, which runs through the center of the southeast quarter of this section; and (2), the 2½ miles between the west line of sec. 23, in the same town, and the exposures near the Forest mine in the eastern portion of the southwest quarter of sec. 25, T. 40 N., R. 30 W.; and (3), the 1½ miles between the exposures in the southeast quarter of the last-named section and those in the center of sec. 32 in the town east.

In these intervals the surface rock is the Lake Superior sandstone. This occupies most of the areas between the known dolomite occurrences, and, together with the drift covering, prevents access to the underlying Huronian rocks. The sandstone, however, has been test-pitted in many places, and in the bottoms of the pits the rock is often discovered to be a conglomerate containing many bowlders of dolomite and dolomitic chert, or light-colored sandstone containing an abundant dolomitic cement. In either case the inference is strong that the dolomite is near at hand. Consequently the Randville formation is mapped as underlying the sandstone in these places.

The belt as outlined by these exposures is not known to be wider than about 870 feet at any point. This width is reached at its eastern end, at Iron Hill, and north of the Indiana mine. For a mile west of the Indiana mine it has a width of not more than 400 feet, but again, in the tunnel near the west line of sec. 21, its known width is said to be 800 feet. As a matter of fact, neither the northern nor the southern border of the belt is well defined for any great distance. At Iron Hill, at the Forest and at the Indiana mines, the position of its southern border is known, and for a mile west of the last-named mine it is known with close approximation to the truth. But only at the Cuff mine has its northern boundary been disclosed. Elsewhere it is buried under the Lake Superior sandstone.

The belt is so narrow that it has produced little effect on the topography. Through most of its extent it appears at or near the base of the southern slopes of a ridge of high hills formed of the Cambrian sandstone. Near the Cuff mine and at Iron Hill, the ledges of the formation appear as small, isolated knolls or they are grouped together, forming little plateaus with steep southern escarpments, their northern escarpments being buried under the overlying sandstone.

THE SOUTHERN BELT.

DISTRIBUTION.

The southern and most important belt of dolomite extends all the way from the western side of Prospect Bluff, west of Iron Mountain, to the village of Waucedah, at the eastern end of the area mapped. Where not exposed at the surface the rock has been found in mines and test shafts and pits, so that there is a reasonable certainty that it exists throughout this distance of 16 miles. Where theie is any doubt of its existence this is due to a considerable thickness of overlying Lake Superior sandstone.

The westernmost exposure is near the Hamilton mine in the southwest quarter of sec. 30, T. 40 N., R. 30 W., but the rock has been met with in underground workings of exploration shafts as far west as the center of sec. 25 in T. 40 N., R. 31 W. (See fig. 16.) From the Hamilton mine eastward the belt is well marked by numerous and often large exposures and by ledges discovered in exploratory and mining operations as far as the northeast quarter of sec. 18, T. 39 N., R. 28 W. Beyond this the country is destitute of exposures, but about 1,175 paces north, 600 paces west of the southeast corner of sec. 17, T. 39 N., R. 28 W., there is a small pit in the dump of which are many fragments of pink dolomite. No direct evidence of the continuation of the belt beyond this point is at hand, since the workings of

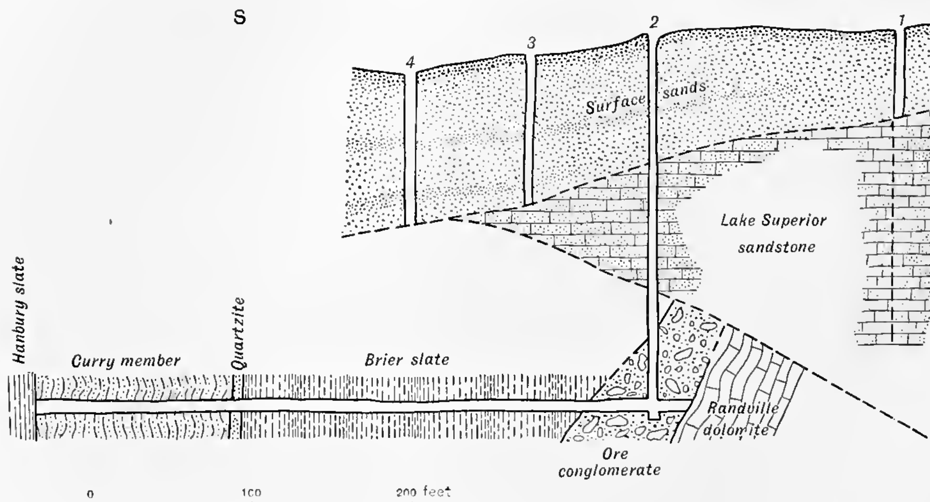


FIG. 16.—Cross section through pits and shafts near the center of sec. 25, T. 40 N., R. 31 W.

the Breen and Emmett mines have not penetrated below the iron formation, and the explorations north of these mines have nowhere exposed the rocks lying beneath the Cambrian sandstone. That the belt continues eastward uninterruptedly through secs. 18, 17, and 16, T. 39 N., R. 28 W., is, however, rendered probable by the fact that two magnetic lines that have their origin in sec. 18, one just north of known exposures of the dolomite and the other to the south of them, can be traced without break into sec. 15 of this township. These indicate that the iron formation continues eastward this far, and since the dolomite is immediately beneath the iron formation, the inference is fair that the dolomite also continues to the same distance.

The belt occupies a narrow strip of country running a little south of east through the southern portions of secs. 23 and 24, and the northern parts of secs. 26 and 25, T. 40 N., R. 31 W., and through the whole or parts of secs. 30, 29, 28, 27, 31, 32, 33, 34, 35, and 36, T. 40 N., R. 30 W.; secs. 2 and 1, T. 39 N., R. 30 W.; secs. 6, 5, 4, 3, 9, 10, 11, and 12, T. 39 N., R. 29 W.; and secs. 7, 18, 17, and 16, T. 39 N., R. 28 W.

The northern boundary of the belt is in general very indefinite. At several places it can be fairly well determined by exposures, viz, just north of the island in Lake Antoine and south of the Loretto mine, in sec. 7, T. 39 N., R. 28 W., but elsewhere it can not be definitely fixed without recourse to test pits and shafts, because it is deeply buried under the drift or is covered by thick deposits of the Cambrian sandstone. As nearly as can be determined this northern boundary is about as follows: Beginning at the Menominee River, near the east-west quarter line of sec. 23, T. 40 N., R. 31 W., it runs a little south of east to the southwest shore of Lake Antoine where it is crossed by the east line of sec. 30, T. 40 N., R. 30 W. Here it is reported to have been found beneath the surface in drill holes. From this point it continues to the southeast shore of the lake, passing just north of the island and the little knoll opposite its east end. It is mapped as passing around this knoll and running west for a short distance, then turning eastward again and continuing its south-of-east course to a point in the northwest quarter of the southeast quarter of sec. 35, T. 40 N., R. 30 W. The reentrant on the southeast shore of Lake Antoine is based solely on topography. On the little knoll east of the island the dolomite is well exposed. It is known by test pits to occur under the sandstone nearly to the base of the northern slope of the large hill to the south. Between this hill and the knoll is a narrow valley and a swamp. The contrast between it and the hills on both sides is noticeable. Since similar low ground elsewhere is known to be underlain by slates, the assumption is made that this valley is likewise carved from these rocks, and the dolomite is mapped as passing around it. From the point in the southeast quarter of sec. 35, the boundary is again supposed to make a reentrant to the west to correspond to the known salient at Quinnesec on the south side of the belt. From the end of the reentrant the line is drawn straight to about the center of the southeast quarter of sec. 3, T. 39 N., R. 29 W. Except at its eastern portion the boundary here is conjectural. Drill holes have shown the existence of dolomite near the north line of the southwest quarter of the southeast quarter of sec. 35, T. 40 N., R. 30 W., and near the northeast corner of sec. 2, T. 39 N., R. 30 W., and a pit exposes it 500 paces east of this corner in sec. 1. To the east no ledges of any rock older than the sandstone are met until the southeast quarter of sec. 3, T. 39 N., R. 29 W., is reached. Here there is a single small ledge of contorted dolomite, with its folds apparently pitching flat to the west. The boundary line is made to pass around this ledge, then to pass southwestward to the center of the southeast quarter of the southeast quarter of sec. 4 and to turn once more to the east, forming a reentrant to correspond to the dolomite salient on the south side of the belt between the Norway and the Aragon mines. From the apex of this reentrant the boundary line is again drawn straight to about the east quarter post of sec. 11, T. 39 N., R. 29 W. Here it turns northwest to a point 500 paces north of the center of this section and then eastward again skirting the north side of the dolomite ridges that stretch in almost a continuous line from this point to another just south of the Appleton mine, in sec. 7, T. 39 N., R. 28 W. The eastward-extending embayment is necessitated by the presence of 13 or more pits in slates stretching along the north–south center line of the southwest quarter of the northeast quarter of sec. 11. The boundary is assumed to be very near the northernmost ledges in secs. 11 and 12, T. 39 N., R. 29 W., because of the marked change in the topography noted here. The area to the south, known to be underlain by dolomite, possesses an undulating surface broken by numerous ledges, ridges, and hillocks of rock, while that to the north is a low, flat, swampy country in which no ledges of any kind are exposed. The continuation of the boundary eastward to the point where the belt is lost under the thick covering of Paleozoic sediments that stretch from the eastern end of the Menominee trough to Lake Michigan, is placed at a uniform distance south of the magnetic line that begins a little west of the Loretto mine and is traced with fairly good success to about the center of sec. 15, T. 39 N., R. 28 W.

It will be noted that the evidence with respect to the position of the northern border of the dolomite belt is mainly negative. There are no exposures north of the dolomite and near it that determine the limit of the belt in this direction. The boundary line is drawn close to the northernmost ledges of the dolomite where such ledges, as indicated by the topography, are plainly near the north side of the belt. Between such ledges the boundary is drawn straight except where sinuosities are clearly indicated by their existence in the south boundary. In these cases it is assumed that the belt is folded throughout its entire breadth and that these folds must find expression at its northern boundary. The only sinuosity in the north boundary indicated by the occurrence of rocks other than those belonging in the dolomite series is that extending southeastward into sec. 11, T. 39 N., R. 29 W., and this is indicated only by a row of very old test pits, on the dumps of which slates have been found. The country near this northern boundary has not been explored anywhere to a depth sufficient to reach the rocks underlying the sandstone except by the pits in sec. 11. Natural exposures of other rocks are unknown. From the foregoing it is clear that the position of the northern boundary of the dolomite must of necessity be largely conjectural.

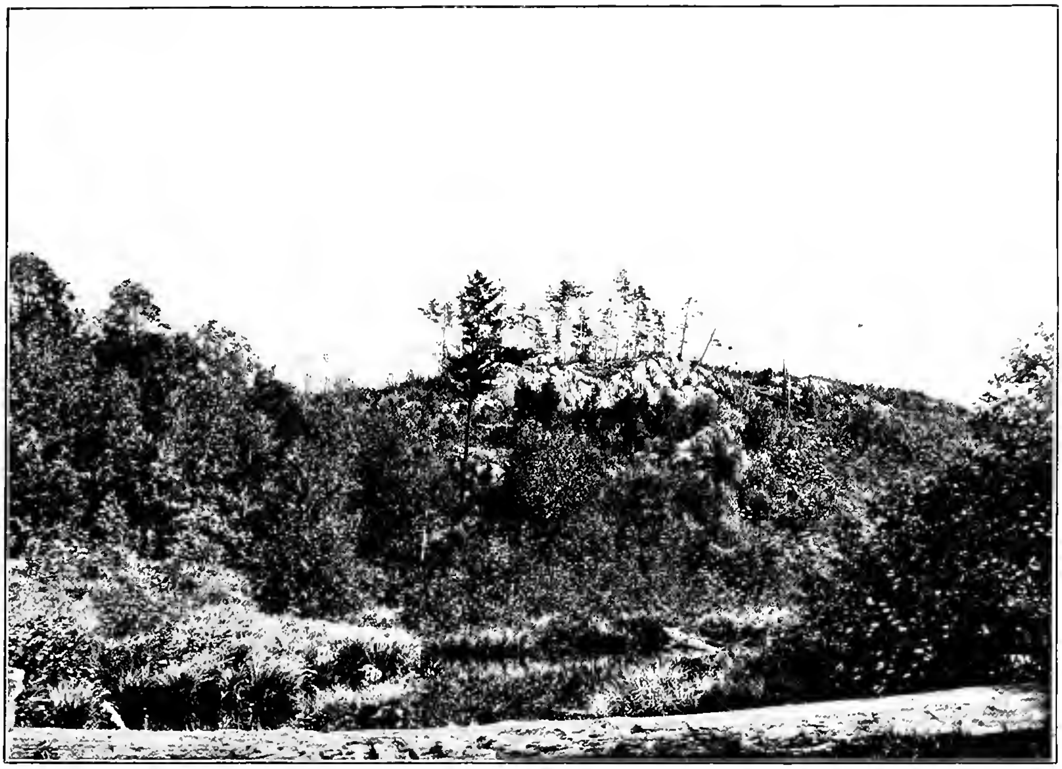
The southern boundary, on the other hand, is rather sharply delimited, not merely by exposures, but also by the underground workings of many of the mines. The evidence is so uniformly distributed along the entire belt that there can be but little doubt that this boundary is very near the position at which it is mapped. The only portions of the boundary that may be considered doubtful are (1) the 2¼ miles between the Menominee River and the old Ludington mine, 500 paces west of the east line of sec. 25, T. 40 N., R. 31 W., and (2) the 3½ miles between the center of sec. 18, T. 39 N , R. 28 W., and the east line of sec. 15 in the same town. Along the belt of the iron formation between the Menominee River and the old Ludington mine test pits have been dug, and from some of these drifts have been run to the north. In only one case, viz, near the center of sec. 25, T. 40 N., R. 31 W. (see fig. 16), was any dolomite met with, but in several instances drifts and drill holes penetrated rock that indicates the close proximity of the dolomite formation. A drill hole put down vertically about 1,000 feet east and 420 feet north of the west quarter post of sec. 25 penetrated a cherty quartzite that is usually found at the top of the dolomite formation. At other places the dump heaps show slaty rocks that are usually found near the dolomite, but at only the two points referred to above is there certain evidence that the southern contact of the dolomite is very near. At the eastern end of the district the evidence used in delineating the southern boundary of the belt is the same as that used in fixing its northern boundary. A magnetic line extends from sec. 18, T. 39 N., R. 28 W., continuously to the Breen mine. In sec. 18 the southern boundary of the dolomite is a short distance north of this line. The relative position of the dolomite and the magnetic line is assumed to be the same to the east, and the mapping is in accordance with this view. At Waucedah there is no definite magnetic line, but there are numerous test pits north of the village by which the existence of the lowermost member of the iron formation, with a steep dip to the south, is well established. Since the dolomite elsewhere lies just under this formation, its southern boundary at Waucedah is placed at a distance north of the southern boundary of the northernmost member of the iron formation corresponding to the average width of this formation in those places where its dip is nearly vertical.

In the 14 miles between sec. 25, T. 40 N., R. 31 W., and sec. 18, T. 39 N., R. 28 W., as has been said, the evidence that fixes the position of the dolomite belt is conclusive. The nature of this evidence need not be referred to here, as it is discussed rather fully in connection with the description of the iron-bearing Vulcan formation. The evidence is exhibited on the maps showing the distribution of the rocks in the neighborhood of the various mines.

TOPOGRAPHY.

From the Menominee River as far east as the Sturgeon River the country underlain by the dolomite is a range of high hills (Pl. XIII, *B*), broken only at Iron Mountain, at Quinnesec, at Norway, and at the Sturgeon River by north-south gaps. The slopes of the ridge are comparatively steep on both the north and the south sides, but the northern slope usually merges gradually into the plains lying at its base, while the southern slope in some places terminates in little precipices, well seen east of Quinnesec along the north side of the wagon road leading to Norway (Pl. XV, *A*). These precipices are rough and rugged masses of dolomite (Pl. XV, *B*) or cherty quartzite rising suddenly out of a plain underlain by slates. Their existence is due to differential weathering, the slates having been eroded much more rapidly than the resisting dolomite. Where the dolomite is bordered on the south by the iron formation the slope is gradual, the dolomite occupying its upper portion and the iron-bearing rocks its lower portion.

While the existence of the ridge is no doubt due to the presence of the



A. VIEW OF DOLOMITE BLUFFS ON NORTH SIDE OF HIGHWAY FROM QUINNESEC TO NORWAY.

Near point where stream crosses road in sec. 2, T. 39 N., R. 30 W.; about one-fourth mile east of Quinnesec. The cliffs are composed of nearly vertically bedded Randville dolomite, traversed by thin seams of chert parallel to bedding. The plain at the base of the cliffs is underlain by Hanbury slate. The view gives some idea of the rough topography produced by the weathering of the dolomite.

B. NEARER VIEW OF DOLOMITE BLUFF SHOWN IN *A*.

The rough character of the topography is very apparent in this view.

dolomite, its present height is determined partly by the horizontal Lake Superior sandstone, which caps it almost universally, and gives it an even or gently undulating sky line. Where the sandstone is lacking, i. e., on the lower portions of the ridge, the dolomite outcrops in small, isolated hillocks and groups of ledges. The former are sometimes very steep on all sides, and exceedingly rugged; at other times they are long, narrow, low ridges with gently sloping sides and smooth, rounded tops. In a few places the rock forms low ledges rising only a few inches above the general surface. Between the exposures are deposits of drift. The differences in the character of the topography underlain by the dolomite seem to depend largely on the completeness with which the glacial sands have been removed. If it could all be removed from above the dolomite the country, except where covered by sandstone, would be extremely rough.

What is true of the present topography of this area is true also of its pre-Potsdam surface. Mining operations in several instances have uncovered the sandstone at considerable depths beneath the present surface. In some cases the rock seems to fill old gorges cut through the dolomite; in other cases it rests against ancient dolomite precipices, and in still other instances it can be seen to rest upon shelving shores, built of this material It is also probable that the transverse gaps referred to as crossing the dolomite ridge at Iron Mountain, Quinnesec, and Norway were once filled with sandstone. While there is by no means sufficient data from which to reconstruct the old topography, it is very clear that the ancient dolomite surface was more rugged than its present surface. Moreover, since the sandstone is found at much lower levels, both north and south of the ridge, than its basal layers on the ridge, it is further plain that the dolomite ridge was in existence in pre-Potsdam time, and that its elevation above the surrounding surface was then not greatly different from its elevation to-day.

LITHOLOGY.

The Randville dolomite consists of a series of beds in which dolomitic layers predominate. With the pure dolomites are associated quartzose dolomites, dolomitic quartzites, argillaceous dolomites, dolomitic slates, cherty quarzites, and talcose schists. Besides these there are present locally, particularly near the ends of folds and along contact zones, dolomitic breccias and conglomerates and cherty quartz breccias.

DOLOMITE AND DOLOMITIC SANDSTONES.

The predominant rock of the series 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. In a few places the rock is a white coarsely crystalline marble, a phase well seen in the ledge 400 paces west of the northeast corner of sec. 14, T. 40 N., R. 30 W.

The lighter-colored, purer dolomites weather with smooth white or very light-pink or light-blue surfaces that are crossed here and there by thin projecting seams. Oftentimes the projecting bands are parallel to the bedding, when they are found to be composed of dolomitic quartzite interbedded with the purer dolomite. In other cases the projecting bands anastomose or run irregularly over the weathered surfaces, often intersecting the bedding planes of the rock at acute angles. These seams are plainly narrow veins of quartz. Their abundance proves clearly that the dolomites, in spite of their homogeneous appearance, have been extensively fractured and crushed.

The weathered surfaces of the darker-colored dolomites are covered with a thin layer of light-brown sandy substance varying in thickness from a fraction of a millimeter to several millimeters, which indicates the presence of iron in the carbonate, and the existence of quartz grains intermingled with the dolomite. At one place nodular weathering was observed. This was in the large ledge underlying the Lake Superior sandstone in the quarry in the southwest quarter of the southeast quarter of sec. 30, T. 40 N., R. 30 W. Here the dolomite strikes regularly N. 75° W., and dips 78° N, and on its eroded edges the sandstone lies horizontal. Near the contact of the two rocks, the dolomite is filled with nodules that differ slightly in color from the surrounding matrix and thus produce a rock strongly resembling in appearance a conglomerate. No difference can be detected between the texture of the nodules and that of the cementing material. The nodules are slightly harder than the rock in which they lie and perhaps they contain a small percentage of silica leached from the overlying sandstone.

While many of the dolomite beds in the Randville series are practically pure dolomites, others contain a large admixture of sand grains. In some cases dolomite is in excess, in others the principal component is sand with dolomite as a sparse cement. The former have been called quartzose dolomites and the latter dolomitic sandstones. These rocks occur in beds from a few inches to 20 or more feet in thickness at various horizons in the series, but more frequently near its bottom than elsewhere. The basal beds, which are gradational in character between the underlying Sturgeon quartzite and the overlying dolomitic phases of the Randville series, are almost exclusively dolomitic sandstone. On the fracture surfaces of fresh specimens of the quartzose dolomites the quartz appears as small, round, glistening spots against a dull groundmass of gray, white, or bluish dolomite. The grains are so evenly distributed through the carbonate that at a hasty glance many specimens resemble oolitic limestones. In the most quartzose varieties the rocks are practically quartzites, and their appearance on fresh fractures is not very different from that of normal quartzite. The intermediate phases between these two extremes exhibit naturally intermediate characters. On weathered surfaces the more dolomitic phases are rough and sandy, and of a light- or a dark-brown color. The dolomite has been partly dissolved and in the cavities thus produced quartz has crystallized. A porous, drusy rock results, which is very friable. It resembles closely many calcareous sandstones. The replacement of the dolomite by the silica is not always confined to the exposed surface, but in some instances weathering has proceeded to so great a depth within the rock mass that no specimens can be obtained which do not possess the drusy character.

A few of the quartzose beds associated with the dolomites are nearly pure quartzites that differ in no essential respect from the quartzites of the Sturgeon formation. They are fairly fine-grained rocks with a gray or purplish color. They occur in thin beds rarely more than 2 or 3 inches thick, and are found at any horizon, but more commonly near the base of the dolomitic series.

Under the microscope the purer dolomites are seen to be crystalline aggregates of dolomite exhibiting all the characteristics of this mineral. The larger grains are synthetically twinned, but the smaller ones as a rule are untwinned. The cause of the various shades of color observed in the hand specimens is not recognizable in the thin section, for usually, with the exception of a few grains of ocher and of hematite, no coloring matter of any kind is noticeable in them. It seems necessary, therefore, to regard the color as residing in the carbonates themselves, and not in any impurities present as cementing material between the individual grains, though of course it may be due to a very small quantity of some clay-like interstitial substance. The slides are crossed occasionally by tiny veins of calcite and sometimes by small quartz veins. Little nests of these minerals are also scattered here and there through the mass of the rock.

The lighter colored of the quartzose dolomites are very similar to the purer phases of the rock except that they contain considerable quantities of quartz in grains and little nests, small fragments of plagioclase, and occasionally a few plates of a light-green chlorite that has evidently been derived from some mica. The quartz grains are usually subangular, in a few sections they are sharp edged, and in many they are beautifully rounded sand grains. In a few instances they are distinctly enlarged These fragmental grains are embedded in a matrix sometimes consisting almost exclusively of the carbonate. In a large number of instances, however, dolomite, calcite, and quartz in grains of equal size are present in approximately equal quantities, composing an aggregate which under low powers of the microscope appears to be thoroughly crystalline. Under high powers the quartz grains are seen to be fragmental and the carbonates to be crystallized about them. Evidently these rocks are mixed dolomitic and clastic sediments that have been partly silicified since their deposition. They mark the transition between the purer dolomites and the rocks that have been called dolomitic sandstones. These present no unusual features. They consist largely of fragmental quartz grains embedded in a crystallized calcitic and dolomitic matrix. Often the carbonates are in such small quantity that the rocks are essentially quartzites, with features closely resembling those of the Sturgeon quartzite.

In the light-colored phases of the dolomitic sandstones there are no constituents other than those mentioned above, but in the darker-colored phases the proportion of colored components present is quite large. These comprise ochers, magnetite, hematite, rutile, an abundance of small flakes of brownish-green chlorite and spicules of light-green sericite or kaolin, a few prisms of tourmaline and grains of epidote. In other words, these rocks appear to be mixtures of muds, sands, and calcareous deposits that were interstratified with the purer dolomites as a consequence of some local changes in the conditions under which deposition took place. With a decrease in the amount of dolomite present these rocks, like the lighter-colored varieties, pass over into quartzites, which differ from the Sturgeon quartzites in the presence of a large quantity of crystallized quartz and chlorite. The quartz is in large grains that are apparently fragmental and in small grains that appear to have crystallized in situ. The latter form a matrix by which the larger grains and the chlorite are surrounded. Through this matrix are also scattered many small spicules of colorless or light-green sericite, or some other micaceous mineral. Under low powers of the microscope the chlorite appears to be fairly homogeneous, but under high powers it is discovered to be filled with tiny quartz grains and with wisps of a colorless mica. These are bound together by radial and divergent groups of chlorite, the whole forming the flakes noticed under low powers. Between the fibers of the chlorite and occasionally embedded in them are rutile, magnetite, and ocher grains. The character of this chlorite and its associated minerals indicate that they are the decomposition products of a biotite. The quartzites thus appear to be made up largely of quartz sand and a fine mud that has undergone considerable alteration. If dolomite was ever present in them it has been removed by silicification processes.

All specimens of the dolomites, even the least quartzose ones, are crossed by little veins of quartz which, under the microscope, are discovered to consist of crystallized quartz of the same character as the material of the cherty quartz rocks to be described hereafter. The laminæ are usually not thicker than a millimeter, but near the top of the formation they sometimes reach a width of 2 or more inches.

Now and then sections of the dolomite exhibit a schistose structure, in that the grains are all elongated in a common direction. There is no crushing or peripheral granulation observable; hence the elongation must be due to the crystallization of these minerals under the influence of pressure. Adams and Nicolson[a] have recently shown that the cataclastic structure in limestone is not common. On the other hand, they have shown that the structure of schistose marbles is due to the flattening of their constituent grains by twinning and gliding. They have further proved by experiment that the flattening of the grains may be produced by differential pressures at temperatures of 300° to 400°. At this temperature, under pressure,

[a] Adams, F D., and Nicolson, J. T., An experimental investigation into the flow of marble Philos Trans. Royal Soc. London, Series A, vol. 95, 1901, p. 363–401.

marbles are deformed by flowage, and in this way schistosity is superinduced. The dolomites of the Randville series are closely folded; hence they were in the zone of flowage for these rocks, and were subjected to great pressure at depths that must have had a much higher temperature than that at the surface. The structure of the schistose phase is that which should be expected under the conditions, and is confirmatory of the implied view of Adams and Nicolson that limestones in folded regions should exhibit schistosity, due to flattening of their components as the result of flowage. That the schistosity of the Randville dolomites is not more marked than it is may be due to the fact that they were raised from the zone of flowage to the zone of fracture at the end of Lower Huronian time, and since then have, in large measure, been recrystallized by percolating waters.

The quartzose dolomites are more apt to exhibit schistosity than the purer varities. Indeed, nearly all the dolomitic rocks that appear schistose in the hand specimen contain more or less quartz. In the nonquartzose dolomites the schistosity is due to flattening of the dolomite grains. There is no granulation of the components. In the quartzose dolomites, on the other hand, granulation is observed on a comparatively large scale. The larger of their quartzose components have been crushed into quartz mosaics, which may be lenticular in shape or which may possess the general outlines of the original grains from which they were formed. From the ends of the lenticules long tails of a very fine-grained mosaic often extend into the surrounding dolomite, and here and there scattered through the matrix are little irregular masses of the same mosaic that may be detached portions of shattered grains. Quartz nests are also found in these rocks. These differ from the mosaics in their very irregular outline and in the very much coarser grain of the mineral composing them. The dolomite matrix shows little evidence of crushing. It is an extremely fine-grained crystalline aggregate, containing here and there an embedded quartz grain, and sometimes a few flakes of chlorite, sericite, or other secondary mineral. The schistosity of these rocks is due almost exclusively to the flattening of the quartz grains.

Not all the dolomites were deformed by plastic flowage, however, for many specimens which in the ledge and in the hand specimen appear to be massive, when examined in thin section are found to be minutely brecciated. They consist of dolomite fragments embedded in a matrix of dolomite, calcite, and quartz. Some of the latter mineral is plainly fragmental, but much of it was deposited as little nests of small grains between large crystalloids of calcite and smaller ones of dolomite.

Only one analysis of the dolomites has been made, so far as known, but it probably represents very accurately the composition of the purer kinds. The specimen analyzed was a pink variety from shaft B of the Chapin mine. It was made by Mr. E. E. Brewster, now chemist of the Pewabic mine, who kindly furnished the results for publication. The constituents as determined and the components in the dolomite corresponding to them are as follows:

Analysis of dolomite from Chapin mine.

CaO	30.97 = $CaCO_3$	55.20
MgO	20.48 = $MgCO_3$	42.84
Fe	.80 = $FeCO_3$	1.66
P_2O_5	.05 = Apatite	.11
Al_2O_3	.20 = Al_2O_3	.20
Residue	.73 = Residue (mostly silica)	.73
Total		100.74

The rock is thus an almost normal dolomite of the composition $CaCO_3 + MgCO_3$.

DOLOMITE BRECCIAS AND CONGLOMERATES.

The presence of anastomosing quartz veins in the massive dolomites, the existence of schistosity in many specimens, and the minutely brecciated structure observed in the thin sections of specimens from apparently homogenous beds, indicate that the dolomite series has been deformed under pressure. In most instances this pressure did not express itself in crushing sufficiently marked to be detected in the ledge. But in some places, more particularly at the apices of folds and along contacts with overlying formations where accommodations to stresses resulted in sudden movements, the crushing was so severe that the rock was actually fractured on a large scale, and breccias produced. These consist of sharp-edged and lenticular fragments of dolomite separated from one another by seams and interstitial masses of dolomitic material with which a small quantity of quartz sand is admixed. In some beds the fragments make up the greater portion of the rock mass, as is the case in the cliff at the northeast end of the little valley east of the Aragon mine (see Pl.

XVI, *A*). In other beds the interstitial substance is in greater quantity and the fragments sparse. In the former case the autoclastic character of the breccia is unquestionable. In the latter case the rock looks very much like a breccia of fragments cemented together by foreign material. This is true of some of the breccia at Iron Hill.

Under the microscope the dolomitic breccias are seen to differ but little from the finely crushed dolomites referred to above (p. 214), except in the greater size of the fragments. These, as has already been described, are mainly angular pieces of dolomite and of the rocks associated with the dolomites. In some instances the matrix surrounding the larger dolomite fragments is made up of small angular fragments of the same rock cemented by an aggregate of large, colorless crystalloids of calcite. The small and the large fragments of the original rock are surrounded by little zones of ocher that seem to have been deposited upon them before the crystallization of the calcite cement. The rocks are undoubted autoclastic breccias produced from the purer dolomite beds.

In most cases the original rock was a quartzose dolomite, and the resulting breccia consequently contains, in addition to dolomite and calcite, more or less fragmental quartz, the quantity present depending upon the quantity in the original rock. Some of the fragmental quartzes show enlargements, with the added material often extending for considerable distances from the fragmental nuclei into the surrounding carbonates. While much of the dolomite in the matrix may originally have been in clastic grains it is now plainly in forms that have crystallized in situ. The calcite, which is nearly always in comparatively large grains, is clearly newly deposited. Much of the recrystallized carbonates have been deposited as fringes around the fragments of dolomite, which are surrounded by zones composed of many elongated grains lying side by side and forming a radial aggregate completely enveloping the fragmental nucleus.

In some places, particularly in the interstices between the larger fragments, the matrix is schistose, when the dolomite grains are flattened in the plane of schistosity and their twinning lamellæ are curved. The breccias in which the schistosity is most marked do not always exhibit this structure in the hand specimens. Usually their embedded fragments can be seen on the weathered surfaces to lie in the matrix with their long axes in a uniform direction, but on the fresh fractures where the fragments can not be distinguished no trace of schistosity can be detected.

PLATE XVI.

PLATE XVI.

FIG. *A*.—BRECCIATED RANDVILLE DOLOMITE. In wall at east end of little gorge running east from the Aragon mine. Fragments and matrix are composed of the same kind of dolomite. Fragments are all sharp edged.

FIG. *B*.—DOLOMITE CONGLOMERATE. At Iron Hill in sec. 32, T. 40 N., R. 29 W. The large fragments are rounded, the smaller ones are angular. Both fragments and matrix are crossed by joint cracks in which cherty quartz has been deposited. The quartz seams now project from the weathered surface. The matrix is more siliceous than the fragments, partly because it contains a thicker network of the quartz seams, and partly because it contains a considerable proportion of sand grains. Consequently surfaces of fragments are depressed. The fragments are, moreover, often surrounded by narrow projecting seams of the cherty quartz. The bedding of the dolomite in the fragments may often be plainly seen.

A. BRECCIATED RANDVILLE DOLOMITE IN WALL AT EAST END OF LITTLE GORGE RUNNING EAST FROM THE ARAGON MINE.

B. DOLOMITE CONGLOMERATE AT IRON HILL IN SEC. 32, T. 40 N., R. 29 W.

In occasional instances beds are met with in which the inclosed fragments are rounded. The rock then is a definite conglomerate. Some of these occur locally, forming layers lying between thick beds of nearly massive dolomite. The conglomerates of this kind are composed of dolomite pebbles of one color in a dolomitic matrix of another color. They may be intraformational in character, like those described by Walcott[a] in the Paleozoic series of New England, Pennsylvania, Virginia, and elsewhere.

Most of these conglomerates differ from the nonconglomeratic beds with which they are associated only in the possession of fragments. The fragments are almost exclusively dolomite in the beds whose matrix is dolomitic. In those conglomerates in which the matrix is strongly quartzose, the fragments may be dolomite or slate. They are identical in character with the material of neighboring dolomite or slate beds, and the matrix is precisely similar to the material of closely associated quartzose beds In no case is there anything discoverable in the thin section that contradicts the view that these conglomerates are intraformational beds. Their material is all from nearby sources. There is intermixed with this no foreign material.

A few other conglomerates are very closely allied to the breccias, from which they differ only in the shapes of their fragments. These are rounded or subangular, and are composed exclusively of dolomitic material and quartz—the former predominating. When the matrix contains but little quartz the fragments usually consist of the purer varieties of dolomite; when quartz is abundant in the matrix the fragments are quartzose dolomite. These rocks are clearly autoclastic, their fragments having been rounded by attrition.

There is, however, another small group of conglomerates represented almost exclusively by the conglomerate of Iron Hill, the origin of which is completely problematical. In the Iron Hill rock the pebbles are nearly all of dolomite. The few remaining ones are mainly chert, and a very few are quartz or quartzite. They vary in size from those of minute dimensions to others more than a foot in diameter. Pl. XVI, *B* is a reproduction of a photograph of a portion of this conglomerate. The

[a] The Cambrian rocks of Pennsylvania: Bull. U. S. Geol. Survey No. 134, 1896, p. 34-46.

sparse matrix between the pebbles is finely ground up dolomite and chert and small grains of sand. The appearance of the rock suggests strongly that it is a true conglomerate formed from the débris of the underlying dolomite and cherty quartzite beds, but its relations with these beds and with typical breccias are so complicated that no certain conclusion to this effect has been arrived at (see pp. 257–260). If a true conglomerate, it naturally belongs at the base of the formation overlying the dolomite, and is probably Upper Huronian. It is referred to in this place because of its lithological similarity to the other members of the Randville series

Another conglomerate that may belong with this group occurs near the center of sec. 35, T. 40 N., R. 30 W., on the branch railroad running through this section. It appears to be a true conglomerate, although it is of a different character from that at Iron Hill. Its matrix is a coarse dolomitic or calcareous sandstone, and its pebbles are largely of slate and other argillaceous rocks associated with the dolomites. The rock may, however, be an intraformational conglomerate, like the majority of the conglomerates in the series.

In the conglomerate at Iron Hill the fragments are rounded and very pebble-like. Most of them consist of dolomite or quartz, but some are composed of chert or quartzite. Most of the fragments are surrounded by narrow black borders made up of numerous scales, grains, and small crystals of an opaque substance, intermingled with indefinitely outlined masses of green chloritic material. The same opaque substance surrounds the larger quartz grains in the matrix and is scattered irregularly through some of the components of the groundmass. Just within the borders the rims of the dolomite fragments sometimes show an irregular zone of quartz, as if the dolomite has been corroded by siliceous solutions and a portion of the carbonate had been replaced by silica.

The matrix of the rock is like that of the ordinary breccias. There are a few more fragmental grains of quartz in it, but otherwise the two are similar. At first glance this conglomerate would be pronounced sedimentary in origin, because of the great number of clastic quartz grains in it, but when it is recalled that much of the nonconglomeratic dolomite is quartzose and that the quartz is present in them as distinctly clastic sand grains, the evidence from this component is valueless. Nevertheless, the general appearance of some of the rocks is strongly suggestive of a sedimentary origin. The presence of the quartzite and chert pebbles lends some support to this view.

TALCOSE SCHISTS.

At some places the dolomites, at their contacts with the overlying iron formation, have been entirely changed from their original condition and are now represented by a very different rock, composed largely of talc and serpentine. This talcose rock seems to be limited in its occurrence to those places where shearing must have been at a maximum. It is found in large quantities facing the dolomite underlying the iron formation in the close folds of the Norway and Aragon mines, in less quantities in the same position in the Walpole and Pewabic folds, and often as a thin layer between the dolomite and the basal members of the iron formation in those portions of the district where subordinate folding has not taken place. It occurs, also, as pebbles in the ore and dolomite conglomerate overlying the bedded dolomite in the Norway mine and to some extent in the matrix of this conglomerate.

The rock is soft and unctuous. It is usually of a dark reddish-purple color, mottled with white patches and cut into prismatic and lenticular masses by three systems of veins, intersecting one another by very acute and very obtuse angles. The rock is thus broken up into a large number of separate portions with long rhomboidal cross sections, all lying in an approximately parallel direction. It therefore possesses as a whole a roughly schistose structure. The material between the veins is generally massive, only incipient schistosity being noted in a few places. Along the walls of the veins, however, differential movement has taken place and slickensides have been produced. The material covering the slickensided surfaces, that causing the white mottling within the rock mass, and the filling of the veins, is all white talc. In the Norway conglomerate the talc rock differs from that just described in that it contains a large quantity of dolomite, intermingled with the talc as small fragments, small crystals, and as druses along little cracks. In the Pewabic mine the rock is lighter in color than commonly, and contains fragmental quartz and other clastic material, probably derived from the upper wall of the shearing zone.

In thin sections the talcose schists do not present any very definite characteristics. A great number of small rounded grains and many crystals of hematite lie in an almost colorless groundmass, which, under crossed nicols, is seen to be made up of small angular grains of quartz and flakes and shreds of micaceous minerals lying in a mass of structureless material which apparently has almost no influence on polarized light. The micaceous minerals are light green in ordinary light and have a small refractive index. Some of the fibers polarize in yellow and reddish tints, and others in the blues and grays of the first order. These are taken to be talc or kaolin and serpentine. The ill-defined mesostasis may be serpentine. Some of the quartz grains have very definite outlines that separate them sharply from the remainder of the rock, but the same mineral is present also in indefinite areas that grade off into the surrounding weakly polarizing material. In these areas the quartz can be detected only by the aid of a mica plate. The distinct grains appear to have a different origin from the indistinct masses, which were probably deposited contemporaneously with the serpentine, talc, and kaolin. Many little veins traverse the sections, and in these there is a predominance of the brightly polarizing talc fibers stained in spots by brown limonite.

A specimen of the rock from the Aragon mine was analyzed by Mr. George Steiger, of the U. S. Geological Survey laboratory. The result of this analysis appears below in column I:

Composition of talcose schist from the Aragon mine.

	I.	Talc.	Serpentine.	Kaolin.	Hematite.	Quartz.	Total.
SiO_2	49.56	19.63	11.13	11.10		7.70	49.56
TiO_2	.60						
Al_2O_3	10.12	.34	.31	9.47			10.12
Fe_2O_3	5.87	.12	.36		5.10		5.58
FeO	.13						
MnO	Trace.	Trace.	Trace.				
BaO	None.						
CaO	.72						
MgO	20.53	10.31	10.32				20.63
K_2O	None.						
Na_2O	None.						
$H_2O-110°$	4.50						
$H_2O+110°$	7.66	1.39	3.64	3.32			8.35
P_2O_5	.04						
CO_2	None.						
Total	99.73	31.79	25.76	23.89	5.10	7.70	94.24

Excluding the Fe_2O_3, which is sufficiently accounted for by the large quantity of hematite in the rock, the essential features of the analysis are the presence of MgO and Al_2O_3 to the practical exclusion of all other constituents except silica and water. The data at hand are not full enough to enable one to calculate with certainty the mineralogical composition of the rock. It is certain, however, that its components are few in number and that they are limited to magnesian and aluminous compounds If we assume that the MgO is all present in talc and serpentine in equal amounts and that the Al_2O_3 is limited to kaolin, and make the further assumption that the magnesian minerals have the same composition as the corresponding substances deposited in the ores (see p. 390), it is a comparatively simple matter to account for all the constituents enumerated in the analysis. A calculation based on the above assumption shows the rock to be composed of 31.79 per cent talc, 25.76 per cent serpentine, 23.89 per cent kaolin, 7.70 per cent quartz, 5 10 per cent hematite, 0.60 per cent rutile (if the TiO_2 is present as rutile needles), 0.42 per cent magnetite, and 0.17 per cent apatite. There remains over unaccounted for only 0.59 per cent CaO, which may well be present in any one of the three principal constituents. The amount of water required to satisfy the demands of this calculation is 0.69 per cent in excess of the amount reported in the analysis of the rock. The calculation, however, is based on the assumption that the serpentine contains 14.08 per cent water (see analysis, p. 390) which is a larger quantity by over 1 per cent than the formula of this mineral requires. Since the determination of this constituent was by loss it is probable that it includes some water driven off at a low temperature.

The proportion of the various components demanded to satisfy the principal mineral constituents are given in the columns above under appropriate headings. To the sum under the column headed "Total" there should be added 6.28, which represents the hygroscopic water, the quantities of magnetite, rutile, and apatite calculated as present in the rock, and the excess of CaO indicated by the analysis, and there should be deducted from this sum 0.69, representing the calculated excess of combined water present in the serpentine, talc, and kaolin above that found by the analysis. The result of these processes will correspond with the sum of the constituents determined as being present in the sample analyzed.

The composition of the schist as given above corresponds very well with the conclusions derived from a study of its thin sections so far as the nature of its constituents is concerned. In most sections, however, the talc appears to be in less amount than the above calculation would indicate, and the serpentine (if the feebly polarizing matrix is composed of this mineral) in greater amount. However, variations in the quantities of these two minerals assumed to be present would effect only the proportion of free silica in the calculation, an increase in the quantity of serpentine causing a corresponding increase in the calculated proportion of the free quartz. The essential features of the chemical and optical study are the same. The rock is composed mainly of talc, serpentine, kaolin, quartz, and hematite. Whether it was derived directly from dolomite or whether it was originally a fragmental rock composed largely of dolomitic débris can not now be told, as all of its original components, except possibly a few quartz grains, have been replaced by secondary minerals that were in all probability deposited from the same kinds of solutions that elsewhere in the ore bodies deposited talc, serpentine, and quartz. The presence of kaolin in the schist may be looked upon as evidence that the original rock was a sediment, but this is only a surmise, as the waters that deposited the talc and serpentine may have brought with them aluminous salts.

If the rock were originally a portion of the dolomite its alteration into talc necessitated the removal of the calcium carbonate and the replacement of the carbon dioxide of the magnesium carbonate by silica. The dissolved calcium carbonate was carried off and some of it was deposited as calcite in the ores and along watercourses (see p. 387). Some of the magnesium carbonate was also carried off in solution. It now appears as dolomite in the ores and another portion, changed to silicates, occurs as deposits of serpentine and talc (see pp. 389–390). The remaining magnesian silicates, together with the impurities originally existing in the dolomite and others contributed by the water, constitute the impure talcose rock. The conditions favoring its production appear to be movement in a shearing zone attended by chemical action brought about by percolating water. These conditions are most perfectly provided for in the pitching subordinate folds occupied by the ore deposits and in the steeply dipping surfaces of contact planes between two formations. To a minor degree the conditions also prevail along fault planes, and it is noticeable that along slickensided surfaces of such fault planes in the dolomite talc is also found.

Because of its impervious character, troughs lined with the talc-schist afford especially favorable situations for the deposition of ore bodies.

ARGILLACEOUS ROCKS.

The argillaceous members of the dolomite series are not abundant. They consist of a few rocks interbedded with the dolomites and dolomitic quartzites at various horizons in layers varying from the fraction of an inch to several feet in thickness. Together with thin beds of quartzite, they also constitute definite congeries of beds that appear to be somewhere near the top of the series. Sometimes the slaty beds in these groups are as much as 40 feet in thickness, but usually the aggregate is made up of alternations of quartzites and slaty rocks in layers not more than 5 or 10 feet thick. The slaty rocks are best exposed along the railroad running through sec. 35, T. 40 N., R. 30 W., and in the ledges south of the center of sec. 12, T. 39 N., R. 29 W.

Most of the slates are soft, light-gray or dark-gray, schistose rocks, some of which resemble very closely some phases of sericite-schists. Others are typical black slates, still plainly marked by bedding lines. These are rare and, so far as known, are confined to the set of interbedded slates and quartzites referred to above as constituting a definite portion of the dolomite series near its top. All the argillaceous rocks except the black slates contain considerable dolomitic material.

In addition to these slates, thin seams of an argillaceous dolomite, with a schistose structure and a purplish-pink color, often occur between massive beds of dolomite. In many instances they appear to be merely the selvages of softer layers of the dolomite rendered schistose by the movements of accommodation between stronger beds. Others may actually represent thin beds of argillaceous material deposited between beds of purer dolomite.

A third group of argillaceous rocks should be referred to here, though the slates may belong at the base of the overlying formation. These are red, white, light-purple, or light-gray, fine-grained, often fissile, calcareous shales, with a dull luster on fresh fracture surfaces. The rocks are known only from test pits and drill holes. They usually occupy an extremely narrow belt between well-defined dolomite and well-characterized members of the overlying iron formation. Their relations with the contiguous rocks have not been seen; consequently their exact position has not been definitely determined. In the coarser varieties quartz grains are easily distinguishable. These rocks may be built up of the detritus of the dolomite series and consequently may be the basal layers of the Upper Huronian beds. On the other hand, they may be integral portions of the Randville series at some distance from its top that have in some places been made to appear at the top of the series by the removal of overlying beds during the inter-Huronian erosion period. In any event, wherever they are found they always mark the near proximity of the contact between the dolomite series and the overlying Vulcan formation.

None of these slates present any features of peculiar interest from a microscopical point of view. The black and the gray slates are like the siliceous slates of the Hanbury formation, to be discussed later (see pp. 463–464), and the sericite phases are like corresponding phases in the Hanbury series.

The white and light-purple slates between the dolomite and the Vulcan formation are composed of small quartz grains, small flakes of chlorite, a few larger ones of muscovite, granules and irregular masses of ocher, and innumerable tiny plates of a light-green or colorless mineral that resembles kaolin. This kaolinitic substance is included in all the other constituents, and forms, together with some secondary quartz, an aggregate by which the other components are surrounded. Some dolomite and calcite are also present in little nests, but not in any considerable quantity. A few rutile needles, irregular grains of zircon, and an occasional group of small epidote grains are also universally present. The color of the pink slates is due to a great number of very small round granules and tiny dust-like particles of hematite and limonite that are scattered indiscriminately through all the other constituents.

The characteristic features of these slates which distinguish them from the younger slates in the district are the abundance of kaolin in them and the absence of any large quantity of sericite and chlorite.

CHERTY QUARTZ ROCKS.

The cherty quartz rocks are found only at the top of the Randville formation and never elsewhere in the series. They are fine-grained, vitreous, or saccharoidal, in places drusy, massive, siliceous rocks with a white, gray, pink, red, or dark-purple color. Because they are composed partly of quartz grains and partly of chemically deposited silica they have been called cherty quartz rocks. The red and purple varieties resemble very closely some of the jaspilites in the iron formation. They all weather with a smooth, polished surface much like that of some of the most exposed ledges of the Sturgeon quartzites. They occur at only a few localities, always overlying normal dolomite. Their best developments are at Iron Hill, in sec. 32, T. 40 N., R. 29 W., and in the cliff north of the Commonwealth pit or the new Keel Ridge mine, in sec. 32, T. 40 N., R. 30 W. (see pp. 261–263).

Wherever found the rock is crossed by quartz veins that sometimes run for short distances in parallel directions and then anastomose, and at other times anastomose irregularly over all exposed surfaces, cutting the rock up into parts, producing a breccia. In other instances the rock is fractured, and the fragments thus produced are cemented by a mixture of fragmental and chemically deposited silica. The breccias produced by both methods are practically identical. They consist of sharply angular fragments of one color in a matrix of some other color. Both matrix and fragments have essentially the same composition and the same texture, though the texture of the matrix in some specimens may be a little coarser than that of the inclosed fragments. In some places it is also drusy through the solution of some constituent and the deposition of quartz in the walls of the cavities thus formed.

The presence of the cherty quartz rocks at some places and their absence from others is accounted for by the supposition that they were once continuous over the dolomite, and that the erosion that marked the interval between Lower Huronian and Upper Huronian times cut down irregularly into the Randville series, in some places removing only the upper layers of the cherts and at other places removing the entire deposit. Their almost universal brecciated character may be due to the fact that they occur along a contact zone where movements of accommodation that must have attended the folding of the district were naturally accentuated and to the further fact that because of their brittle character the cherty rocks yielded to stresses more easily by fracture than by shearing.

In natural light, under low powers of the microscope, the more massive phases of the cherty quartzites appear as very light-yellow, transparent, homogeneous rocks speckled by little clumps of a dark-yellow substance, which under high powers is resolved into masses of ocher, and dusted with little opaque dots, which on stronger magnification are seen to be grains of hematite. In polarized light the sections become very fine-grained aggregates of interlocking quartz grains, cut here and there by veins of quartz, and containing occasionally little areas of the same mineral in which the grains are several times the size of those in the surrounding aggregate. Very small flakes of a colorless micaceous mineral are scattered here and there through the aggregates. In one or two sections calcite or dolomite is abundant. It is in very small rounded grains embedded in the quartz and in irregular masses apparently interlocking with the quartz grains. Occasionally there is a grain of quartz present in the slide which looks as though it might be fragmental, but usually no traces of clastic characters can be detected in any of the components. Here and there in the midst of the fine-grained aggregate round and irregularly shaped areas of quartz mosaics are met with that may perhaps mark the positions of large grains in an original sediment. The structure of the mosaic is always much coarser than that of the main portion of the rock mass, and often many of its constituent grains are crossed by strain shadows.

Like the cherts in the Gogebic district, those in the Menominee district are markedly brecciated. Reference has already been made to the abundance of brecciated forms in the descriptions of the macroscopic features of the rocks. When examined in thin section it is soon noted that many of the specimens which appear in the ledge to be completely homogeneous are in fact made up of fragments in a well-defined matrix. The brecciated structure is almost universal. The fragments are mainly sharp edged and range in size from those of microscopic dimensions to those several inches across. Sometimes the distinction between fragments and matrix is difficult to make, since the material of the two is similar in composition and in the coarseness of texture. Usually, however, they are distinguished by differences in color due to the presence in them of hematite, ocher, and magnetite grains, chlorite, and sericite, or kaolin flakes, and certain indefinite greenish and brownish stains in different amounts. Occasionally the fragments are darker colored than the matrix, but usually the reverse is the case. The snow-white varieties so characteristic of the Gogebic cherts occur only as fragments in the Randville breccias. There is also frequently noted a difference in texture between the fragments and the inclosing matrix. In the fragments the texture is very fine, but in the matrix it is often quite coarse. Often the coarsest texture is in a zone immediately surrounding the fragments. These coarsest portions may be traced continuously into stringers extending into the fragments and often separating them into several portions. Usually the stringers are extremely narrow, but sometimes they are rather wide. They cross the fragments in all directions, constituting the quartz filaments and veins noticed in the hand specimens.

In some specimens the filaments also cross the material of the matrix, and sometimes little irregular areas of the coarsely textured aggregate occur in the midst of the finer-textured aggregates, as though they represented cross and oblique sections through tiny quartz veins. In still other cases the coarse quartz grains form little round areas composed of a central grain surrounded by a zone of grains radially arranged around the nucleal grain. In short, the rocks look as though they may originally have been nearly homogeneous cherts, containing here and there a fragmental quartz grain, which were subsequently very thoroughly shattered and then healed by infiltrated quartz. Moreover, they seem to have been subjected to thorough silicification, so that it is doubtful if in some sections any of the original rock material remains. Sections which in natural light show plainly the presence of fragments in a matrix, between crossed nicols appear as a nearly homogeneous mosaic of small quartz grains of uniform size and character, interrupted here and there by lines of coarser mosaics, marking the positions of quartz veins.

CONCLUSIONS FROM MICROSCOPICAL STUDY AND COMPARISON WITH SIMILAR ROCKS IN THE MARQUETTE AND GOGEBIC DISTRICTS.

The microscopical features of these cherty quartz rocks are nearly identical with those of the cherts associated with the limestone in the Gogebic district, except that forms composed of individualized quartz grains, with crystal outlines, have not been seen among the Menominee rocks. The concretionary structure that Irving and Van Hise[a] detected among the Gogebic cherts also seems to be lacking in the Menominee ones, but this may be due to the few specimens that have been seen that are free from brecciation. In the breccias a concretionary arrangement of

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[a] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsion: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 132–133, and Pl. XVI, figs. 2, 3, 4.

the quartz is sometimes suggested in the groundmass surrounding the fragments, and occasionally in the fragments themselves, but the suggestion is a very obscure one.

The principal conclusion deduced from the study of the cherty quartzites is to the effect that they may be regarded as intermediate forms linking the dolomites beneath them with the jaspilites of the Negaunee formation that must at some time have existed above them. While we have no specimens of the Negaunee formation from this district, except in the form of small pebbles in the basal conglomerate of the Upper Huronian, in the Marquette district the Negaunee formation is well exhibited,[a] and its cherts and jaspilites have been carefully studied.

The Randville cherts are found to have many of the features of these rocks, and may well be transition phases between them and the underlying dolomites. The latter are in many instances silicified, and in some instances are so much so that they might well be described as cherty dolomite. However, these cherty forms are not as common in the Menominee district as they are in the Marquette district.[b] Otherwise the dolomites and cherts of the two districts are very similar, and the words used by Van Hise in describing those of the Kona formation in the Marquette district might almost equally well be used in the descriptions of the dolomite and cherts of the Randville series in the Menominee district. If lithological features are of any value as criteria upon which to base conclusions as to the stratigraphical continuity of formations in sedimentary basins situated in the same general geological province, then the identity of character between the dolomite and cherts in the Gogebic, Marquette, and Menominee districts must mean that they are at the same geological horizon, although their continuity on the surface is interrupted by wide stretches of younger sediments.

ORIGIN OF THE DOLOMITES AND CHERTY QUARTZ ROCKS.

From the statements above made concerning the character of the dolomites and cherts, it is evident that their origin must be the same as the origin of the corresponding rocks in the Gogebic and Marquette districts.

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[a] Van Hise, C. R., and Bayley, W. S., The Marquette iron-bearing district of Michigan, with atlas, including a chapter on the Republic trough by H. L. Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 370–371.

[b] Ibid., pp. 248–249.

Irving and Van Hise[a] have discussed the origin of the Gogebic rocks, and have reached the conclusion that there is no definite proof as to whether the dolomite is of chemical or of organic origin, but that many geologists would assert that the very nature of the rock precludes the possibility of its having been produced by other than life agencies. Where there are no fossils, as in these dolomites, it is at best a matter of opinion as to their origin, but in making up a judgment upon this point the organic beds of chert of later times associated with limestones and the beds of iron carbonate and carbonaceous material in higher horizons of the series are facts to be taken into account. While not expressing any definite opinion as to the origin of the dolomites, the impression left by the discussion is that they might well be looked upon as organic deposits.

As for the cherts, they declare that—

The vein-like character of a part of the chert implies that the silica has been rearranged to some extent, or partially introduced subsequently to the deposition of the main body of the belt. The deposition of similar cherty carbonates of great thickness is definitely known to occur in the Carboniferous and Permian[b] periods. The chert is here probably all of organic origin. Whether the chert in the limestones under discussion is an organic or a chemical substance it is impossible to say; but it is certain that in later time we have the exact analogue of the deposits described, which are definitely known to be organic deposits.

It appears that the chert of the limestone belt, whether original or secondary, had in the main reached its present condition before the accumulation of the immediately overlying formation. That the chert has been rearranged to a greater or less extent since its deposition, and that in the cracks infiltrating solutions have brought additional silica, is more than probable.

Again in summarizing their conclusions they state:[c]

The chert and limestone are water-deposited sediments; whether chemical or organic is uncertain, but it is not improbable that they are partly or wholly the latter. However, if this is the case, the silica has subsequently changed to the mineral form [quartz], and has been extensively rearranged, while the limestone has become dolomitized.

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[a] Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 140–141.

[b] Hinde, G. J., On the organic origin of the chert in the Carboniferous limestone series of Iceland, and its similarity to that in the corresponding strata in North Wales and Yorkshire: Geol. Mag., London, new series, decade 3, vol. 4, pp. 435–446. Also on the chert and siliceous schists of the Permo-Carboniferous strata of Spitzbergen, and on the characters of the sponges therefrom, which have been described by Dr. R. von Dunikowski: Idem, vol. 5, pp. 241–251.

[c] Mon. U. S. Geol. Survey, vol. 19, 1892, p. 142.

These words are so entirely applicable to the Randville cherts and dolomites that they have been quoted here, partly as a summary of the conclusions that must be arrived at after studying these rocks, and partly to emphasize the fact that what is true of the dolomite formation in the Gogebic district is true also of the corresponding formation in the Menominee district. The two formations are almost identical in all their characteristics. There can be little doubt that they represent dissevered parts of a formation that once extended continuously over both districts.

FOLDING.

A knowledge of the folds of the Randville dolomite is the key to the knowledge of the folding of the entire series of Algonkian rocks in the district. Moreover, the distribution of the folds determines the distribution of the productive ore bodies, as will be shown later. Consequently it is necessary to study the folding of this formation with some minuteness in order that a better understanding may be had of the conditions which have made the district of such economic importance.

The formation, as can easily be discerned from its mapped distribution (Pl. IX), occurs in two anticlines and three synclines in the western portion of the district and two synclines and one anticline in its eastern portion. Structurally the northern belt of dolomite is a southward-dipping monocline. The central and southern belts are anticlines. Between the belts are synclines. South of the southern belt is a syncline, on the southern limb of which one would expect to find a belt of dolomite. This belt might be expected to appear above a belt of Sturgeon quartzite, both overlying the Quinnesec schists of the Menominee River. Apparently, however, the quartzite and limestone were not deposited, or both have been completely removed by erosion during inter-Menominee time, so that the formations of the Upper Menominee series lie upon the greenstone-schists (see map and structure section AA, Pl. IX).

MAJOR FOLDING.

From the mapped distribution of the dolomite formation (Pl. IX) and its relations to the iron formation (see p. 251), it is clear that the central and southern belts are two anticlines with axes striking a little north of west, connected with one another by a syncline, and that a syncline also connects the central belt with the northern one.

In the central belt the northern and southern borders of the formation are known accurately only in the neighborhood of the Indiana mine. Just south of the Cuff mine shaft the dip of the dolomite is about 25° N. At the Indiana mine, near the southern border of the belt, the dip of the upper contact of the dolomite is south at an angle of about 60°, but, if the evidence of drill holes is to be relied upon, the dip flattens at greater depths. West of the Cuff mine are a number of ledges situated near the center of the belt whose bedding, as well as can be determined, is vertical. Thus the dips in this, the only portion of the central belt that can be examined across the strike from its southern to its northern contacts, are in accordance with the view that the belt is structurally an anticline.

The southern belt over much of its extent presents the appearance of a uniform succession of isoclinal beds—i. e., it appears as a monocline. In its western portion near the Chapin mine the dips of the beds exposed on the surface are uniformly at high angles to the north.

Farther east, in the neighborhood of the line between secs. 32 and 33, T. 40 N., R. 30 W., they are high to the south. In the longitude of Quinnesec they are high to the north in the southern half of the belt and high to the south in its northern half. East of this longitude the dips are uniformly to the south except where minor folds are encountered, but the angle of dip becomes flatter and flatter as we proceed eastward. Near the Sturgeon River it rarely exceeds 55°.

Consideration of these dips indicates that the southern anticline is a very closely compressed fold with a warped axial plane. At its western end this plane is overturned to the south; a little farther east it is overturned to the north; in the longitude of Quinnesec the fold appears to be fan shaped, and at its eastern end it is again overturned to the north.

CROSS FOLDING.

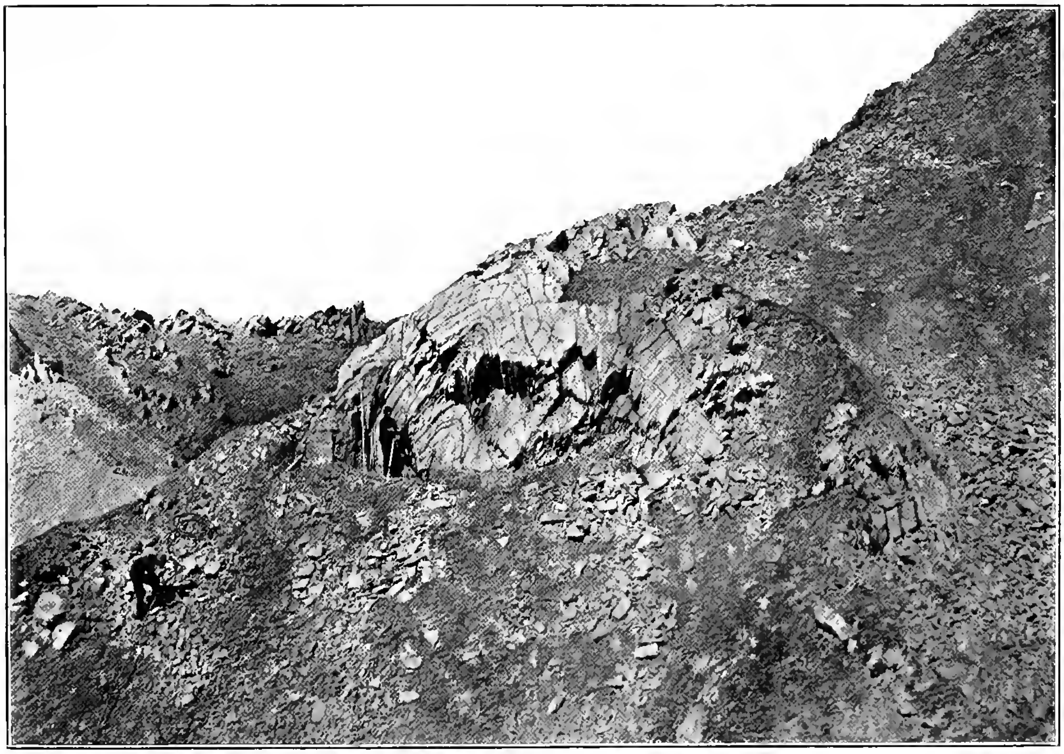
The attitude of minor folds is, as is well known, an indication of the attitude of the major folds on which they are superimposed. By using this principle it is concluded that the major anticlines in this district disappear to the east and to the west by plunging beneath the Upper Menominee sediments. Detailed examination of the ends of the anticline north of Lakes Antoine and Fumee seems to show that this belt does actually disappear in this way, and the sudden disappearances of the southern belt toward the west points to a similar conclusion with respect to its termination in this direction.

The most easterly exposures of the central belt are at Iron Hill in sec. 32, T. 40 N., R. 29 W. Most of the width of the belt in this neighborhood is covered by the Lake Superior sandstone, but at the southwest margin of the sandstone covering abundant exposures of the dolomites occur. Their bedding is very distinct, with a definite strike N. 50° to 60° W. This strike projected southeastwardly would carry the dolomite into a well-characterized area of ferruginous chert and slates. These slates and cherts are above the dolomite, hence the latter rock must plunge under them on its line of strike. Corroborative evidence for this conclusion is found in the fact that the easternmost exposure of the dolomite formation consists of dolomitic cherts. These rocks not only limit the normal dolomite to the east, but they are found also wrapping around the end of the hill and appearing again in the southeast side and along the southern side of the dolomite exposures (see Pl. XVII, *A*). Where its relations to the normal dolomite can be seen, the chert clearly overlies the latter. In other portions of the district where it is exposed, it is likewise seen to be above the normal dolomite. Since, then, the uppermost layers of the dolomite formation at Iron Hill are the last to disappear to the east, the formation must be terminated by an eastward-plunging anticline.

At the west end of the belt the conditions are very unfavorable for determining the method of its disappearance in this direction. The westernmost place to which the formation is known to extend is in the tunnel and drill hole near the quarter post between secs. 20 and 21, T. 40 N., R. 30 W., on the south side of the great hill overlooking Lake Antoine. This hill, like nearly all of the other higher elevations in the district, is covered with sandstone, so that the areal distribution of the dolomite in this neighborhood can not be determined. The west and northwest slopes of the hill, however, are broken by the mining and exploration pits of the Cornell, the Traders, and Clifford mines, so that the extension of the dolomite in this direction is impossible. Moreover, the magnetic observations in sec. 20 indicate that this section is underlain by a broad area of the iron-formation rocks. These facts seem to show that the west end of the central dolomite belt, like its east end, must terminate in an anticline which, in this case, pitches to the west.

A. FOLD IN CHERT AT IRON HILL IN SEC. 32, T. 40 N., R. 29 W.

The underlying rock is a conglomerate dolomite like that shown in Pl. XVI, *B*. The overlying chert is brecciated.



B. SMALL FOLDS IN TRADERS JASPILITE, WEST SIDE OF CLIFFORD PIT, TRADERS MINE.

The rocks are brecciated, but folds can nevertheless be plainly recognized in them. In the view one anticline and one syncline can easily be made out

The behavior of the ends of the southern anticline can not be described, since both are covered with sandstone and drift. But for this belt, the evidence of the minor folds is fairly conclusive, so that it appears safe to assume that this dolomite plunges below the Upper Menominee rocks. The westernmost point at which the dolomite is known to occur is near the center of sec. 25, T. 40 N., R. 31 W., where it was reached by a drift running about 50 feet north from the bottom of a shaft located 150 feet southwest of the center of the section (fig. 16). The dolomite lies to the north of a slate and ore formation and is overlain unconformably by the Lake Superior sandstone. The dip of the dolomite is apparently to the south, but the surface on which the sandstone was deposited slopes to the north. Unfortunately we are here, as at other important places, met by the sandstone covering which completely hides from view the relations of the rocks beneath it. From the magnetic observations made on the west slope of the hill and in the valley of the Menominee at the base of this slope it appears that the iron formation occupies a large part of the area between the hill and the river and nearly surrounds its west end. At its east end the southern belt is covered completely by Paleozoic beds, so that the manner of its disappearance with respect to the Upper Huronian sediments is not known.

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 anticlinorium with axis running approximately north-south.

MINOR FOLDING.

THE NORTHERN BELT.

In the northern belt minor folding, if it exists, can not be discovered except at the extreme western end, where the belt makes the turn northward into the Calumet trough (see p. 189). The area occupied by the belt is included within the valley of Pine Creek. Throughout nearly its entire extent the rock is buried beneath the valley sands. The few exposures belonging to it exhibit no evidence of folding.

THE CENTRAL BELT.

In the central belt the exposures are almost uniformly low, massive ledges, in which strikes and dips are not always easy to obtain. Where observations were taken the strike is invariably in the direction of the trend of the belt. West of the Cuff mine the dips are practically vertical, and the belt appears to be isoclinal. East of the Indiana mine the dips are usually 70° to 80° S. But here only the southern side of the belt is open to inspection, since the northern side is buried under sandstone. At the Cuff mine test pits show that the northern boundary of the dolomite swings suddenly to the north, and a dolomite ledge exposed at the southwest end

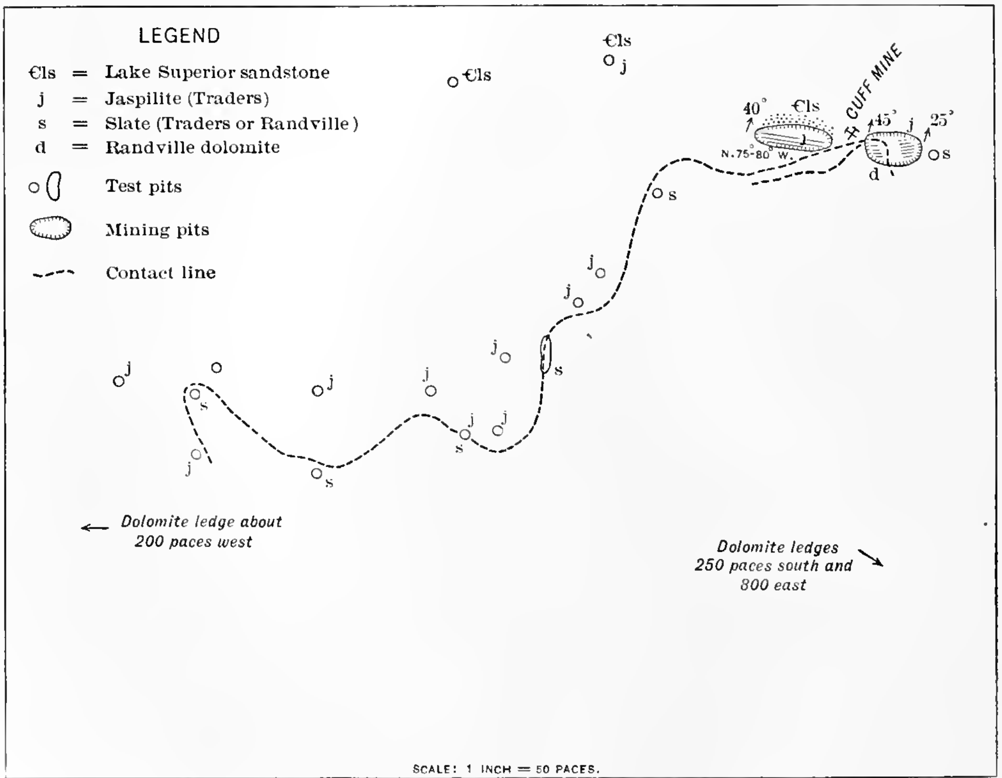


Fig. 17.—Sketch plan of Cuff mine and vicinity.

of the open pit east of the shaft strikes east–west and dips 45° N. There is here plainly a small subordinate anticline (fig. 17).

At Iron Hill, at the eastern extremity of the belt, there is also clear evidence of minor folding. Near the east quarter post of sec. 32, T. 40 N., R. 29 W., are two small knolls of dolomitic chert separated by a small valley. The rock in the northern knoll dips 75° to 90° S. Across the valley, and at a distance of only about 50 feet, the rock on the northern side of the southern ledge dips 45° N. On the southern side of the same knoll the dip is 45° S. The dips of the beds in the great ledges of dolomite farther south are 85° to 86° S. There are here, then, at least one minor syncline and two anticlines, superimposed on the major anticline that gives rise to the belt (see map, Pl. XLII).

The southern boundary of the dolomite in places terminates in little cliffs. One of these is situated 500 paces west of the east line of the section. The face of the cliff consists of white cherty quartzite, under which is a much-jointed, conglomeratic or brecciated dolomite. A side view of the cliff (see Pl. XVII, *A*) shows the chert extending vertically up its face to the top and then suddenly bending northward and becoming horizontal and covering the dolomite with a distinct layer which finally disappears under the soil. The photograph also shows plainly that not only does the chert roll over the dolomite but that it is further folded into crumples of small dimensions. The intensity of the folding at this place is also indicated by the brecciated character of the chert. Here the folding is no doubt connected with the existence of the pitching anticline which carries the dolomite beneath the Hanbury slates.

THE SOUTHERN BELT.

MARGINAL FOLDS.

The southern belt appears to be practically isoclinal throughout nearly its entire exposed extent. Nevertheless close folding may be observed in a number of places. Minor folding is abundantly exhibited on the south side of the formation, where it is in contact with the overlying iron formation. The numerous synclines found here afforded suitable conditions for the concentration of the ores, and it is in them that the larger mines are situated. The mining operations have brought to our knowledge the underground relations of the two formations so fully that the nature of the folds in them has been made very clear. The most important ones may be named from the mines occupying them as follows: The Walpole, the Pewabic, the Quinnesec, the Norway, the Aragon, and the West Vulcan. All of these are closely compressed folds pitching to the west at angles varying between 25° and 80°, usually becoming flatter at greater and greater depths. The western folds are overturned to the south and the eastern ones to the north. The axial planes of the Walpole and the Pewabic folds dip about 70° N. and that of the Quinnesec fold 60° in the same direction, while the Norway fold dips 70° S., the Aragon fold 60° S., and the West Vulcan fold is nearly vertical. Although these folds are discussed rather fully in connection with the description of the ore deposits, a brief summary of the evidence upon which their recognition is based may conveniently be given in this place.

Walpole fold.—The most westerly fold whose existence is made certain by mining operations is that in which the Chapin, Millie, and the Walpole ore deposits are found. This is not anywhere to be seen on the surface, since the Lake Superior sandstone and the loose materials of the drift cover all the ground in its vicinity. The existence of the fold, however, is well established by the underground working of the Walpole mine, the old shaft (No. 1) of this mine being on its north limb, and the southern, or No. 2, shaft on its southern limb (fig. 34). The dolomite has not been met with in No. 1 shaft, and no crosscuts have been driven to the north from this shaft to locate it. About 550 feet to the west, however, is the A shaft of the Chapin mine, and 110 feet north of this on the surface is the southern limit of the dolomite. The dolomite is again met with at the east end of the third level of the Walpole, at a point 1,625 feet east and 525 feet south of the shaft. Just before reaching the dolomite the drift encountered a light-colored slate known to occur elsewhere at the base of the Traders formation. This rock, varying somewhat in appearance, but nevertheless essentially the same in composition, is disclosed again at several points at the ends of crosscuts running north from the main drift. The dolomite is immediately behind this. The Traders slate is again found at the end of a south crosscut at 1,425 feet east and 475 feet south of the shaft, and the same slate, underlain by a narrow bed of quartzite (Traders quartzite), back of which is the dolomite, occurs again 900 feet east and 425 feet south of the shaft. These exposures outline a narrow syncline of dolomite pitching to the west. No. 2 shaft is a little over 1,000 feet south of shaft No 1. South of it on the third level the quartzite that is so frequently associated with the dolomite again appears, and at a point 375 feet east of the shaft the east end of a drift terminates in the same rock. No other indications of the presence of the dolomite are met with on the third level, but in a long crosscut running north from the southern shaft and connecting it with the workings of the northern shaft, at a place midway between the two, three belts of ore-bearing material are uncovered, like the material lying above the Traders slate and quartzite elsewhere in the mine. The inference is plain that the dolomite lies a short distance to the east of this crosscut, and that its border is crenulated. Further, it is evident that the dolomite must form an anticline between the syncline in which the workings of the northern shaft are developed and another syncline partly outlined by the exposures in the workings of the southern shaft. The Walpole fold is thus composed of two synclines and an intermediate anticline. The folds pitch to the west and dip to the north.

Pewabic fold.—The Pewabic fold, like the Walpole fold, has been developed solely by underground work (fig. 35). Dolomite was reached at the end of a crosscut running a little east of north from No. 1 shaft of the Pewabic mine, at the first level, and at a distance of 870 feet from the shaft. This point is about 1,250 feet east and about 150 feet south of the Walpole shaft No. 2, just south of which, as was stated in the preceding paragraph, dolomite was found. There is then an anticline of this rock between the Walpole and the Pewabic basins. The latter basin is further outlined by the discovery of dolomite by means of two drill holes put in to the north and the south from the east end of the third level of the Pewabic mine, and a third hole driven to the south from the drift extending southward from the same level, about 500 feet east of shaft No. 1. Normal dolomite was not encountered in this drill hole, but the drill ended in the Traders quartzite, which is found only in close association with this rock. On the sixth level, however, a hole drilled in the same direction reached the dolomite. The east end of the fold is complicated by a fault the exact character of which has not been worked out. By these explorations it is shown that the iron formation of the Pewabic mine and the rocks associated with them lie in a syncline of the dolomite which widens to the west. The mining operations show that the pitch is to the west and the dip of the fold to the north.

Quinnesec fold.—The underground workings of the Quinnesec and the Cundy mines have not yet reached the typical dolomite on either side of the ore formation, though its presence north of the Quinnesec pit is indicated by the nature of the rocks met with. The principal evidence we have of the existence of a fold here is found on the surface (Pl. XXX). Near the corner, between secs. 34 and 35, T. 40 N., R. 30 W., and secs. 2

and 3, T. 39 N., R. 30 W., is a large ledge of well-bedded dolomite with a dip of 80° S. and a strike N. 70° W. This dolomite, if continued along its strike, would pass through the large open pit of the Quinnesec mine, in which the ore formation is well exposed. Exposures of the dolomite occur as far west as the road running north to the Indiana mine, and it is found again in the Quinnesec public well, situated about 750 feet west of the corner. The strike of the dolomite beds projected beyond this point would carry them south of the Quinnesec mine into an area dotted with ledges and test pits in the jaspers and slates of the iron formation.

North of the well there are no exposures of the dolomite for 300 paces (about 780 feet), though a drill hole put down about 525 feet east of the Quinnesec shaft disclosed the rock under the surface about 250 feet south of the southernmost exposure. North of this drill hole exposures are found at short intervals for 1,000 feet, and then at greater intervals for 2,500 feet beyond. The beds in the southern ledges strike from 3° to 8° north of west and dip nearly vertically.

Between the well that marks the westernmost point at which the dolomite has been found south of the mine and the next most southern occurrence of the same rock is a valley 530 feet wide in which no exposures of any kind are found. Artificial openings, however, show that the valley is occupied by the slates and other rocks of the iron formation. The displacement of the dolomite is thus a little over 500 feet. A glance at the geological map (Pl. XXX) will make these relations plain. This displacement must be due either to a fault trending a little east of north or to a syncline pitching west. Since there is no direct evidence of a fault at this place, nor in the dolomite beds almost continuously exposed a short distance east of the section line, and since faults of important dimensions are not common elsewhere in the district, it is concluded that the displacement must be due to folding. The dolomite ledge near the corner is at the crest of an anticline. The dolomite north of the mine is the south side of another anticline, and the interval between is occupied by a synclinal trough filled with iron formation rocks.

Norway fold.—The folds in which the Norway and the Aragon mines are situated are as well known as any others in the district because of their extensive exploration by mining operations. On the surface a ledge of dolomite exists near the corner between secs. 4, 5, 8, and 9, and four other ledges of the same rock are exposed northeast of this one, i. e., in the southeast quarter of the southeast quarter of sec. 4, T. 39 N., R. 29 W. (see Pl. XXXI). On the north, south, and west of these exposures the iron formation is known to occur. There is, consequently, an anticline of dolomite between the northern area of the iron formation, which is the basin of the Norway deposits, and the southern area, in which the Aragon deposits lie. The two folds—the Norway and the Aragon—are comparable with the Walpole-Pewabic folds farther west. The analogy is all the more striking since the Norway fold, like the Walpole, is a double syncline pitching to the west.

The northern side of the Norway syncline is quite sharply delimited on the surface by a number of dolomite exposures stretching for a distance of about 1,400 feet along a line running about N. 77° W. immediately north of the great open pits of the Norway and Perkins mines.

The south limb of the fold is indicated by the exposures in the southeast quarter of sec. 4, already referred to. To the east of the mine the country for some distance is sand covered, and there are no pits nor mine openings that yield information as to the nature of the underlying rock. Consequently the eastern limit of the fold can not be designated with any close degree of accuracy. A diamond drill located about 1,000 feet north of the south quarter post of sec. 4, however, encountered dolomite. Since this hole is nearly on the strike of the iron formation as exposed in the Norway and the Perkins pits, it is plain that this must terminate to the east before the position of the drill hole is reached.

In the underground workings of the Norway mine the syncline is beautifully disclosed, and it is by means of the mine explorations that we discover the syncline to be compound. At a number of places drifts and shafts have penetrated the dolomite or the slates that lie immediately above it. On the north side of the mine the upper contact of the dolomite dips south at angles varying between 45° and 65°. At the bottom of the mine the dips are flat for short distances and then on the south side of the ore basin they become northerly at steep angles (see sections on Pl. XXXII and fig. 18). The anticline thus formed nowhere reaches the surface, though its apex sometimes reaches a height of 100 feet or more above the bottom of the syncline. On the south side of the anticline the dolomite falls rapidly to the south and rises again in the anticline separating the

Norway and the Aragon ore basins. This southern portion of the Norway fold, which may be designated as the Cyclops syncline, has not yet been thoroughly explored, but we know that its north side at one place dips 60° S.

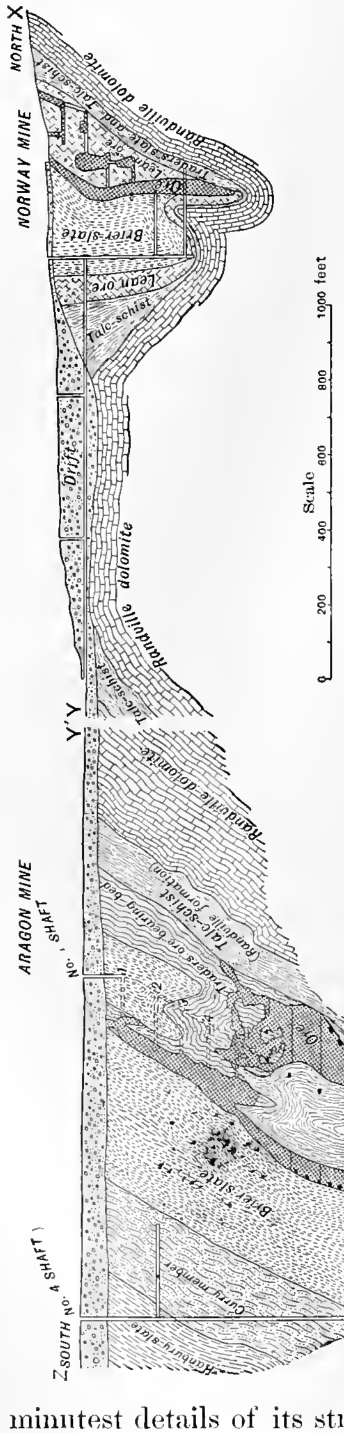


Fig. 18.—Vertical north-south cross section of the Norway and Aragon mines. Section along XY-Y'Z in Pl. XXXI.

An inspection of the cross sections of the Norway syncline will show that it differs from the more westerly folds in that its axial plane is either vertical or has a high dip to the south. The character of the Cyclops syncline in this respect is not known, although it probably also dips southward. The Norway fold must be a double east-west syncline, pitching to the west and in general dipping slightly to the south.

But the fold is not simply a pair of westward-plunging synclines. It is also gently folded along a north-south axis. A longitudinal section through the Norway pit (fig. 19) shows the dolomite rising under No. 8 shaft as a flat ridge and sloping down into valleys to the east and the west. It has been followed to the east until it again begins to rise in an anticline, but has not been traced to the surface. To the west it has been followed only sufficiently far to show that the dip of its upper contact is westward beyond the point at which it is flat.

Aragon fold.—The anticline of dolomite near the corner of secs. 4, 5, 8, and 9, already referred to, separates the Norway fold on its northern side from a southern fold in which lies the ore body of the Aragon mine. Although not developed on the surface, this fold has been so thoroughly explored by the lower workings of the Aragon mine that the minutest details of its structure at these depths are known. Like the Norway fold, the Aragon fold is also double, consisting of two synclines with an anticline between (see fig. 18). The northern syncline is, however, much

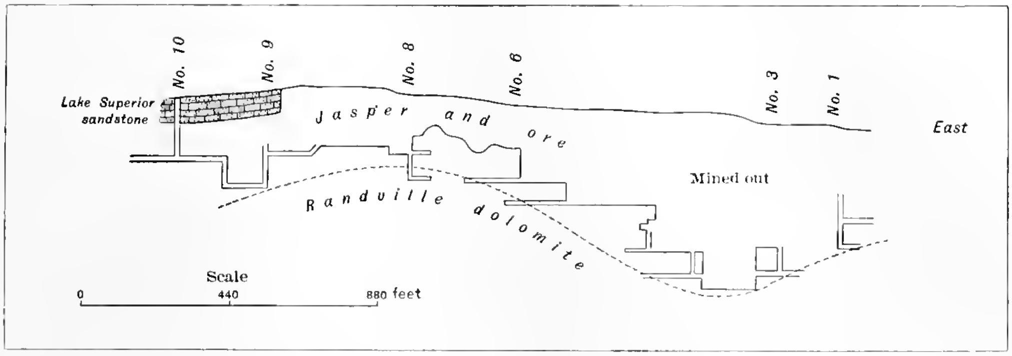


Fig. 19.—Longitudinal section through the Norway pit, showing position of dolomite beneath the ore. Only the bottoms of the shafts and lowermost galleries are shown.

larger than the southern one, which, measured from the crest of the anticline north of it, is only 100 feet in depth. The northern syncline is narrow,

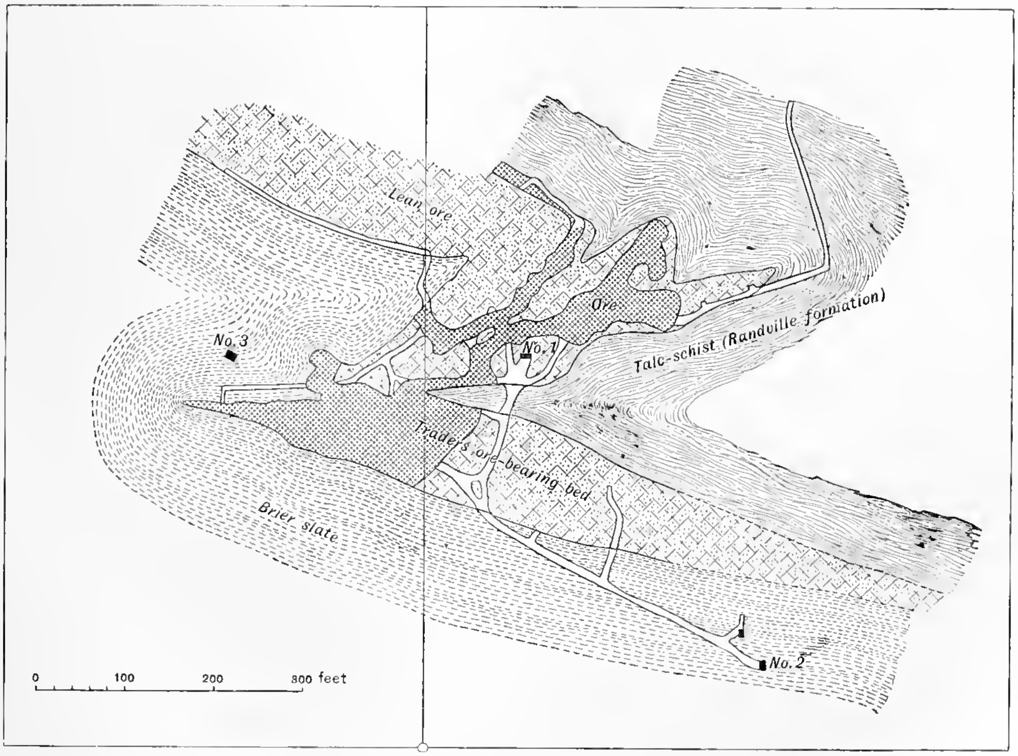


Fig. 20.—Horizontal section of the Aragon mine at the fifth level.

but its depth exceeds 800 feet. Both synclines are overturned to the north, the dip of their axial planes being about 70° S. Typical dolomite is rarely observed in the mine workings, but in its place is a talc-schist into which the dolomite seems to be altered on and near its contact with the overlying rocks. If this schist is an altered product of the dolomite, its contact with the overlying rocks delimits the dolomite syncline.

The plan of the fifth level of the mine exhibits a good horizontal section through the northern syncline and the anticline separating this fold from the southern one (see fig. 20). The plan of the sixth level (see fig. 21) shows in addition an apparently isolated mass of talc-schist, separated by ore from a more northerly mass of the same rock, which is plainly a lower

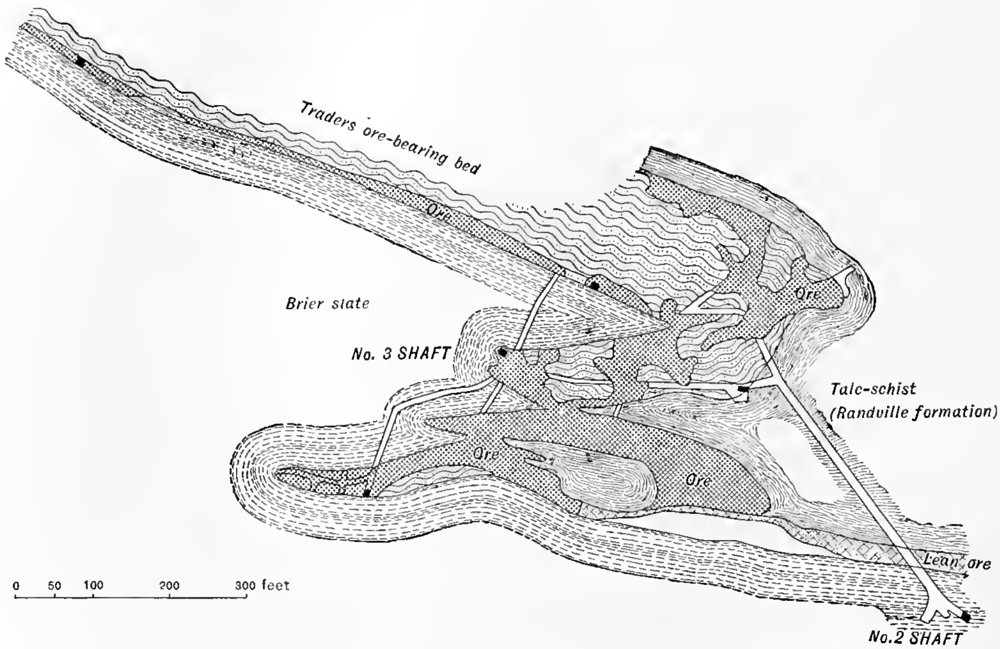


FIG. 21.—Horizontal section of the Aragon mine at the sixth level.

portion of the anticline cut on the fifth level. On the seventh and lower levels this mass is found to be joined with the main portion of the schist, and the intervening ore has disappeared. The isolated area of schist on the sixth level is thus a section through the upper portion of a dome-shaped mass of the schists that is united with the schist to the north and that to the east by synclines.

Projecting upward the contact of the schist with the iron formation north of No. 1 shaft, along a line whose direction corresponds to the average dip of this contact below the fifth level, we find the north side of the northern syncline reaching the rock surface about 75 feet below the top of the drift covering at a point about 400 feet south of the north section line of sec. 9. The southern side of the fold does not reach the surface. Its top, that is, the apex of the anticline, is at a depth of about 375 feet. To the west it is deeper, and to the east it becomes shallower.

The southern fold, as has been said, has a vertical dimension of only about 80 feet. Its northern limb is formed by the anticline just referred to. Its southern limb is formed by another anticline, whose apex is about 120 feet south of that of the more northerly one and a few feet lower. The relation of these anticlines and synclines are well shown on the cross sections of the mine reproduced in fig. 18 and Pl. XXXII.

In attempting to define the eastern extension of the Aragon folds on the surface we are met by the same difficulties as were encountered in attempting to define the eastern end of the Norway fold. At about 750 feet east of No. 1 shaft, however, a series of great ledges of dolomite begins and runs eastward continuously for over 1,000 feet (see Pl. XXXIII). Hence the fold can not extend farther in this direction. The projection of the trough of the syncline along its pitch, as calculated from its known position on the fifth and sixth levels of the mine, would bring it to the surface at just about the west end of these exposures.

In the discussions of the folds of the Aragon mine no reference has been made to the small folds imposed upon the larger ones. If the Aragon synclines are secondary folds, these smaller ones are tertiary. Upon these, in some places, folds of the fourth order are known to occur, but they have not been carefully enough worked out to warrant platting. The tertiary folds are well seen on the sides of the syncline shown in the plan of the fifth level of the mine (see fig. 20). This is the northern syncline. On the plats of some of the other levels tertiary folds are also indicated, but nowhere else are they as strikingly exhibited as on the maps of the fifth level.

West Vulcan fold.—East of the Aragon mine the southern margin of the dolomite belt is covered by thick beds of the Lake Superior sandstone, except at a very few widely scattered points. Moreover, the mining operations have disclosed the dolomite in only a few places within the underground workings. Therefore no definite folds of the dolomite series have been recognized in this portion of the belt. There are, however, abundant indications that such folds exist.

In contact with the dolomite and south of it is the belt of the iron-bearing Vulcan formation. In this several folds have been discovered by explorations for ore. In the western portions of the district, where both the dolomite and the iron formation are exposed, the former is seen to behave like the latter. Where this is folded the underlying dolomite is likewise folded, and the folds possess the same character as those of the overlying rocks. If the two formations behave in the same way in the eastern portion of the belt, and there is no reason to suppose that they do not, there must be several minor folds on the margin of the dolomite between the Aragon mine and Waucedah. The best defined of the folds in the iron formation has been developed near the west quarter post of sec. 10, T. 39 N., R. 29 W., on the surface, and in the West Vulcan mine underground (see figs. 45–50). The plan of this fold on the surface is shown on Pl. XXXIV. Its axis pitches nearly west and its axial plane probably dips nearly vertically. The corresponding fold in the dolomite to the north must have approximately the same pitch and dip. It is, however, covered by the Cambrian sandstone, and consequently is not visible. Its position on the surface must be somewhere near the center of the section.

Other secondary folds at the southern margin.—Another fold within the iron formation has been observed west of No. 3 shaft of the East Vulcan mine in the southwest portion of sec. 11, T. 39 N., R. 29 W. (Pl. XXXV), and within the workings of this shaft and No. 4 shaft of the same mine farther east (figs. 51–53). This fold, however, is known to exist only in the upper members of the Vulcan formation. Its presence in the lower member has not yet been recognized, and consequently it is not certain that the dolomite which is still lower in the succession was involved in the folding.

There are no other folds indicated along the southern margin of the southern dolomite belt, though they may exist. The country east of the East Vulcan mine has not been thoroughly explored, and until explorations are sufficiently numerous to delineate the margin of the dolomite area with a close degree of accuracy it will be impossible to declare whether folds exist in it or not.

Secondary folds at the northern margin.—The recognition of the existence of secondary folds along the northern border of the southern dolomite belt is dependent on the distribution of the dolomite with respect to the overlying rocks. The mapping of this distribution exhibits the fact that the dolomite contact in several places is marked by embayments (see pp. 205–206), which can only be explained as due to crumpling into synclines and anticlines. Corroborative evidence that such crumpling does exist at some of these places is afforded by the attitude of the dolomite beds at the apices of the assumed folds. The most notable instances of this kind of evidence are found in sec. 35, T. 40 N., R. 30 W., and sec. 3, T. 39 N., R. 29 W. Near the center of sec. 35, just east of the apex of a supposed anticline, a number of exposures occur along both sides of the branch of the Chicago and Northwestern Railway that connects with the main line east of Quinnesec (see Pl. XXXIX). The ledges consist of beds of quartzose and normal dolomite, which in places are distinctly schistose. In many instances the schistosity is parallel to the bedding, both having a strike of N. 70° to 85° W., and a dip of 78° to 80° N. to 70° S., but in several instances the bedding and the schistosity are at variance. The latter is more pronounced, but close examination of the ledges will always reveal the former. Often the two structures will be found to coincide, but in many cases the schistosity will be seen to cut the bedding at varying angles up to 90°. North-south strikes are sometimes observed and dips of 35° to 45° W. The platting of these indicates the existence of small folds at these points with a pitch of 30° to 40° W. Thus is corroborated the view that a fold of greater magnitude exists in the dolomite at this place.

In the southeast quarter of sec. 3, T. 39 N., R. 29 W., is a single exposure of dolomite, the bedding and schistosity of which are not coincident. The beds are much crumpled and the little folds seem to have a low pitch to the west. The location of the exposure is at the apex of the assumed anticline opposite the Norway syncline in the south side of the belt. Its presence adds plausibility to the mapping of a fold at this place.

In sec. 11, T. 39 N., R. 29 W., the presence of a marginal fold is also indicated by the existence of slates within the area, which, in the absence of a fold, would be occupied by dolomite. This is the only evidence of the presence of the fold in this place.

INTERIOR FOLDS.

In the interior of the dolomite areas indications of close folding are but rarely met with, and when seen the folds are not sufficiently characterized to warrant safe conclusions as to their exact nature. Moreover, it is only in the southern belt that they are exhibited. At several places in the interior of this belt the dips and strikes over small areas are in different directions, thus showing the presence of folds of some kind.

One of the places at which folding may be observed is at the west end of the hill north of the Chapin mine. Here a large ledge is exposed at from 670 to 780 paces west and from 560 to 650 paces north of the southeast corner of sec. 30, T. 40 N., R. 30 W. As a whole the layers composing the ledge are evenly bedded with a strike N. 74° W., and a dip 85° to 87° N., but some of the beds, consisting of thin layers of dolomite and quartzite, are folded within themselves into numerous sharp anticlines and synclines following each other in rapid succession. The axes of the folds plunge almost vertically to the north.

In the large ledges north and east of Quinnesec folding is common (see Pl. XXXIX). The beds in some places are crossed by faults with throws of a few inches to a few feet. In other places the rock is much fractured and all traces of bedding have been obliterated. In the southeast quarter of sec. 34, northeast of the Quinnesec mine, distinct crumplings are noted. In a few instances the beds strike nearly north. At one place a strike of N. 25° W. was measured, but this is maintained for only a short distance. The normal strike is N. 70° to 80° W.

In other portions of the belt the beds are for the most part very uniform in their strikes and for a given area also in their dips. These are for the most part nearly vertical, but occasionally, near the borders of all the belts, dips as low as 37° have been observed, and in one case a dip of 25° was measured, but in these instances the low dips are local phenomena, for the beds in neighboring ledges have high dips. These rapid local variations in dips indicate close folding, but since the strikes are maintained with a uniform direction the exact character of the folding is not discernible.

THICKNESS.

At no place within the area mapped is the dolomite known to be exposed from the bottom to the top. On the northern 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 we can not be sure that the dolomite occupies the entire breadth.

If, however, we assume that in the wider portions of the belt the entire formation is exposed, we are still unable to estimate its thickness accurately, since we know that it has been subjected to subordinate folding, and we can not determine the exact amount of duplication of beds resulting therefrom.

It is only in the southern area that data can be obtained for estimating even approximately the thickness of the formation. The width of the exposed portion of this belt is about 4,000 feet, measured across the strike of the beds north of the Quinnesec mine. The dips vary from 88° N. to 70° S. Assuming the dips to average 80° S., and the formation to be folded into a simple anticline, the corresponding thickness would be 1,900 feet. This estimate is, however, of little value, since, on the one hand, we can not know what proportion that part of the formation which is here exposed bears to the entire formation, nor can we, on the other hand, estimate the amount of thickening due to minor folding. That the entire formation is not exposed from bottom to top is evident from the fact that the contact with the underlying Sturgeon quartzite is not seen. Moreover, the layers of chert that are believed to be characteristic of the upper horizons of the formation are likewise absent, probably as the result of the erosion that took place between Lower and Upper Menominee time. In view of these facts alone, the estimate given above would seem to be too small. But minor folding must exist in this area. The variations in the strikes and dips of the dolomite beds northeast of Quinnesec have already been referred to as indicative of folding. Moreover, the existence of a syncline in the belt just east of the section under discussion (see pp. 239–240) has been mentioned. This syncline is so near the present section that its influence must extend to it, and an apparent thickening of the formation must be the result. How great the reduplication of beds due to these folds is can not be determined, but it is clear that the estimate given is higher than it should be were the formations not affected by them. Whether the estimate would be increased or diminished by the elimination of the doubtful elements from the discussion is entirely unknown.

In the center of sec. 12, T. 39 N., R. 29 W., we find the most continuous set of dolomite exposures in the district. Near the north-south quarter line the belt is about 3,000 feet wide and has an average dip of 55° S. This corresponds to a breadth of approximately 2,450 feet, which must be at least twice the thickness of the formation, since this belt is an anticline.

So far as we can learn, there are no minor folds here, so that 1,225 feet must be accepted as the greatest possible thickness of the formation exposed at this place. The entire formation, however, does not reach the surface, for the beds in the center of the belt—those at the apex of the anticline, and consequently the lowest members exposed—are not the basal members of the formation. Moreover, while the southern limit of the dolomite is well established by exposures of the Vulcan formation, it is not known whether the contact is at the top of the dolomite or whether some of this rock had been removed by erosion before the deposition of the iron formation. Further, the northern limit of the dolomite belt is not definitely known, for north of the exposures of this dolomite the country is covered with swamps and sand plains.

An estimate of the thickness of the formation based upon the above statement of facts would appear to be too small, because the lower and higher beds of the dolomite are not exposed. However, superimposed upon the major folds, as already pointed out, are many minor folds. To what extent the beds are duplicated by this minor folding it is practically imposible to determine. The difficulties here are practically the same as were met with in the attempt to calculate the thickness of the formation in the Quinnesec section. Although the data are more complete in these two sections than anywhere else in the entire district, there is still a great deal to be demanded before the calculations based upon them can be accepted as possessing a close degree of accuracy. If one should make calculations so as to obtain a minimum figure, 1,000 feet or less could be obtained. If, on the other hand, one were to make calculations on the supposition that all of the isoclinal beds in the sections are different layers, an estimate as great as 5,000 feet could be obtained. 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.

RELATIONS TO ADJACENT FORMATIONS.

Relations to underlying Sturgeon quartzite.—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 three dolomite ledges nearest to the quartzite are as follows: One in the northeast quarter of sec. 33, T. 40 N., R. 29 W.; one on the south bank of the Sturgeon River, near the center of sec. 8, T. 39 N., R. 28 W.; and the third in the northeast quarter of sec. 3, T. 40 N., R. 30 W. None of these ledges are so near the quartzite that they can be said to represent undoubted transition phases between the two formations. They unquestionably indicate the character of the transition, however, for all three ledges are near the base of the dolomite series, and all three are composed largely or exclusively of quartzose dolomites. The westernmost ledge has already been described in some detail (see p. 193). That in sec. 33 is compact in the interior and drusy on the surface. The easternmost ledge is friable and sandy. The inference seems to be safe that the two formations grade into one another through dolomitic quartzites or quartzitic dolomites, and therefore that they are conformable.

Relations to overlying Negaunee formation.—While there is no evidence that any of the Negaunee formation now occurs in the Menominee district, there is abundant evidence that it occurred above the dolomite before the erosion interval that separates the Lower Menominee and the Upper Menominee series. In most places the erosion not only removed the Negaunee formation, but it also cut down into the Randville series, and in most places removed its upper portions. In a few places above the normal dolomite there still remain beds of cherty quartzite, sometimes brecciated, but at other times nonbrecciated, and distinctly bedded. The nature of the cherty quartzite suggests the idea that it may represent a transition between the dolomite beneath it to an iron formation that may have been immediately above it. In its macroscopic, as well as its microscopic character, the cherty rock resembles some phases of the jaspilites associated with the ores of the Marquette district. The pebbles in the conglomerates that prove the former existence of the Negaunee formation in the Menominee district show that the iron formation in this district was identical with the corresponding formation so well developed in the Marquette district. While conclusive evidence of the fact is lacking, nevertheless it is probable that the formation which in this report has been called the Randville formation graded into the now absent Negaunee formation through these cherts. It is possible that had a considerable quantity of the iron formation remained for study the line between this formation and the underlying dolomite series would be found more naturally to belong between the dolomite and the cherty quartzite than at the top of the latter rock, which would then belong at the base of the Negaunee formation as the lowest portion of a jaspilite member.

The relations of the dolomite with this rock would thus become significant. So far as has been observed in the few cases where contacts have been seen, the dolomite and the nonbrecciated phases of the cherty quartzite are conformable. The contact between the two is in some cases sharp, a well-defined layer of chert resting directly upon dolomite. In other cases the two rocks seem to grade by interlaminations. This seems to be the condition just north of the Norway pit, where near the top of the dolomite at this place a few alterations of the typical carbonate with a red cherty quartzite occur, and where occasionally what look like veins of the latter rock penetrate the underlying rock. There are no definite cherty beds of any great thickness above the dolomite at this place, though the chert seems to be most prevalent in the uppermost of the exposed horizons.

The shattered and jointed character of the autoclastic breccias makes it exceedingly difficult to discern the true relations of these phases of the rock to the dolomite with which they are in contact, though there seems to be little doubt that they are also conformable with the underlying rock. No place has been seen where the cherty breccias are in direct contact with the members of the underlying formation, except at Iron Hill, where the cherts are associated with a dolomite conglomerate. But at this place the relations are so exceedingly complicated that little can be learned from them (see p. 256).

Relations to basal member of the Upper Huronian.—Contacts between the dolomite and the overlying formation of the Upper Huronian 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 an iron formation are very close together, but their actual contact is covered. The dolomites and the slates on either side of the contact plane strike N. 81° W., and dip 65° S., and no evidence of discordance between them can be discovered. However, 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. The presence of the jaspilite fragments in the conglomerate is proof that beneath this rock layer there existed somewhere in the Lower Menominee series an iron formation containing considerable jasper. This formation has now completely or almost completely disappeared, so far as the surface indications show. It is assumed that it has been cut away by erosion, and that its débris furnished the jaspilite fragments in the conglomerate.

In the mines and the open pits a similar conglomerate or a coarse quartzite is frequently found lying upon the dolomite. Jaspilite fragments can not in all places be detected in it, but they can be observed in so many localities that the only acceptable interpretation of the phenomenon is that the dolomite and the quartzite are separated by an unconformity. The contact between the two rocks is sharp. There is no gradation of any kind between them. The dolomite near the contact is usually schistose, so much so that in most cases it is a talc-schist. The schist was probably formed in connection with movement along the contact plane after the Upper Huronian deposits were laid down and contemporaneously with the folding and metamorphism that affected both the Lower Menominee and Upper Menominee series. 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 formation is not a coarse quartzite, it is usually a bedded red slate; or more nearly a schist composed of small grains of quartz and considerable dolomite and sometimes 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. At the open pit of the Indiana mine this rock is represented by a fine-grained pink and gray slate that lies between the dolomite to the north and the iron formation to the south. The rock may be seen in the north wall of the pit, but its contact with the dolomite is covered. Drill holes in the vicinity of the mine which encountered the slate passed through about 25 feet of it directly into the dolomite. In the records this slate is spoken of as a "broken slate" formation, by which it is inferred that the rock is either brecciated or conglomeratic. If the latter, it is confirmatory evidence of an unconformity between the dolomite and the bottom of the iron formation.

At the Norway open pit and in the pits in the northeast quarter sec. 9, T. 39 N., R. 29 W., the original relations existing between the dolomite and the overlying iron formation have been greatly obscured by deformations due to movement. The overlying iron formation is a coarse schistose conglomerate or breccia composed of fragments of dolomite, slates, and ore, in a matrix composed of the same substances subsequently enriched by the deposition of ferruginous material. Many of the fragments are angular, others are rounded. In some instances the brecciated bands may be seen to cut diagonally across unbrecciated layers of the same composition, indicating that the former is autoclastic in origin (see Pl. XXI, *B*). The more conglomeratic phases are usually richer in dolomitic fragments than are the brecciated phases. Their material is more varied in character and their inclosed fragments more pebble-like. In all its aspects the rock much resembles a sedimentary conglomerate. But it is also brecciated. Large-sized angular fragments of the rock are here and there scattered through a conglomeratic matrix of the same composition as the fragments.

The rock underlying these brecciated ones is either a talcose schist, or slate, or a quartzose dolomite. In each case this rock also is brecciated, the included fragments and the inclosing matrix being of the same composition. There is in some localities a gradation between these underlying rocks and the rocks lying above them, while in other places the line of division between them is well defined. Often there has been extensive movement along this crushed zone, as indicated by the schistosity of both breccias. This has resulted in a very irregular contact between the two, causing the relations between them to be so obscure that they are difficult to decipher. The only probable explanation of the facts observed seems to be that the conglomeratic rock is a true conglomerate which was deposited on the eroded surface of the dolomite and then, together with the underlying rock, was brecciated and rendered schistose by the accommodation movements along the contact plane that took place when the district was folded. If this view is correct, the presence of the conglomerate above the dolomite is further evidence of an unconformity between the dolomite series and the overlying iron formation.

Relations to other formations.—The relations existing between the dolomite and the contiguous formations younger than the base of the iron formation will be discussed in connection with the descriptions of these formations (pp. 361 and 366).

INTERESTING LOCALITIES.

Although the dolomite series is for the most part covered by the Lake Superior sandstone, there are many places where excellent exposures can be studied. These are mainly in the area of the southern belt and generally near the transverse gaps that have been described as crossing the belt at several places, or on the southern slope of the ridge of hills north of the line of the most important mines. Though no continuous section across the entire formation has been seen, nevertheless it is thought that practically all of its beds from bottom to top are exposed at different places.

IN THE NORTHERN BELT.

Northeast quarter of sec. 3, T. 40 N., R. 30 W.—The only exposures of the northern belt that are at all extensive are those in the northeast quarter of sec. 3, T. 40 N., R. 30 W., and those in the northeast quarter of sec. 14 in the same town. The former have already been described in connection with the description of the near-by exposures of Sturgeon quartzites (see p. 193).

Northeast quarter of sec. 14, T. 40 N., R. 30 W.—Near the north quarter post of sec. 14, T. 40 N., R. 30 W., four distinct ledges outcrop on the south slope of the valley of the stream that empties into Pine Creek at Hamilton and Merryman's camp No. 6. They occur along a line trending about southwest, and, taken together, they exhibit a cross section of the formation about 800 feet in length. The northernmost ledge, which is on the north line of the section, 250 paces east of the quarter post, is a massive, white, crystalline, dolomitic marble without noticeable strike or dip. About 75 paces east and the same distance southwest are two other ledges in which the rock is a dolomitic quartzite, likewise without distinct strike or dip. The southernmost ledge, about 100 paces east and 225 paces south of the quarter post is a fine-grained, nearly pure white quartz rock that strikes N. 75° W. and dips 75° N. It is indistinctly marked by pink and light-gray bands that apparently indicate bedding, and is traversed by a great profusion of quartz veins. In some places it is cellular or drusy. On a fresh fracture the luster is dull and resinous and quite unlike the vitreous luster of the Sturgeon quartzites. The rock is a fairly good type of the cherty quartz rocks occurring at the top of the Randville formation. The exposure is interesting as indicating the near proximity of the upper boundary of the dolomite formation.

IN THE CENTRAL BELT.

In the area of the central belt the only exposures of note are those just west of the Cuff mine, in the southwest quarter of sec. 22, T. 40 N., R. 30 W., and those at Iron Hill, in sec. 32, T. 40 N., R. 29 W.

Southwest quarter of sec. 22, T. 40 N., R. 30 W.—In the southern portion of the southwest quarter of sec. 22, T. 40 N., R. 29 W., and the neighboring portion of sec. 21 are six isolated little knobs of typical dolomite, forming together a ridge of ledges extending for about half a mile along the north side of the road from Lake Antoine to the Cuff mine. Some of the ledges are in sight of the road. These appear as rough knobs partially covered with trees and bushes. Others are buried in scrubby second growth and are invisible from short distances. The exposures are interesting mainly as illustrative of the massive character of much of the dolomite and as evidence of the existence of the Randville formation between the Cuff mine and the Indiana mine. The rock in the ledges is a massive pink or gray dolomite, heavily bedded, with indistinct bedding structure striking about N. 70° to 80° W. and dipping vertically. The exposures are traversed by gaping cracks or hollows where weathering has opened up the bedding planes, and by cross gashes opened up along joint cracks. Their surfaces are therefore rough and rugged, with projecting portions separated by hollows.

Iron Hill.—The central belt of dolomite terminates on the surface in the southeast quarter of sec. 32, T. 40 N., R. 29 W., where dolomites, cherts, breccias, and conglomerates occur in such relations as to suggest the presence of an eastward-pitching anticline with superimposed minor folds. The exposures at this place have already been referred to several times on preceding pages (pp. 219–220, and 234 and Pl. XVI, *B*, Pl. XVII, *A*, and Pl. XLII). They are easily reached from Norway by the road running north around the east end of the Norway open pit.

The ledges constitute a little plateau overlooking a swamp to the south and southeast. The southern limit of this plateau is a steep slope broken at four places by projecting buttresses of rock with precipitous fronts ranging from 15 to 20 feet high. On the top of the plateau the exposures are all of one kind except at the eastern end. Together they form practically a continuous ledge about a quarter of a mile long and from 200 feet to 500 feet wide, extending in a direction N. 60° W. The main portion of the ledges is a well-bedded, light-gray or dark-gray dolomite dipping nearly vertically and striking N. 50° to 60° W. Interbedded with this are a few thin layers of a very schistose quartzose dolomite. North and west of the ledges the ground rises toward a low hill underlain by the Lake Superior sandstone with a basal layer of conglomerate, which can be well seen at several places on the east of the dolomite along the eastern slope of the plateau and in the valley at its eastern base. On the slope the sandstone conglomerate occurs as patches lying upon a cherty quartz rock and a chert breccia in such a way as to permit of no doubt that it is unconformably above them. Although this rock in many places consists largely of cherty and dolomitic fragments in a cherty and dolomitic matrix, it nevertheless grades upward into a horizontally bedded rock with the characteristics of the normal Cambrian sand rock. The rocks beneath this conglomerate, while in many places possessing the same general appearance as the latter, are a little more compact. They moreover show abundant evidences of folding and are cut by joint cracks and penetrated by quartz veins, both of which features are lacking from the sandstone conglomerate. Farther up on the slope cherts are well exposed in a number of small ledges. In some ledges the rock is a fine-grained, pink, homogeneous quartzite indistinctly bedded and folded into definite folds. Most of the ledges, however, especially those to the south, consist of a cherty breccia composed of sharp-edged fragments of a white chert lying in a pink or red matrix composed of small grains of the same white chert in an extremely fine-grained siliceous groundmass that looks not unlike a red felsite. This chert breccia may be seen in places to lie upon the dolomite. It also occurs as patches plastering the faces of the little cliffs overlooking the swamp to the south and as layers a foot or two thick coating these cliffs and bending up over them (see Pl. XVII, *A*). The main rock in the cliffs is a dolomite conglomerate which differs from the chert breccia in the nature of its pebbles and also in the character of its groundmass. The rock is dark gray in color when viewed in the ledge. Its matrix is an almost black cherty dolomite with intermingled quartz grains, cut by tiny veins of calcite and quartz. In this are numerous pebbles of all shapes and sizes, the largest 20 inches in diameter. The majority are elongated and lie with their larger dimensions in approximately the same direction, though variations from this position are very numerous. Most of them consist of dolomites; the remaining ones are mainly white chert, though a very few consist of quartz or quartzite. Many of the dolomite pebbles still retain their bedding lines, and these run in all directions across the pebbles irrespective of their elongation, though naturally, in the greater number of cases, the bedding and elongation are parallel. Both pebbles and matrix alike are traversed by many fractures that have been cemented by quartz, forming veins which now stand up as tiny projecting ridges intersecting one another diagonally. Some of these may be seen in Pl. XVI, *B*. The main fracture lines intersect one another at angles of 40° and 140°, the acute angles opening in a direction a little to the east of north, about 20°, and to the west of south, and the obtuse ones nearly east and west. Since the beds are probably folded and the apex of the folds strike about N. 60° W., and pitch steeply to the east, the direction of the joints and their angular relations correspond very closely to the directions which they should have according to the discussions of Van Hise.[a] On the horizontal surfaces of some ledges a third set of joints may be observed that appear as a series of fine parallel cracks nearly bisecting the obtuse angles of the two main sets. This series in direction nearly coincides with the strike of the beds as observed in other ledges. Along the main-joint cracks minor displacements have often taken place and the rock within a small fraction of an inch on both sides of the fractures has been sheared. Moreover, many of the pebbles are mashed and faulted, thus showing that the district was deformed after the conglomerate was laid down.

In the ledges forming the cliffs the conglomerate appears to overlie the chert breccia in some places, but in others the reverse condition obtains. In the eastern ledges, as has been stated, the breccia is usually above the bedded dolomite. In one of these ledges, however, the chert breccia is interbanded with beds of massive dolomite. Although the breccia in the eastern ledges and the conglomerate in the southern and western ledges appear to be very different rocks, if one begins at the east and traces carefully the breccia, step by step, in the successive ledges, he must be struck with the fact that the breccia fragments become more and more rounded as he proceeds westward, and the rock assumes more and more the character of a conglomerate, until finally the typical conglomerate is reached. No

[a] Principles of North American pre-Cambrian geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1894, pp. 651–654 and 671–672.

line of demarcation between the two rocks can be detected, but the one seems to grade imperceptibly into the other. This observation suggests the possibility that the conglomerate is an autoclastic rock and that its conglomeratic character is due to the easy attrition of the dolomite pebbles as compared with the difficult attrition of the chert fragments in the breccia. At one place toward the east end of the hill a conglomerate band is between solid ledges of dolomite, and is in such a position as to indicate that it cuts diagonally across the bedding of the nonconglomeratic rock.

These relations between the dolomite, the chert breccia, and the conglomerate are exceedingly complicated. The attempt to interpret them leads to one or the other of the following conclusions: (1) The conglomerate may be a true sedimentary intraformational conglomerate whose complex relations to the remainder of the Randville dolomite are due to the crushing and close folding to which the series at this place has been subjected; (2) the conglomerate, like the breccia, may be an autoclastic rock formed by crushing and abrasion of the autoclastic fragments which in the case of the breccia, because of their hardness, retained their sharp-edged forms; or (3) it may be a true conglomerate at the base of the Hanbury slate, made to appear like an intraformational conglomerate by repeated close folding at the end of the eastward-pitching anticline which terminates the dolomite belt. Since several minor folds are superimposed on the anticline the conglomerate would naturally be folded in between the underlying dolomite, and upon erosion would appear as an intraformational conglomerate. In this case the chert breccia would have to be considered a sedimentary rock. The difference in the character between it and the conglomerate might be due to the fact that the former was deposited against a shore composed of chert and the latter against a dolomite shore line from which the overlying chert had been removed by erosion. The Hanbury slate—an Upper Huronian formation—borders the dolomite to the south and the east, though its contact with the dolomite is not visible. The normal Hanbury slate is a typical gray argillaceous rock quite different in composition from the conglomerate and breccia, but this difference is easily explained by the latter rocks being the first deposits along a shore line composed of dolomite and chert.

While the third view is the one that seems most satisfactory to explain the phenomena, nevertheless there are a few facts that are not explained by it. The presence of a band of conglomerate cutting diagonally across several dolomite beds is explained best by the second view. If the breccia and the conglomerate do not actually grade into one another as they have been described to do, it is possible that the breccia is an autoclastic rock and the conglomerate the basal member of the Hanbury series. The inability to distinguish a line of demarcation between them may well be due to exceedingly close folding and a welding together of the two rocks where they are in contact. No unprejudiced observer, however, after reviewing the facts impartially, would be willing to declare without reservation that the conglomerate is not a member of the dolomite formation; nevertheless, after repeated visits to the ledges and careful examination of them, it seems most plausible to regard the conglomerate as the basal member of the Hanbury formation and the breccia as an autoclastic rock formed from the uppermost (cherty) members of the dolomite formation by the fracturing that accompanied close folding. That the whole series of deposits in this place was indeed fractured is shown by the numerous quartz veins that traverse them, but since these veins cut indifferently all the rocks, the conglomerate as well as the massive dolomites, and the pebbles in the conglomerate as well as its matrix, this fracturing must have taken place after the conglomerates were laid down. It is conceivable, of course, that before the conglomerate was made, an earlier fracturing took place and that its effects are preserved in the breccias.

IN THE SOUTHERN BELT.

In the southern belt of dolomite the opportunities for the study of the formation are exceptionally good. Exposures are fairly abundant, and, though limited very largely to the south side of the belt, they exhibit the character of the formation in all its phases. Some of the most interesting groups of exposures are those discussed in the following paragraphs. There are many others in addition to those described that are worth study, but these represent all the phases of the formation, and, besides, they are easily accessible.

Southeast side of Lake Antoine.—The ledges on the southeast side of Lake Antoine are best reached by the road from Iron Mountain that passes along the south side of the lake. They form a little hillock on the east and south sides of the road almost due east of the little island in the southern portion of the lake.

The rocks outcropping on the top and along the south slope of this hillock are well-bedded dolomites and dolomitic quartzites, the latter often exhibiting cross bedding. The surfaces of the ledges are roughly corrugated. The dolomite, weathering more rapidly than the quartzite, forms the hollows of the corrugations, while the quartzite forms the ridges. All the beds dip vertically and strike N. 71° to 75° W. The predominant dolomite is a bluish-gray rock, containing here and there a grain of quartz. It is cut by small veins of quartz, and others of a mixture of quartz and dolomite. On a fresh fracture surface the rock is fine grained, homogeneous, and entirely massive. On the light-brown weathered surface, however, many very distinct oval grains of quartz are apparent, scattered indiscriminately through the rock in particles measuring a millimeter in their longest diameters, which are nearly always in the plane of the rock's bedding. Moreover, the rock appears distinctly schistose through the presence of a great number of very thin seams of argillaceous dolomite, which run parallel to the bedding for short distances and then disappear, their places being taken by other seams starting near the terminations of the first ones and disappearing in turn a centimeter or so beyond their starting points. The effect of these seams, which are approximately parallel, but which sometimes make very acute angles with one another, is to break the surface up into a number of elongated areas, some of which are flat rhombs, thus producing an appearance of schistosity. There is no evidence of shearing in the dolomite. The phenomenon just described is probably a direct result of sedimentation.

Interbedded with the gray dolomite is a lighter-colored one of a pinkish-gray tint, that differs from the gray variety only in color and in the presence of a few more quartz grains. The dolomitic quartzite is evidently only a very quartzose phase of the dolomite. It forms beds from 1 inch to 2 feet in thickness between beds of the dolomite. Often these are so very quartzose that the rock weathers with a surface almost identical with that of the Sturgeon quartzite. These ledges are interesting as exhibiting the best illustration of the interlaminations of dolomitic and quartzose beds observed in the district.

Southeast quarter of sec. 32 and southwest quarter of sec. 33, T. 40 N., R. 30 W.—The upper cherty members of the dolomite series are well shown in the large ledges occurring in the southeast quarter of sec. 32, and the southwest quarter of sec. 33, T. 40 N., R. 30 W., south and southwest of the Pewabic ore pit near the east quarter post of sec. 32 (Pls. XXIX and XXXVIII).

Through this area a number of hillocks of dolomite occur, forming a little plateau whose south escarpment consists of little cliffs faced with a porous, mottled red and white, drusy and saccharoidal quartz rock, crossed by numerous narrow streaks of a darker red color and gashed by short, irregular crevices. No bedding can be discovered in the quartz rock, but on the plateau a little back from the edge of the cliff dolomite occurs with a well-defined strike N. 66° W., and an almost vertical dip. The narrow dark-red streaks that traverse the quartz rock run in approximately parallel directions. They seem to be tiny veins of quartz that occupy crevices parallel to the bedding planes. In places the cracks which they occupy widen out and hollows are formed, the walls of which are covered with druses of tiny quartz crystals. Often the veins anastomose, cut across the portions of the rock included between two parallel veins, and separate it into isolated portions that look like fragments derived from a preexisting rock. Near the top of the cliff the vein material predominates over the fragments, causing the rock to resemble a typical breccia composed of sharp-edged white chert and fine-grained quartzite fragments in a dark-red quartzite matrix. In other places, probably where movement within the rock mass has separated fragments, crushed some and caused others to assume new positions, quite different from their original ones, the rock resembles a basal breccia or conglomerate of the Lake Superior sandstone, from which it can be distinguished only by the coarser grain of the latter rock and the greater drusiness of the former. At the top of the cliff and a little back from its face the two rocks are in contact, the sandstone breccia overlying the cherty quartz breccia. Even when so near together, it is not always possible to discriminate between the two. From the base of the sandstone breccia veins and dikes of sandstone extend down for some little distance into the cherty rock. Back from the edge of the cliff, for a width of 100 paces or more, the dolomite is well exposed in an almost continuous ledge of a pink and gray fine-grained massive rock, cut by the usual quartz veins. The dips and strikes vary somewhat in different portions of the ledge, but the general strike is N. 66° W. for the southern portion of the exposure and N. 80° W. for the northern part. The dip remains nearly constant. Where good observation can be made it is about 85° to 87° S.

Farther east the dolomite is exposed in a number of smaller ledges that rise above the general surface of the country in little hillocks. Here the strike bends a little farther to the west and the dip in some places is as low as 37° S. The tops of the hillocks in several instances, both in secs. 32 and 33, are covered with remnants of the basal Lake Superior conglomerate, which to the north is replaced by the usual sandstone that nearly everywhere caps the high ridge lying north of the belt of mines along the main line of the railroad. This conglomerate, or, in some places, more properly breccia, is made up of many angular fragments of quartzite in a red sandy matrix, which in some instances is highly calcareous. At the Pewabic pit it consists of many bowlders of a high-grade iron ore embedded in a sandstone matrix which differs from the ordinary sandstone simply in being admixed with considerable finely comminuted ore. At several places within and near the pit the conglomerate can be seen resting unconformably upon the underlying dolomite, with its horizontal beds capping the upturned beds of the dolomite and filling all the many irregularities of its surface.

North and northeast of Quinnesec.—Another interesting group of exposures is in secs. 2 and 3, T. 39 N., R. 30 W., and secs. 34 and 35, T. 40 N., R. 30 W., north and northeast of Quinnesec. The most instructing ledges are easily reached from the wagon road between Quinnesec and Norway and from the branch of the Chicago and Northwestern Railway running through secs. 2 and 35. These exposures have already been referred to several times in previous pages (see pp. 239–240, and Pl. XV, *A* and *B*, and Pl. XXXIX).

Just north of the Norway wagon road, east of Quinnesec and parallel to it, an almost bare ledge extends for a quarter of a mile, forming a series of rough knobs with nearly precipitous south sides (see Pl. XV, *A* and *B*). The rock of these knobs is a heavily bedded light-gray, fine-grained, and usually massive dolomite, striking N. 70° W. and dipping 70° to 80° S. It is banded with the usual quartzose dolomite layers, and is cut by small irregular quartz veins.

To the north and northwest of this are other ledges of smaller dimensions in which the rock is similar. The strike, however, is more nearly east and west, and the dip is much higher, sometimes being vertical or even slightly inclined to the north. The color of the rock also changes to dark gray, pink, or red. Here and there the beds show strong evidence of compression in the existence of a well-marked schistosity. Usually the schistosity escapes detection because it is parallel to the bedding, but in the ledge 200 paces north, 25 to 150 paces east of the southwest corner of sec. 35 the schistosity is inclined to the bedding at 15°, so that the two structures are easily differentiated. The strike of the bedding in this ledge is N. 70° W. and that of the schistosity is N. 55° W.

In the southeast quarter of sec. 34 there are also ledges in which the strike of the bedding and the schistosity depart even more from parallelism. In all these instances it is usually the bedding that is disturbed, the schistosity striking nearly uniformly in a direction N. 55° to 70° W., while the strike of the bedding varies between this direction and due north. Here, too, and in the neighboring portion of sec. 35, there are many exposures in which minor faulting of a few inches to a few feet is noticeable and some ledges in which the dolomite is much fractured and all traces of its original bedding are lost. These disturbances are plainly connected with the great fold at Quinnesec (see p. 239), since in other portions of the district at a distance from known folds disturbances of this kind are lacking.

The exposures along the branch railroad exhibit one of the best sections across the formation anywhere met with in the district. In length it measures a little over three-quarters of a mile. If the view with respect to the structure advanced in previous pages (see p. 239) is correct, the section cuts a broad anticline to the south, a narrower one to the north, and a narrow syncline between these. The rocks of the southern half of the southern syncline are described in the preceding paragraphs. Those of the remainder of the section are somewhat different from these, and are described in the following paragraphs. The difference is probably due to the fact that the northern portion of the section is through the upper portions of the formation while its southern part is across lower portions, the upper members having been removed by erosion during inter-Huronian time.

The exposures along the railroad embrace a dozen or more ledges, some small and some large, lying on both sides of the right of way. Those in sec. 2 and in the southeast quarter of the southwest quarter of sec. 35 are mainly even-bedded massive and schistose dolomites like those described above. In some places the roadbed passes through solid ledges in open cuts that exhibit beautifully the massive character of the rock. At the stream crossing about 400 feet north of the south line of sec. 35 the exposures are particularly good, since in addition to the railroad cut there is here a natural section made by the stream which tumbles through a little gorge in a series of small cataracts and rapids. In all its essential features the dolomite here is like that to the south. It is banded by thin parallel seams of argillaceous dolomite, that extend from the weathered surfaces as little projecting ridges, and is cut by the usual quartz veins. The strike is N. 85° W., and the dip is 85° S. North of the stream the road traverses a swamp which drill holes show to be underlain by Lake Superior sandstone lying above dolomite.

North of the swamp, toward the center of sec. 35, exposures again begin, and extend north almost continuously on both sides of the road for a distance of about 800 feet. The ledges are usually small and flat on the east side of the road and somewhat larger and more knob like on the western side. There is no regularity in the succession of beds exposed, though slates and conglomerates predominate toward the south and dolomites toward the north. Traveling northward, and examining the ledges now on one side and now on the other side of the roadbed, we find first a series of black slates, dolomitic quartzites and conglomerates, and pink dolomites, followed by interbedded gray slates and dolomites, and finally a succession of thick beds of bluish-gray dolomite.

The black slates, quartzites, conglomerates, and dolomites are definitely interbedded. The slates are dark-gray, almost black, rocks with thin laminæ preserving the bedding very perfectly. The cleavage is parallel to the bedding, which strikes about N. 70° W. North of the slate ledges are others in which the interbanded quartzites and dolomites are well exposed. The quartzites are rather coarse-grained pink varieties composed largely of intermingled quartz grains and crystalline dolomite. Their beds, varying in thickness from a few inches to 2 feet, weather with a dark-red color and a rough porous surface. In them are occasional fragments of dolomite, of a dark-gray, fine-grained rock resembling chert in its general appearance, and of a white or light-colored schist that looks something like the light-colored slates associated with the dolomites farther north. In a few ledges the fragments are so abundant that the rock may be denominated a conglomerate. From the relations of the conglomerate to the quartzites and the dolomite, it is clear that it can mark no important stratigraphic break in the series. It is intraformational. The dolomite interstratified with the quartzites and conglomerates is also pink in color. On fresh fractures the principal difference noted between the first two rocks named is the finer grain of the dolomite and less abundance of quartz grains in it. Quartz is present, however, but only in small grains and in no great quantity. The weathered surface of the dolomite is depressed below that of the quartzite and its texture is much more finely granular. Ledges in which both rocks occur have therefore a corrugated surface made up of projecting bands of a coarsely granular structure alternating with depressed bands of a finely granular structure.

Farther north slates again appear. These, however, are unlike the dark slates to the south. They are usually light gray, more or less schistose rocks containing considerable dolomite, constituting beds from a few inches to 50 feet in thickness. In all their essential features they resemble very closely the slates associated with the Kona dolomite in the Marquette district.[a] None of the wider beds are composed exclusively of slate. There are always interlaminated with this rock thin seams of dolomite, but the slate predominates. Alternating with the beds composed principally of slates are others composed exclusively of dolomite. As we proceed northward we find the dolomite becoming more prominent, the northernmost ledges consisting exclusively of this rock. The dolomites in this portion of the section are schistose bluish-gray varieties interlaminated with thin layers of a more siliceous phase that projects above the general surfaces of the ledges as dark-red ridges no thicker than sheets of wrapping paper. In many places the ridges are crinkled and closely folded, while the dolomite between them seems to be quite devoid of any evidences of minor contortions. The schistosity of the dolomite strikes N. 70° to 80° W. and dips 70° to 80° S.; i. e., it is concordant with that of the rock elsewhere throughout this portion of the district. In some ledges the bedding and schistosity strike and dip in the same directions, but in most exposures the two structures intersect each other at greatly varying angles, the strike of the bedding changing rapidly within short distances. In the two small ledges on opposite sides of the roadbed at the northern end of the section definite folds pitching to the west are plainly apparent. In the ledge on the west side of the road the schistosity strikes N. 85°

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 244–245, 259–260.

W. and dips 78° to 80° N. This is the most prominent structure and the one most easily discerned in the ledge. Close inspection will show, however, that the little projecting quartzose layers referred to above do not always run in this direction, but that, on the contrary, they frequently depart from it very widely, the variation in the two directions sometimes amounting to 90°. Since these bands mark the bedding, it becomes plain that while the two structures, bedding and schistosity, coincide in some places, in others they are distinct, and the difference is due to the variation in the bedding. An inspection of the bedding shows a fold pitching to the west at an angle of 35° to 40°, which accounts completely for the discrepancies noted in the two structures. On the east side of the road a similar condition obtains, except that the strike of the schistosity is N. 70° W. and its dip 70° S., and the pitch of the fold 30° to 40° W. The presence of minor folding at this place has been used as an argument in favor of the existence of a larger fold in the series (see p. 247).

Northwest quarter of sec. 9, T. 39 N., R. 29 W.—The south half of this quarter section is underlain by the iron-bearing Upper Menominee beds and by Hanbury slates. In its north half are magnificent exposures of the dolomite formation, showing nearly all of its phases, except some of the slaty ones. Just east of the Aragon shaft No. 1 is the mouth of a little gully about 130 paces wide (see Pl. XXXIII), which extends a few degrees south of east for about a quarter of a mile. Its north side and east end are bounded by high and almost precipitous ledges of dolomite and its south side by a low ridge of jaspilite and quartzite belonging with the Vulcan iron formation. The latter will be described in another place (p. 435). The floor of the gully is flat and even. It is now occupied as a little garden patch, but was evidently once more or less swampy It is probably underlain in part at least by talcose schists. The cliffs on the north side of the valley rise abruptly from the valley floor to a height of about 50 feet, forming the south side of a little range of rough hills which separate this valley from the great plain that extends eastward from the open pits of the Norway and Perkins mines. The hills are nearly bare of vegetation, but a light covering of soil obscures the relations of the rocks to a considerable extent. Bedded and brecciated dolomites, brecciated cherts, and a few light-colored slates constitute the principal rock types exposed. For the most part the distinctly bedded rocks strike about N. 65° W. and dip between 40° and 50° S., but at the eastern and western ends of the range the rocks are in plunging folds that naturally cause rapid variations in strikes and dips. In many ledges, moreover, even where the dolomite layers have a uniform strike, the slates interbedded with these are deformed into many little folds.

In the little hillock at the west end of the ridge the folding is very pronounced. On the top of the hillock dolomites and slates are well exposed, with strikes varying between N. 83° E. and N. 70° W. and dips between 30° and 45° S. Small folds are abundant in the slates, and several larger ones affect the slates and dolomites alike. On the east side of the exposed surface these pitch to the west and on the west side they pitch to the east.

Southeast of this exposure is another one forming a westward-facing bluff. In this the strike of the dolomite beds varies from north on the northwest side of the cliff through N. 45° W. to N. 70° W. on its south side. The dip varies between 25° and 80° SW. At this place there is evidently a fold pitching fairly steeply to the west. At its apex, i. e., between the points at which the strikes are north and northwest, the rock is shattered and a well-marked dolomite-breccia has developed.

From the south side of this bluff dolomites extend eastward with a uniform strike of about N. 70° W. and a dip of about 40° to 50° for about 500 paces, forming the line of little cliffs bordering the north side of the valley. Similar rocks with the same strikes and dip likewise constitute the north slope of the ridge. The top of the ridge consists of chert. This begins at a point between the two little hillocks above referred to as exhibiting folds, and stretches as an almost continuous ledge the entire length of the ridge and finally disappears under the soil. On both sides it is flanked by the dolomite forming the north and the south slopes of the ridge. The chert appears on fresh surfaces as a fine-grained rock mottled with gray, red, blue, and white streaks, and cut by short cracks the walls of which are coated by druses of tiny quartz crystals. On surfaces that have been exposed to the weather a brecciated structure becomes very apparent and the irregular mottling observed on the fresh surfaces is seen to be due to the presence of white and bluish-gray fragments cemented together by a reddish groundmass. Nearly all the chert in these hills seems to be brecciated in this way. The brecciation does not appear to bear any definite relation to the axes of folds. Although best exhibited where folds are recognizable in the associated dolomites, it is by no means limited to these positions. Here as elsewhere the chert seems to be characterized by the brecciated structure, as though its brittleness caused it to yield to compressing stresses more easily by fracture than by flowage even when confined between dolomite beds that were deformed by flowage exclusively.

At the east end of the ridge the relations of cherts and dolomites again become complicated. From the northeast corner of the main valley, where the cliffs bordering its north side meet those bordering its east end, two little side valleys or ravines extend northward. The more westerly one affords an excellent section through the ridge at a point where the folding seems to be the most complicated—indeed it appears that the ravine is a consequence of the folding. The west side of the ravine is a bluff exposing a sharp fold in dolomites overturned to the north and pitching to the east. On its south face, overlooking the main valley, the dolomite has the normal strike, N. 70° W., and a dip of 40° S Passing northward along the edge of the bluff, however, the strike is observed to swing to the east, and then to become northeast, north, and northwest, successively, and finally to resume a direction on the north side of the hill parallel to that observed on its south side, i. e., N. 70° W. Where the strike is approximately north, i. e., at the point which may be supposed to be in the axis of the fold, the dip is 30° N. On the north limb of the fold the dip corresponds to that on the south limb, viz, 40° S.

Beyond this fold, on the top of the ridge, even-bedded dolomites with the usual strike and dip are again exposed in a large ledge, and in contact with them to the east appear equally large exposures of the chert. The dolomite is apparently the continuation of the beds flanking the north side of the chert band on top of the ridge to the west. The chert, on the other hand, seems to be a distinct bed, quite independent of the beds on the top of the ridge, though it may possibly be the same bed repeated by folding or faulting. This chert extends practically continuously for about 150 paces to the southeast, and is in contact on its south side with bedded dolomite and dolomitic and cherty breccias. On its west side its contact is with the dolomite forming the north slope of the ridge, as already mentioned. This contact is extremely sharp. It cuts diagonally across the bedding of the dolomite, so that the chert rests directly upon the truncated layers of this rock. From the relations of the chert to the dolomite elsewhere it is plain that the two rocks are not separated by an unconformity, nor is it probable that the chert in this instance occurs as a vein in the dolomite. The phenomenon is best explained as due to the presence of a little fault along the contact line. On the east wall of the little ravine, opposite the exposures just described, are others of the same character. Dolomitic breccias are particularly well developed here, the picture reproduced in Pl. XVI, *A*, exhibiting the appearance of one of them, in which the fragments and matrix are practically all dolomite. On the top of the bluff the breccia can be seen to be interbedded with nonbrecciated dolomites. Evidence of folding is as marked on this wall of the ravine as on the western wall, but the exposures are not as continuous, and consequently the character of the folding can not be as well worked out. It is probable that the folds pitch to the west. Since the dip in the dolomite beds immediately to the north of the breccia figured (Pl. XVI, *A*) is to the north and that in the bed to the south is southerly, it is possible that the brecciated band is situated along the axis of the fold. However, in other portions of the hills smaller exposures of the same kind of breccias are frequently met with in which the relations to folding are not so plain. It is true that in almost all these cases departures from the normal dips and strikes may be observed, but it is not always certain, or even probable, that the breccias mark the axis of the folds.

From the distribution of the folds and of the breccias, and from the relations of the latter to the former, as well as the relations of the cherts to the dolomites it would seem that the dolomite series in this range of hills is affected by a close east-west folding and a more open north–south folding, with occasionally subordinate faulting. The chert is apparently interbedded with the dolomite near but not at the top of the series. That this folding is connected with that which gave rise to the Norway and Aragon ore basins can admit of no doubt.

The cliffs at the east end of the main ravine consist exclusively of well-bedded dolomites striking uniformly about N. 65° W. and dipping 35° to 40° S. At the extreme southeast corner of the ravine the strike becomes more nearly east–west (N. 85° W.) and the dip higher (50°). To the east and to the west of this exposure are several pits in iron-formation material which are just a trifle south of the projection of the strike of the southernmost portion of the ledge. This fact indicates that the ledge is very near the contact of the dolomite formation with the iron-bearing Vulcan formation. No direct contact is observable, but by digging into the little gully that runs down the cliff on the south side of the dolomite exposure large loose pieces of a white quartzite conglomerate containing numerous jasper fragments may be picked from the soil. The abundance of these fragments and the fact that they comprise the only kinds found in this place point to the conclusion that the ledge from which they were separated is but a short distance beneath and that the rock marks an unconformity between the dolomite and the overlying iron formation.

Secs. 12 and 13, T. 39 N., R. 29 W.—The most extensive exposures of the dolomite series is in the group of hills and hillocks in the valley of the Sturgeon River, secs. 12 and 13, T. 39 N., R. 29 W. The ledges are almost bare of vegetation, and therefore present exceptionally favorable opportunities for study. Those in sec. 13 are near the north quarter post of the section, just north of the wagon road from Vulcan to Loretto, on the south side of a high hill, the top of which in all probability is covered with the Lake Superior sandstone (see Pl. XLI). A walk of a quarter of a mile due north will bring one to the principal group of ledges, lying between the front of the hill just referred to and the track of the Escanaba and Iron Mountain Railroad (Chicago and Northwestern), one-fourth mile farther north. Most of the ledges are small, flat exposures, but here and there a little hillock rises from the valley floor, and on the south side of the railroad a very large, bare, smooth knob lifts its top about 75 feet almost vertically above the rails. It is an almost solid ledge of dolomite, but at its eastern end, where its slope is gradual, the rock is covered with drift material. This large ledge and the smaller ones to the south afford an almost continuous exposure of the series for a distance of about 600 paces across its strike. The distance from the southernmost ledge, near the wagon road, to the northernmost one, in the center of sec. 12, on the side of the railroad track, is about 3,100 feet.

From the center of the section the ledges extend eastward toward the lower portions of the Sturgeon Valley, where they are buried beneath thick deposits of sands. On the east side of the river, however, the rocks of the series again emerge from beneath the sands and outcrop in a number of small hills in the northeast quarter of sec. 13, T. 39 N., R. 29 W., and in the southwest quarter of sec. 7 and the north half of sec. 18, in T. 39 N., R. 28 W. A network of roads radiating from the bridge across the Sturgeon on the main road from Loretto to Waucedah passes between the outcrops and approaches many of them so closely that they may be examined from the seat of a carriage. These outcrops are not as interesting as those on the west side of the river, however, as they consist almost uniformly of a heavy-bedded, almost massive dolomite, striking and dipping in uniform directions.

The southernmost dolomite ledge in sec. 13 is situated about 200 paces south of the north quarter post of the section and about 75 paces north of a deep shaft in the iron formation, from which a large quantity of poor ore has been taken. The ledge is made up of alternating bands of pink and dark reddish-brown dolomite striking N. 85° E. and dipping 70° S. The lighter-colored bands are divided into layers by very thin seams of darker color, and are traversed by little joint cracks and fault planes. In many places the fine bedding lines show distinct contortions, which, however, are not observable in the broader bands. In other words, while the broad bands of dolomite have a uniform strike and dip throughout the ledge, they exhibit within themselves complex minor corrugations. In some instances the corrugations are so sharp that the contorted bands are actually fractured and the rock becomes a breccia.

Another ledge just east of the quarter post is a more typical dolomite breccia than that just described. On the weathered surface angular fragments of pink dolomite and others with rounded edges are seen to be separated from one another by stringers and small triangular patches of a dark-colored sandy nature. Where the rock is not brecciated it is contorted in the most complex way. Evidently a breccia of this kind was formed by mechanical means after the rock itself had been laid down as a series of alternating layers of dolomite and dolomitic quartzite.

The ledges in the northern portion of the south half of sec. 12 are composed of interbedded dolomites, dolomitic quartzites, and slates. In the southernmost ledge, on the north-south quarter line of the section, for instance, are to be found a 15-foot bed of dark, pinkish-gray, thin-bedded dolomitic quartzite, interlaminated with thin bands of a bluish-gray slate, a bed of purple dolomite 12 feet thick, interbanded with thin seams of a light-gray slate, a 7-foot bed of coarse dolomitic quartzite containing thin beds of dolomite, a band of dolomite and slate 25 feet wide, 10 feet of quartzite, and 10 feet of dolomite. The bedding of all these rocks strikes N. 65° to 70° W. and dips 45° to 52° S.

As we pass northward the sandstones and slates become less prominent and the dolomites more abundant. The hill next north of the ledge described in the last paragraph is composed of interlaminated dolomite and thin beds of slate. The rocks strike as in the ledge to the south, but the dips vary from 50° S. to nearly horizontal. The steeper dips occur on the slopes of the hill and the flat ones on top. In places, however, on the top the layers are closely folded into sharp little folds, pitching very steeply, the westernmost ones to the west and the easternmost ones to the east.

North of this hillock only thick-bedded dolomites appear. These rocks form the large hill already referred to as being south of the railroad track in the center of the section. Bedding lines with a dip of 45° S. can be observed on the southern side of the hill. As we pass north over the hill the dolomite becomes more and more massive until on the ridge no distinct strikes nor dips are noticeable. On the cliff overhanging the track, however, the dip is vertical in one place and at its east end there is an exposure with a dip to the south. North of this ledge there are no exposures for some distance. The outlook from the top of the hill is over a swamp, bordered on the north by a steep sand slope leading upward to a sand plateau.

This section afforded the data for the best estimate of the thickness of the Randville formation that was obtained.

NEGAUNEE FORMATION.

The identification of an iron-bearing formation in the Lower Menominee series corresponding to the Negaunee formation of the Lower Marquette series in the Marquette and Felch Mountain districts is based mainly on the fact that the lower layers of the Upper Menominee series contain fragments of jasper and ore that must have been derived from an older series. Whether the formation that yielded these fragments was exactly equivalent to the Negaunee formation in the Marquette district or not can not be definitely determined; but it must have rested upon the Randville dolomite and occurred below the Upper Menominee Vulcan formation, which in many places is immediately above the dolomite, for jaspilites are not known in the Archean rocks surrounding the Menominee trough nor in the Huronian beds below the top of the Randville formation. The position of this supposed formation in the Menominee district corresponds exactly with that of the Negaunee formation in the Marquette district. No distinctive name has been given it in the Menominee district, because of the impossibility of deciding positively whether or not there are any remnants of it now exposed on the surface. It must, however, be referred to in any discussion on the geology of the district, because only on the assumption of its presence can be explained some of the deposits of ore and jasper in the Upper Menominee series.

The jaspilites described in the immediately succeeding pages, while probably members of the Vulcan formation of the Upper Menominee series, are nevertheless somewhat different in their lithological features from the other jaspilites of the formation, and very like those in the Negaunee formation in the Marquette district. They are also very similar to the jasper in the pebbles of the coarse quartzite at the base of the Vulcan beds, and therefore must be similar to the jaspilites that furnished these pebbles. For these reasons they are discussed at greater length than their areal importance in the district would otherwise warrant, and not because it is believed that they are actually remnants of Negaunee beds that have escaped erosion. The Negaunee jaspilites were like these in all essential respects, and so the latter may serve to illustrate the features of the former.

DISTRIBUTION.

Remnants of the Negaunee formation may exist in the Aragon mine, the Pewabic mine, and some of the other mines of the district, but of this we have no definite knowledge, as the mining plats can not discriminate between two iron formations so nearly alike in their macroscopical features as are those of the supposed Negaunee and the Vulcan formations. The exposures above referred to, consisting of a jaspilite similar to that which furnished the pebbles to the basal conglomerate in the Upper Menominee series, lie in a narrow belt bordering the south side of the Randville dolomite area near the center of sec. 9, T. 39 N., R. 29 W. (see map, Pl. XXXIII). This belt is outlined by three test pits, a ledge, and several large abandoned mining pits. It begins a short distance east of the shaft of the old Brier Hill mine, embraces the north portion of the large, flat exposure lying a few degrees north of east of Curry shaft No. 2, and ends, so far as observed, at the northwest corner of the old mining pit No. 3 in the center of the southeast quarter of the northwest quarter of sec. 9.

LITHOLOGY.

The rocks from the narrow belt of iron formation just mentioned comprise even-banded beds of jasper and ore which have a range in thickness from the fraction of an inch to three inches or more. The jasper, which is of a dark purplish-red color, is very fine grained. It has a flinty texture and a completely homogeneous aspect. Here and there it is cut by little cracks lined with small plates of brilliant hematite. Sometimes the rock is faulted and hematite has penetrated between the faulted surfaces. The ore interlaminated with the jasper is a hard, dense, finely granular hematite, often possessing a slaty cleavage, but rarely exhibiting a specular character. It is sometimes spangled with tiny, brilliantly reflecting crystals of hematite, that appear to be due to infiltration, and sometimes it contains a small quantity of minute magnetite crystals. While some of the ore bands are homogeneous throughout, most of them when examined carefully are observed to be made up of interlaminations of very thin layers of ore and jasper. The contact between the hematite and the jasper layers is usually sharp and even, and often the rock will split more easily along this contact plane than anywhere else. Frequently, however, there is a gradation between the layers, the jasper near the ore bands becoming more and more thickly impregnated with hematite until it is apparently replaced entirely by the iron oxide. The ore layers, like the jasper beds, are traversed by cracks lined by hematite crystals, producing bright, glistening streaks across the dull surface of the ore. Both ore and jasper are cut by tiny veins of quartz.

In natural light sections of the jasper appear to be composed of a uniform aggregate of colorless quartz grains elongated in a common direction, which is parallel to the bedding, crystals and aggregates of crystals of blood-red hematite, a few small flakes of some micaceous mineral, and an abundance of hematite dust particles. Their most noticeable structural feature is the presence of numerous little oval masses or lenses arranged in lines that are parallel to the bedding. The lenses are all elongated in this same direction, and are separated from one another by a groundmass without distinctive structure other than the schistosity due to the elongation of the quartz grains. The lenticular areas are composed of the same kind of quartz-hematite aggregate as that composing the groundmass in which they lie. The distinguishing characteristics that mark them off from the surrounding material are a greater richness in hematite crystals and sometimes a difference in the coarseness of grain of their quartzose component as compared with that of the groundmass quartz. Moreover, in some instances the ore in the lenses is in a different form from that of the ore in the groundmass. The former is frequently in rods that may be the cross sections of flat rhombohedra, while the latter is in plumper crystals, whose cross sections are more nearly square. In many instances, also, the presence of the lenses is emphasized by the fact that there is an accumulation of ore particles near their peripheries which seems to mark their outlines very distinctly.

Between crossed nicols the sections break up into an almost uniform mosaic of interlocking quartz grains, many of which exhibit strain shadows. The hematite grains occur indiscriminately between the quartzes, and inclosed within them. No distinction can be noted between the quartz of the lenses and that of the groundmass, except that occasionally the latter is a little coarser than the former. There is no sharp line of demarcation between the two. The mosaic, in most instances, seems to continue uninterruptedly from lens to groundmass, and many grains seem to lie partly within the lens and partly without. The mosaic is plainly a crystalline aggregate; no trace of a fragmental grain can anywhere be detected in it.

It is extremely difficult to reconstruct the original character of the rock. The lenses may be regarded either as mashed jasper fragments that lay in a finer-grained quartzite, or as having been originally concretionary masses in a cherty sediment, such as gave rise to the jaspilites of the Penokee district and those belonging in the Negaunee formation of the Marquette district. Whatever the original character of the rock, it has been so completely silicified that definite traces of its structure have disappeared. From the fact, however, that in a silicified quartzite the fragmental cores of quartz to which the new quartz was added can in almost all cases be detected, whereas none have been recognized in the jaspers under discussion, it is concluded that the rock can not have been a quartzite made up partly of jasper fragments. From analogy with the Penokee and Marquette jaspilites, and because the rocks are like many of the concretionary jaspilites from these districts, except that they are more squeezed, it is thought that the lenses noted in the Menominee jaspers may be mashed concretions and the jaspers themselves may be silicified rocks comprised largely of ferruginous carbonates or of greenalite.[a]

[a] These lenses are identical in every respect with those pictured by Leith in The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, Pl. XV, *C* and *D*, and regarded by him as being altered greenalite grains.

While the deformation of the jaspers is due principally to mashing, nevertheless there has been some crushing. A few quartz veins cut through them in several directions, most commonly in a direction nearly perpendicular to the schistosity. A few tiny veins filled with hematite are detected and some of the little lenses are broken into pieces and faulted. These phenomena were evidently produced subsequent to the mashing and the resulting schistosity.

The ore bands associated with the jasper differ from the latter mainly in the presence of a much greater quantity of hematite. This is usually in long, irregularly shaped stringers running parallel to the bedding. The stringers consist of open aggregates of crystals united at a few points only and of masses made up of crystals fused together compactly. Occasionally these rod-like aggregates are in curved lines, as though they originally surrounded a waterworn grain or a concretion. The relation of the hematite to the quartz is difficult to determine, but from the fact that the former is idiomorphic with respect to the latter wherever the two are in contact, and the further fact that toward the ends of the ore aggregates individual crystals of the hematite are to be seen embedded in quartz grains, it is concluded that most, if not all, the hematite is older than the quartz. The relations between the ore and the quartz are exactly the same as those existing in the ferruginous cherts of the Negaunee formation in the Marquette district where "there is no apparent concentration of the iron oxides between the quartz grains, but they occur concentrated in laminæ or as separate flecks included in the grains of quartz just as though they were all in their present positions before the silica began to crystallize."[a]

RELATIONS TO ADJACENT FORMATIONS.

The contacts of the jaspilites with the underlying rocks are covered. The relations of the Negaunee-like jaspilites with others that are unquestionably members of the Upper Menominee series are well seen in the ledge east of Curry shaft No. 2. On the north side of the ledge the jaspilites are of the character described above. On the south side they are more nearly like the jaspilites characterizing some portions of the Traders member of the Vulcan formation. The jasper layers particularly are more granular and less vitreous than those to the north, and they are frequently mottled with little oval spots of a bright-red color. The

[a] Mon. U. S. Geol. Survey, vol. 28, 1897, p. 370.

northern jasper is dull red and breaks with a conchoidal fracture. The southern jasper, while red on the weathered surface, is darker on the fresh fracture, and has a grayish-purple color. Moreover, it breaks with an uneven, fragmental aspect, the surface being roughened by little projecting splinters with a white color and a granular texture. All the rocks strike uniformly N. 85° W. and dip 82° S. at the west end of the exposure, and strike N. 70° W. and dip 60° S. at its east end. At the two extremities of the ledge, north and south, the differences in the aspects of the jaspers are easily recognized, but as its central line is approached the difficulty of discriminating between them becomes greater, and finally in the middle of the ledge it becomes impossible to distinguish any difference between them. There is certainly no distinguishable unconformity between them and no bed of conglomerate that might mark an erosion interval. To all appearances the beds form a conformable series.

On the northwest side of pit No. 3, about 350 feet northeast of the eastern edge of the ledge, the same kind of flinty jasper is found. Here it is at the base of a series of conformable beds forming the wall of the pit. The upper layers are distinctly quartzites, containing abundant fragments of jasper interlaminated with layers of lean ore, some of which apparently contain large bowlders of ore (see Pl. XXII, *A*). Above the lowermost distinctly fragmental quartzites there are no beds of the cherty-looking jaspers. These are confined to the part of the series below the quartzite. The base of the series is not visible, however, so that it is not known whether beds containing fragmental jasper occur again below the cherty jasper beds or whether these latter are actually beneath the entire fragmental series.

CONCLUSIONS FROM FOREGOING STUDY.

It is clear that there is no structural evidence to indicate that the jaspilites under consideration are members of the Lower Menominee series and represent an iron formation corresponding to the iron-bearing Negaunee formation in the Marquette and Felch Mountain districts. The only evidence that bears on the case is lithological. The jaspilites are different in appearance from most of the jaspilites of Upper Menominee age, and in their composition and texture are similar to the jaspilites of Negaunee age in other districts. So far as has been noted they contain no fragmental material, but, on the other hand, they seem to have an oolitic structure. Since they are beneath beds that are certainly members of the lowest iron formation in the Upper Menominee series, it might be concluded that they represent a small portion of the iron-bearing Lower Menominee formation which has yielded so much material to the overlying iron-bearing Upper Menominee formation. There are other considerations, however, which tend to cast doubt on this conclusion. If the jaspilites are Negaunee in age, the immediately underlying rocks should be the cherty upper members of the dolomite formation. The absence of these cherts seems to demand the assumption of an erosion interval between the jaspilites and the dolomite formation of sufficient duration to allow of the entire removal of the cherts. If this assumption is a correct one, it would necessitate the placing of the jaspilites in the Upper Menominee series with the Traders member of the Vulcan formation. It is not certain, however, that the chert was ever a uniform layer overlying the dolomite and coextensive with it, in spite of the fact that wherever found it is at or near the top of the formation. Of course, if it never existed in this place its absence indicates nothing with respect to the age of the jaspilites.

It is almost impossible to reconcile the absence of an unconformity between these jaspilites and the overlying jaspilites of the Vulcan formation with the view that the two jaspilites belong to two different series. In many places it might be difficult to recognize such an unconformity, even if present, because of the fact that the contact between the Lower and the Upper Menominee series was a zone of accommodation along which the original relations between the beds in contact were often obliterated by shearing. In the present instance, however, where the two jaspilites strike and dip uniformly, there has been no marked disturbance of the beds, and, in spite of this fact, no evidence of an unconformity between them can be detected. Indeed, the two varieties of jaspilites grade into one another like the beds of a single formation.

In a word, while the evidence that has thus far been adduced as bearing upon the age of the cherty jaspilites is not entirely conclusive, it seems to point to the fact that they are parts of the Traders member of the Vulcan formation. They are recognized, however, as being, on the whole, different lithologically from the characteristic jaspilites of the Traders member, although in the open pit of the Quinnesec mine and at one or two other places in the district there are beds that look very much like the jaspilites considered here. These beds are above the quartzite which contains fragments of jasper, and so are unquestionably younger than Negaunee.

SECTION 2. UPPER MENOMINEE SERIES.

CHARACTER AND OCCURRENCE.

COMPONENT FORMATIONS.

The Upper Menominee series comprises all the beds between the top of the Randville dolomite and the bottom of the Lake Superior sandstone. It includes two formations which have been called the iron-bearing Vulcan formation and the Hanbury slate. The former—the lower of the two—is made up of three members, which in the order of succession are the iron-bearing Traders member, the Brier slate, and the iron-bearing Curry member. The Traders member is in some places further divisible into a lower portion consisting mainly of slates and quartzite, and an upper portion, consisting principally of ore and jasper beds.

SEPARATION FROM THE OVERLYING SANDSTONE AND THE UNDERLYING LOWER MENOMINEE SERIES.

The separation of the series from the overlying Lake Superior sandstone is necessitated by the universal presence of a profound unconformity between the two, the existence of which is made evident not only by many visible contacts showing horizontal layers of sandstone resting upon the eroded edges of the upturned lower rocks, but by the presence everywhere of immense fragments of the iron-formation rocks in the basal member of the sandstone.

The necessity for the separation of the Upper Menominee series from the Lower Menominee series is not very evident at first sight. Visible contacts between the iron-bearing Traders beds and the Randville dolomite are rare. In those instances where the contacts are seen the two formations appear to be conformable. The folding of the district has been so severe that the slight discordances in bedding that may have once existed have been entirely obliterated by movements of accommodation.

The principal evidence that is relied upon as a basis for the separation of the two series is the character of the lower layers of the iron-bearing Traders member and the structure of many of its ore and jasper beds. In many places immediately over the dolomite, especially along the southern border of the southern dolomite area, a distinct and very definite bed of coarse quartzite occurs, through which small fragments of bright-red jasper and small rounded grains of a black hematite are plentifully sprinkled. The rock is usually not so coarse grained as to warrant its being called a conglomerate, but it has the essential characteristics of the conglomerate at the base of the Ishpeming formation in the Upper Marquette series. The components of the Menominee rock are not so large as those of the Marquette rock, nor are the ore and jasper fragments so abundant. Nevertheless, these fragments possess characters as distinctly fragmental as do those in the Marquette conglomerate. The latter has been employed as evidence that the iron formation underlying the Ishpeming quartzite is of much greater age than the latter, and therefore that the Marquette bedded rocks are divisible into a lower series and an upper series. In this district the iron-bearing Negaunee formation is visible at many places beneath the conglomerate, so that comparison of its nature with that of the fragments in the conglomerate is easy. The character of the fragments is so like that of much of the material in the bedded Negaunee rocks that no doubt can be felt as to their origin. They were plainly derived from the Negaunee rocks by wave action along a shore line. In the Menominee district the coarse quartzite was also a shore-line deposit, and its ore and jasper fragments must have been derived from an older formation. But no source for these fragments has yet been discovered. There is no iron formation in the district corresponding to the Negaunee formation in the Marquette district, nor has there been discovered anywhere in the Archean schists of the district any evidence of the existence of jaspilites interbedded with the greenstones similar to those associated with the green schists of the Marquette and the Vermilion districts. In the two districts last named the jaspilites in the Archean have furnished jasper and a few ore pebbles to the conglomerates at the base of the Huronian series, so that even if the jaspilites had not been observed in position their presence somewhere in the Archean series would have been inferred from the presence of these pebbles in the lowest member of the overlying series. The basal conglomerates of the Lower Menominee series show no jasper pebbles, though they exhibit specimens of practically all the rocks known to exist in the Archean. The plain inference from these two facts—(1) the absence of jaspers from those portions of the Menominee Archean that have come under observation, and (2) the absence of jasper pebbles from the conglomerates at the base of the Huronian—is to the effect that the source of the jasper and ore in the coarse quartzite must be referred to the bedded series between the basal conglomerates at the bottom of the Sturgeon quartzite and the jasper-bearing quartzite near the base of the Traders member. From the evident analogy that exists between the geology of the Menominee and that of the Marquette districts, we should expect to find an iron formation above the Randville dolomite. The fact that no such formation exists in this place at the present time is easily explained on the supposition that it was removed by the same erosion processes that were instrumental in producing the débris found now in the quartzite. No remnants of the formation remain, hence it is plain that the shore line must have transgressed across the formation, and at the time the quartzite was deposited it was against the dolomite. In the Marquette district the shore line was in the iron formation at the time the conglomerates now exposed to study were formed, hence these are composed very largely of the débris of the iron formation. In the Menominee district the shore line adjacent to the deposits now exposed was not composed of iron-formation material, hence comparatively little of this material is found in these deposits. The greater portion of it must be in deposits that are now deeply buried, and it is possible that at these depths remnants of the original iron formation may still exist.

The constitution of the Traders member points to the same conclusions as those indicated above. Much of the material of this formation consists of the débris of a more ancient jaspilite formation. The only place for this seems to be at the top of the Randville dolomite. Since it does not exist there at present, it must have been removed by erosion. The assumption necessitates the supposition of a lapse of time between the deposition of the dolomite and the deposition of the overlying iron formations, and it is for this reason that a line of division between an older series and a younger series in the Menominee district is placed at this horizon.

Although no discordance in stratification has been observed between the top member of the lower series and the bottom member of the upper series, the evidence outlined above is sufficiently strong to warrant the assumption of the existence of a time interval between them, and to warrant the separation of the bedded rocks between the unconformity at the top of the Archean and that at the bottom of the Cambrian into a Lower

Menominee series and an Upper Menominee series, analagous to the Lower Marquette and the Upper Marquette series in the Marquette district, and to corresponding Lower and Upper Huronian series in the other iron-ore districts of the Lake Superior region.

DISTRIBUTION.

The rocks of the Upper Menominee series occupy the synclinal areas lying between the dolomite belts and between these and the areas occupied by the Quinnesec schists (see Pl. IX). To the east, like the formations of the Lower Menominee, they pass under the thick covering of Paleozoic beds and are lost to view. To the west they merge together beyond the Menominee River and constitute the surface rocks over the larger part of the Florence district in Wisconsin.

In the central portion of the Menominee district the Upper Menominee rocks comprise three belts, two lying between the three dolomite belts and the third between the southern dolomite belt and the Quinnesec schists along the Menominee River. East of Iron Hill the northern and central belts coalesce and the three belts are reduced to two. At about the meridian of Lake Antoine the central belt coalesces with the southern portion of the northern belt, and the two extend to the Menominee River between the southern dolomite and the western area of the Quinnesec schists. In this portion of the district, however, three belts are still maintained, for the western area of Quinnesec schists, extending eastward from the Menominee River like a wedge, splits the northern Upper Huronian belt into two arms, the southern one coalescing with the central belt as already related and the northern one bending northward and following the Lower Huronian rocks into the Calumet trough.

Over most of the areas described as occupied by these belts the Upper Menominee beds can be traced by means of outcrops and test pits, but in the northwest corner of the district, in that portion described as occupied by the northern arm of the northern belt, the drift covering is so thick that no outcrops are found. The presence of the Upper Menominee sediments here is inferred from the presence of outcrops of the Sturgeon quartzite and Randville dolomite at the northern limit of the district and the presence of outcrops of the Upper Menominee beds in the Calumet trough farther north.

FOLDING.

The character of the major folding of the Upper Menominee series can not be determined by the observation of strikes and dips, since the exposures are very few and the minor folding is very pronounced. From the distribution of the Upper series with reference to the Lower series, however, it is clear that the former must exist in three synclines and two anticlines with approximately east-west axes and in two anticlines and three synclines with north-south axes.

A north-south section across the center of the district, along the range line between R. 29 W. and R. 30 W., cuts all the folds with east-west axes. Where the section crosses the synclines the surface rocks belong to the Upper Menominee beds; where it cuts the anticlines the Lower series is exposed, the Upper beds having been removed by erosion from the anticlinal portions of the folds. A section along the central line of R. 29 W. cuts two synclines and a connecting anticline, the top of which has likewise been eroded; and a section along the line between R. 30 W. and R. 31 W. again cuts three synclines and two anticlines. In the latter case one anticline is over the western area of the Quinnesec schists and the other over the southern dolomite belt.

The central dolomite belt, as has already been explained (see p. 234), is an inverted canoe-shaped anticline entirely surrounded by Upper Menominee sediments. At each end the dolomite terminates in plunging anticlines, overlain by the Upper Menominee beds, which must therefore also be in closely similar anticlines. The two taken together constitute a broad anticline with an approximately north-south axis. In the vicinity of the Loretto mine, near the line between R. 28 W. and R. 29 W., is the axis of another north-south anticline. Here the lowermost beds exposed belong in the Upper Menominee series, hence, so far as the surface is concerned, only the beds of the Upper series are involved in the fold. The east limb of a third anticline must occur at the eastern end of the western area of Quinnesec schists, if these rocks are older than Algonkian, as has been supposed. Its western limb is a dozen or more miles to the west in Wisconsin.

The Upper Menominee beds thus are affected by two, and in a portion of the district by three, closely compressed folds with axes trending a little north of west and by two broad and open folds with axes trending a little east of north.

The minor folding of the series will be discussed in connection with the folding of its individual formations.

VULCAN FORMATION.

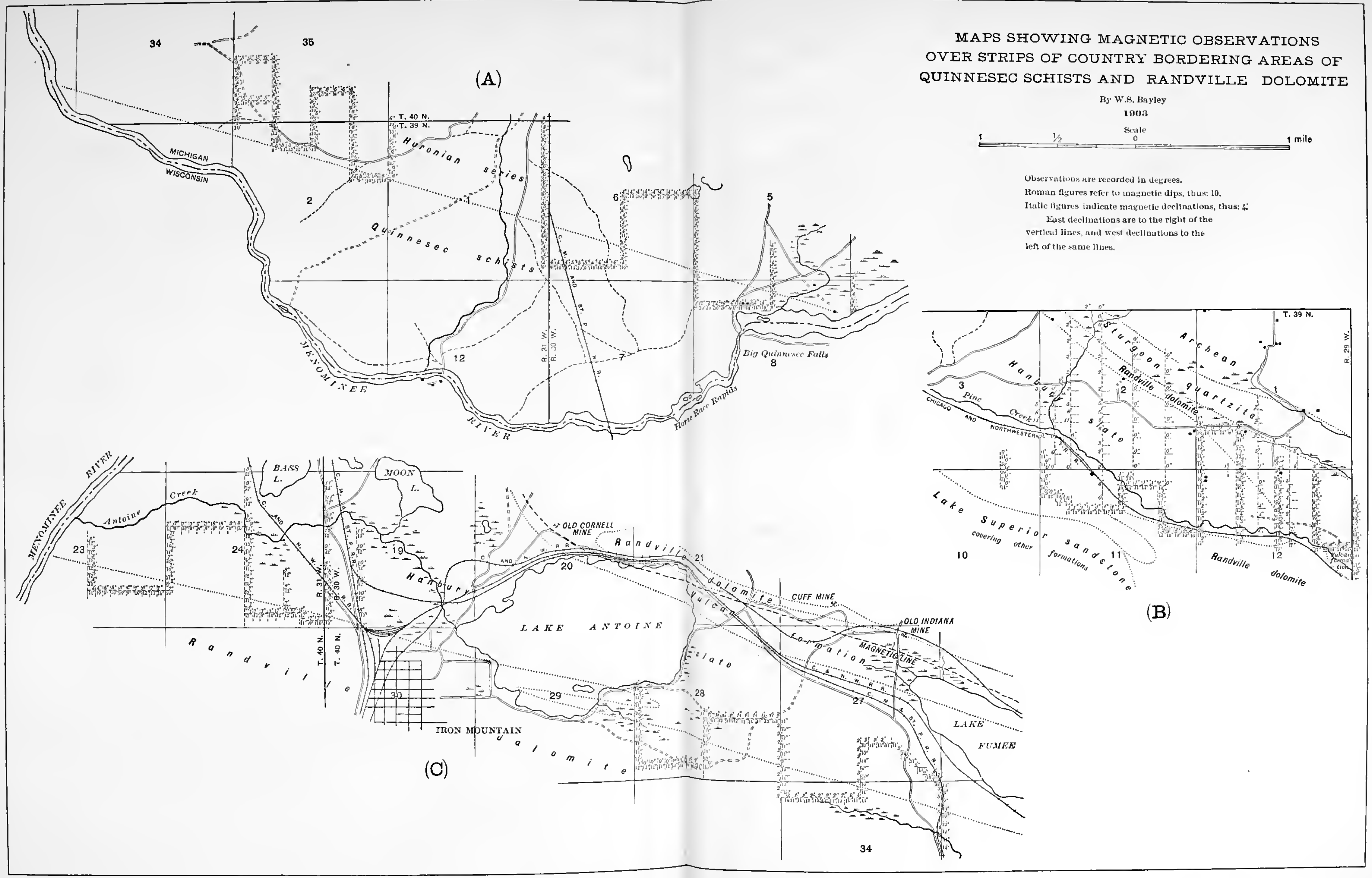
DISTRIBUTION.

From the position of the Vulcan formation immediately upon the Lower Menominee beds, we would naturally expect the distribution of the ore-bearing formation to be determined by the distribution of the Lower series, and, as a matter of fact, wherever the Vulcan formation exists it is found immediately above the Randville dolomite of the Lower Menominee series and below the Hanbury slate of the Upper Menominee. But at some places within the district where we would naturally expect to find it the dolomite is in immediate contact with the Hanbury slate, or is separated from exposures of the latter formation 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 the folding. Along only one stretch, about a mile in length, is the iron formation known to be absent. This is in the west half of sec. 1 and the east half of sec. 2, T. 39 N., R. 30 W., where the Hanbury slate lies against ledges of the typical dolomite.

On the north side of the southern dolomite belt the iron formation has nowhere been found, nor has any indication of its presence been detected except at the Loretto mine in the eastern part of the district. Near the dolomite in the central and eastern portions of the belt magnetic lines are weak or absent altogether, and no exposures of the Vulcan formation have been discovered either in ledges or by test pits. On the other hand, rock has been uncovered by test pits in the east half of sec. 11, T. 39 N., R. 29 W., and near the northwest corner of sec. 10, T. 39 N., R. 29 W. In every instance the pits bottomed in slate, which in sec. 11 appears to make an eastward-extending embayment into the dolomite north of the East Vulcan mines, and in sec. 10 forms a portion of the embayment extending westward into the dolomite area east of Norway. In both cases the dolomite and the slate are so near together that there is no room between them for the Vulcan formation. Elsewhere the country bordering this portion of the dolomite belt is thickly drift covered, so that it is not known whether it is underlain by a belt of the iron-bearing formation or not. In the eastern portion of the district the Vulcan beds border the northern margin of the belt from the Loretto mine eastward for a short distance. At the Loretto mine the ore formation exists in an eastward-pitching syncline. Beyond this place it is traced by a line of magnetic attractions to 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 formation is that in which the Traders, the Cuff, the Indiana, and the Forest mines are situated. It stretches for about 5 miles along the south side of the central dolomite belt, beginning north of Lake Antoine and ending, so far as present information indicates, somewhere about the east line of R. 30 W. Beyond this point for a mile and a half there are no outcrops near the southern boundary of the dolomite, nor have any test pits, so far as our present knowledge goes, uncovered the underlying rock. Moreover, the magnetic line which can be traced as far east as the center of sec. 25, T. 40 N., R. 30 W., gradually dies out at this point and can not be rediscovered to the east. We are therefore ignorant as to whether or not the ore-bearing formation continues through this interval. At the east end of the dolomite belt, however, the country has been very thoroughly explored and the underlying rocks have been exposed by pits and trenches. Lean iron-bearing slates are so abundant here that the locality is known locally as Iron Hill, but the slates are different from those of the Vulcan formation and similar to the lean iron-bearing slates discovered at several localities in the Hanbury slate areas. Further, a diamond-drill hole recently put down under the pits to within a short distance of the dolomite reveals the existence only of gray slates like those of the Hanbury formation. The contact of the two formations has not been reached by this drill hole (see pp. 481–483), but the interval between the last-known position of the slate and the nearest exposure of the dolomite is so narrow that there seems



MAPS SHOWING MAGNETIC OBSERVATIONS OVER STRIPS OF COUNTRY BORDERING AREAS OF QUINNESEC SCHISTS AND RANDVILLE DOLOMITE

By W.S. Bayley

1903

Scale

1 ½ 0 1 mile

Observations are recorded in degrees.
Roman figures refer to magnetic dips, thus: 10.
Italic figures indicate magnetic declinations, thus: *4*.
East declinations are to the right of the vertical lines, and west declinations to the left of the same lines.

to be no room there for the Vulcan formation. Again, a line of auger borings has been carried from the northernmost exposures of the Hanbury slate north across the swamp which separates them from the southernmost exposures of the dolomite belt to within a few feet of the base of a dolomite cliff, and these revealed only slate. While little confidence should, perhaps, be placed in the results of these borings, the evidence of the absence of the Vulcan formation and the presence of the Hanbury slate at this place seems so strong that on the map the color of the latter formation has been carried to the very edge of the dolomite area.

On the north side of this same dolomite belt the iron 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. To the east and west the country is thickly covered by drift and sandstone, and nothing has been learned of the nature of the underlying rock.

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 Hanbury slate, and present to some extent in the jaspilites of the Curry member of the Vulcan formation. In this case the rocks are believed to belong to the Curry horizon.

In the neighborhood of the Loretto mine (Pl. XXIII) the Vulcan formation appears to occupy the entire breadth between the north side of the southernmost belt of dolomite and the south side of the northernmost belt of this rock. A short portion of this distance has not yet been explored, but all that portion which has been opened up by the Loretto and Appleton workings reveals the presence of one or the other members of the Vulcan formation. Of the area east of the Appleton mine nothing is known. The country is here covered with thick deposits of sand and sandstone.

The other areas in which the Vulcan formation may occur are those bordering the Quinnesec schists. From the order of succession on the northern side of the Menominee trough one would expect on the southern side of the trough to find in passing north from the Quinnesec schists of the Menominee River the following formations: (1) The Sturgeon quartzite, (2) the Randville dolomite, (3) the Vulcan formation, and (4) the Hanbury slate. As a matter of fact, the only rocks exposed near the Quinnesec schists are the Hanbury slates. In several places east of the mouth of the Sturgeon River, in the northwest quarter of sec. 26, T. 39 N., R. 29 W. (see

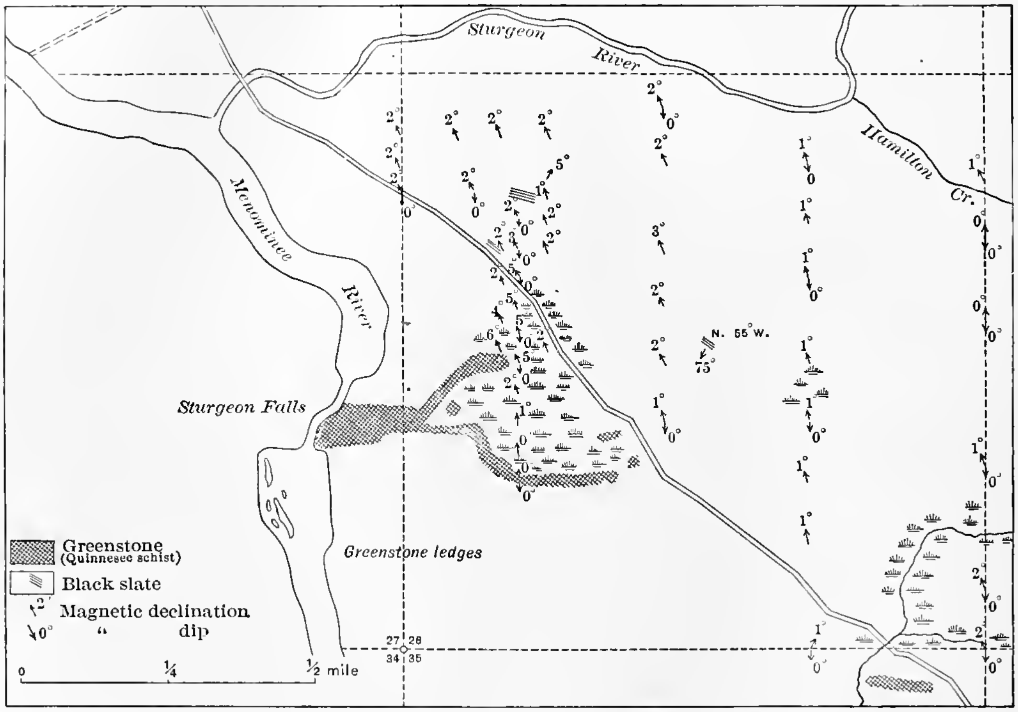


Fig. 22.—Sketch map of exposures near Sturgeon Falls, sec. 26, T. 39 N., R. 29 W.

map, fig. 22), the slates and the schists are only 750 feet apart on the surface, but west of this point no exposures of any kind have been found north of the schists within the distance of less than a mile.

The direction of movement of the glacial drift in the Menominee area was from the northeast toward the southwest. The Quinnesec schists occupy relatively high ground, and therefore heavy masses of drift were banked against their northern borders. This may be the explanation of the absence of exposures in this belt. But the Sturgeon quartzite, the Randville dolomite, and the Vulcan jaspilites are hard, resistant formations, probably much more resistant than the Quinnesec schists, hence it is thought to be highly probable that these formations do not rest upon the schists, otherwise they would likely be exposed in some portion of the belt, especially on the banks of the Menominee River where it enters and leaves the schist areas. The absence of the Sturgeon and Randville formations is easily explained on the supposition that they were eroded during the interval that developed the unconformity between the Lower Menominee series and the Upper Menominee series. It is otherwise, however, with the Vulcan formation. This belongs in the upper series along with the Hanbury slate, and unconformity can not be appealed to for an explanation of its absence.

The Vulcan rocks are fully as resistant as the quartzite and the dolomite, and when they exist they usually occupy elevated areas. The belt north of the Quinnesec schists, however, is a depressed area; at any rate, its surface is nowhere above the average elevation of the plain to the north which is known to be underlain by Hanbury slates. Moreover, a magnetic survey of the belt showed no evidence of the presence through it of a definite magnetic line (see map, Pl. XVIII, *A*). Since, then, there is no evidence that the Vulcan formation underlies the belt, while, on the other hand, its topography indicates that it is underlain by the same rocks that underlie the surface immediately to the north, and since slate exposures are found in the eastern end of the belt within about 750 feet of the schists, it is believed that the conclusion that the Vulcan formation does not border the schist area is well substantiated.

The situation is nearly similar about the western area of Quinnesec schists. Only two exposures are known within one-half mile from the schist ledges. One of these is unquestionably an exposure of Hanbury slate. It lies on both sides of the Menominee River and in the bed of the stream, forming a ledge about 900 feet long, in which the rocks are gray slates with a well-marked cleavage dipping high to the north. The north end of the exposure on the Michigan side of the river is south of and less than 350 feet distant from the southernmost ledge of green schists which are exposed under the railroad bridge of the Florence branch of the Chicago and Northwestern Railway in sec. 13, T. 40 N., R. 31 W. The second exposure, within less than one-half mile of the schists, is exposed in the dump of an old shaft in the northwest quarter of the southwest quarter of sec. 15, T. 40 N., R. 30 W. The distance from the shaft to the nearest outcrop of schistose greenstone is about 1,000 feet. The rock exposed in the dump is a ferruginous slate that resembles very closely some of the ferruginous slates of the Hanbury formation (see p. 476). These exposures are both on the southern side of the schist area and are more than 4 miles apart. Absolutely nothing is known of the geology of the intervening strip of country. Nor is anything known of the belt of country bordering this schist area on the north. This area is so deeply buried under sand and gravel that we are not even certain that the northern limit of the schists has been correctly outlined.

No magnetic line was found after careful search surrounding the schist area, and no evidence of any kind was detected that indicated the presence of an ore formation in this place (see Pl. XVIII, *C*). The occurrence of the slate ledges on the banks of the Menominee within 375 feet of the schist exposures renders the probabilities more favorable to the belief that the Quinnesec schists are surrounded by the Hanbury slate than to the view that they are surrounded by a belt of the Vulcan formation. On the map the color of the Hanbury slate is made to cover the belts bordering the Quinnesec schists in both areas, although it is recognized that in some places portions of these belts may be underlain by small areas of the Vulcan formation.

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 stratigraphical position of the iron-bearing formation one would expect it to occur as continuous belts surrounding the dolomite anticlines, bordering the south side of the northern dolomite monocline and the areas of Quinnesec schist. In several places, however, it is seen that these relations do not exist. It is known that in various parts of the district the iron-bearing formation is absent from the position it would naturally be expected to occupy, and that the Hanbury slates, which stratigraphically overlie the ore-bearing strata, are in immediate contact with the dolomite that underlies the Vulcan formation. Furthermore, at least at one place it is known that the slates are exposed in natural ledges at so short a distance from the western area of Quinnesec schists that there would seem to be no possibility of the occurrence of the iron-bearing formation between them. It is probable that the larger parts of these belts, in which the underlying rock is unknown, are underlain by the Hanbury slate rather than the Vulcan formation, but it is possible that the Vulcan formation underlies portions of them.

TOPOGRAPHY.

The Vulcan formation is so thin that, although in its usual form it is very resistant to denuding agencies, it has produced but little effect upon the topography of the district. Where the formation is well developed it usually forms the slopes of higher ridges of dolomite. Where not so well developed, its topography, except in a few instances, gives no evidence of its existence beneath. Its ledges generally present smooth, flat surfaces that rise very slightly above the surrounding country. At the Traders mine and in Hughitt Bluff, east of Iron Mountain, however, they form marked elevations that can be seen for long distances. Because of the uniformity in hardness of the different components of the formation and the lack of prominent joint cracks through it, differential erosion of its parts is not noticeable, and rough craggy ledges, such as those characterizing the resistant dolomite formation, are absent.

SUBDIVISION INTO MEMBERS.

The Vulcan formation consists of three distinct parts, that may easily be recognized throughout a large portion of the extent of the formation. Where only one of these parts is present it is believed that it is always the uppermost one. On the general map of the district the formation is not differentiated in the mapping, but on the special, large-scale maps, the formation is separated into its parts where the limits of these are known. The lowermost of the divisions is composed of slates, conglomerates, quartzites, jaspilites, and ore deposits. It has been called the Traders member because of the typical occurrence of its ferruginous phases at the Traders mine, north of Lake Antoine. The second or intermediate division comprises a belt of black ferruginous slate. It is known as the Brier slate because it is so well exhibited at Brier Hill, east of Norway. The third or uppermost portion consists of interbedded ferruginous quartzites, jaspilites, and ores. These are worked for ore at the Curry mine, east of Norway, hence they have been named the Curry member.

TRADERS MEMBER.

DISTRIBUTION.

In spite of the fact that the Traders member is better developed than either of the other two members of the Vulcan formation, where all are exposed, nevertheless it seems probable, at present, that its distribution is not coextensive with that of the iron-bearing formation. In some portions of the district only one iron-bearing member appears to exist and this, so far as the evidence now at hand indicates, is the Curry member.

The Traders member has been identified only along the south sides of the central and the southern dolomite belts, except at the Cuff mine, where the iron-bearing beds are either north of the dolomite or folded within it, and at the east end of the district, where the Traders beds occur at the Loretto and Appleton mines in the syncline between the south side of the northern dolomite belt and the north side of the southern belt. The identity of the iron-bearing member at this place is established by the occurrence above it of uneroded remnants of a slate with the lithological characters of the Brier slate. In the western portion of the district a few pits have exposed iron-bearing rocks in sec. 14, T. 40 N., R. 30 W., but for reasons to be referred to later (p. 331) these rocks are believed to belong in the Curry member. Between them and the nearest exposures of dolomite to the north there is apparently abundant room for the occurrence of the Traders member with its average thickness, but the interval is covered, and the nature of the underlying rocks is unknown. Nowhere else along the south side of the northern dolomite belt are iron-bearing beds known to occur, except, as before mentioned, in the vicinity of the Loretto and Appleton mines.

On the south side of the central dolomite belt the Traders rocks are found at the Traders, the Cornell, the Cuff, the Indiana, and the Forest mines. At the two mines first named the iron-bearing rocks have the general characteristics of the Traders rocks elsewhere. They are, moreover, overlain by slates like the Brier slates at the type locality, Brier Hill, and are sheared and brecciated like the unquestionable Traders beds at their contact with the underlying dolomite. None of this rock, however, has yet been discovered in the neighborhood of these mines. At the Cuff mine, farther east, dolomite is on the south of the ore-bearing beds, and it is reported that diamond-drill holes encountered the same rock beneath sandstone to the north. The Cuff deposits, which rest directly upon the dolomite, are identified as belonging in the Traders member by their position and their character. In all essential respects they are similar to the beds at the Traders and Indiana mines. The ores are in part sheared into specular varieties and in part are brecciated. In the neighborhood of the Indiana mine, which is south of the dolomite, the presence of all three members of the formation has been disclosed by drilling. The lowermost member—that one in which the shaft was sunk—lies between the dolomite and a set of ferruginous siliceous slates which are identified as Brier. This member is therefore in the stratigraphical position of the Traders member. East and west of the Indiana mine a strong magnetic line and the rock pile of an occasional test pit shows the presence of the iron formation on the southern side of the dolomite belt between Lakes Antoine and Fumee, but whether the ore-bearing beds belong in the Traders or the Curry member is not known. It seems probable, however, from the character of the rocks on the dumps of the pits that the Traders member is present, at least for a portion of the distance between the Indiana mine and Lake Antoine, and it is probable that the Indiana beds extend continuously as far east as the Forest mine. At this locality the explorations have developed two iron-bearing members separated by a slate. The northerly one, lying immediately above a dolomite, must be Traders. Beyond the Forest mine to the east the entire Vulcan formation disappears and consequently, of course, the Traders member.

South of the southern dolomite belt the Traders member is well exposed in ledges, pits, and mine workings at many different points between Waucedah and the Aragon mine in sec. 9, T. 39 N., R. 29 W. Through most of this distance all three members of the iron formation have been identified, the Traders member being well developed throughout nearly its whole extent. Indeed, practically all of the working mines of this stretch of country are mining Traders ore. Between the west line of sec. 22, T. 39 N., R. 28 W., and the Sturgeon River, a distance of about 3½ miles, there is no direct evidence of the presence of the Traders member, but since the iron formation is developed with all of its members both at the east and the west ends of this belt, and since a distinct magnetic line shows that the formation extends through this distance, the probable view is that it continues from east to west with all of its members. From the Aragon mine westward to the center of sec. 1, T. 39 N., R. 30 W., where the entire formation disappears, the iron formation is well exposed by test-pitting and mining operations. At the Norway and Cyclops mines the Traders and the Curry members are both developed. West of these mines, in sec. 6, T. 39 N., R. 29 W., however, only one iron-bearing member is exposed. No

Brier slate is recognized as being associated with the jaspilites, but, on the other hand, these rocks appear to be bordered on the south by the slates of the Hanbury formation. The Traders member, therefore, appears to be generally absent from this belt of country. At any rate, it has not yet been shown to be present. One or two drill holes put down in this region are, however, reported to have penetrated a series of slates lying between a considerable thickness of iron-bearing beds and a thin series of similar beds, the latter being against the dolomite. Portions of the Traders member may therefore exist at a little depth beneath the surface; but immediately at the surface there is no indication of the presence of the member between the Norway mine and Quinnesec. From the Quinnesec mine westward about a mile there are three belts of iron formation material separated by Brier slates. The belt between the northernmost slate belt and the dolomite is unquestionably a part of the Traders member, and it is believed that the belt to the south of this is also Traders. On this supposition the Traders member in the Quinnesec syncline borders the north and east sides of the basin and forms a narrow anticlinal tongue extending three-fourths of a mile westward through its center. To the east the Traders member disappears in sec. 2, T. 39 N., R. 30 W., with the entire Vulcan formation, and to the west it is believed to thin out in the southwest quarter of sec. 34, T. 40 N., R. 30 W., to reappear again at the Pewabic, Walpole, Millie, and Chapin mines as a narrow belt bordering the dolomite and following it in all its complicated folding. At the anticlines the iron-bearing member extends westward much farther than the dolomite, producing several belts bounded on both sides by Brier slates (see map, Pl. XXVIII, for details). Beyond the old Ludington mine in the southeast quarter of sec. 25, T. 40 N., R. 31 W., the Traders member seems again to disappear, the most westerly point at which its rocks can be identified being on the dump heaps of the old Ludington shafts.

While the Traders member is not as continuous as the Curry member, nearly all the mines of the district have obtained their ores from its deposits, so that a map of the active and abandoned mine shafts would serve to show the approximate distribution of the member.

LITHOLOGY.

The Traders member consists of a conformable set of beds composed of thin layers of light-colored shaly slates, heavily ferruginous quartzose slates, ferruginous conglomerates, ferruginous quartzites, jaspilites, and iron-ore deposits. On the sections of mine workings these are designated the Traders slate, Traders quartzite, and Traders ore-bearing beds.

SLATES.

Macroscopical.—The slates of the Traders member are commonly either light-colored argillaceous phases that may contain considerable talc, or dark-gray sandy hematitic slates that differ from the fragmental ores mainly in containing too little hematite to be profitably mined. These slates are usually at the base of the Traders member, although in some places thin layers of the lighter-colored slates are interbedded with conglomerates and quartzites a short distance above the base. The relations between the argillaceous and the ferruginous slates have not been observed, as the two phases have not been found together. The latter seem to be more locally developed than the former, which appear to be almost universally present between the Randville dolomite and the adjacent iron-bearing formation. Some of the slates that are described in preceding pages as occurring at the top of the Randville dolomite may belong here. These are almost identical in character with the slates of the Vulcan formation and are not separable from the latter upon structural grounds. Where represented on the maps in this volume the argillaceous slates are denominated "The Traders slate." The ferruginous slates, which are more closely related to the iron-bearing deposits than to the true slates, are distinguished as the "Traders ferruginous slates." They are separated from the remainder of the hematite beds mainly for economic reasons. On the mine plats the argillaceous slates are frequently mapped as "talcose slates." From the fact that they are always found in juxtaposition with the dolomite, and, in appearance resemble very closely the slates that are interbedded with the dolomite beds, they are popularly spoken of in the district as "marble slates."

The argillaceous slates vary from dark purple to white, through various shades of red or yellow. Originally, perhaps, nearly all were white or light yellow, for in most cases the darker color is plainly due to staining by iron oxides. Nearly all phases are dull in luster and thus are usually easily distinguished from certain white leached slates of the Hanbury formation, which are highly sericitic. Here and there, however, where slipping has taken place parallel to the bedding, slickensides have been produced, and along the slipping surfaces talcose or micaceous minerals have developed. On such surfaces the slates are, of course, lustrous; but a fracture across the bedding layers will usually show surfaces that are dull and earthy.

In many places the slates may be seen to grade into fine-grained quartzites through the increase in the proportion of quartz present and the diminution of the clayey constituents. On the other hand, the gradation is sometimes accomplished through the alternation of thin slate and quartzite layers, the latter increasing in number and thickness until the former entirely disappear.

In some localities the slates are much sheared, usually along their bedding planes, but sometimes transversely. In these phases the slaty cleavage is well developed. Most specimens exhibit no cleavage, but split easily along the bedding planes between the layers into thin shaly fragments. Movements of accommodation occurred here. The layers readjusted themselves to the new stresses produced by folding and slipped over one another, as is to be expected of thin slate beds between two resistant rocks like the dolomite and the jaspilite. Where the folding was sharp the movements of readjustment were greater than elsewhere and the slates were more intensely sheared. The resulting rock, with its cleavage surfaces often covered with a coating of talc, kaolin, or other micaceous mineral, like the talcose schists already referred to, furnished nearly impervious linings to many of the synclines in the underlying dolomite and thus provided suitable troughs for the concentration of the ores.

The argillaceous or talcose slates, as has already been observed, are found at or near the base of the Traders member, often interleaved with the coarse quartzites or fine-grained conglomerates to be described later. Where the quartzites and conglomerates are abundant the slate beds are apt to be thin and few; where the quartzose deposits are few and thin the slates are thick. Usually there is a distinct band of slate between the lowermost conglomerate bed and the neighboring dolomite, though it may not be more than a foot thick. At first this was thought to be evidence that the slates under discussion always belong in the dolomite series with the conglomerates at the base of the Vulcan formation. Since, however, beds of slate identical with those immediately above the dolomite are now known to occur between conglomerate beds, it is believed that many of these slates are members of the Vulcan formation. Their character would indicate deep-sea conditions at the beginning of Upper Huronian time. This conclusion is also suggested by the fact that no coarse basal conglomerates were laid down at the base of the Vulcan formation such as were deposited at the base of the Ishpeming formation in the Marquette district. When we consider that the deposits derived from the hard jasper of the Lower Huronian, which, in shallow water along shores, would naturally contain large bowlders of this excessively hard substance, consist of quartzites containing but a few small pebbles of jasper, the inference that the water was comparatively deep at the places where the deposits now occur seems to be fairly warranted. If this inference is correct, we have a ready explanation of the lack of apparent discordance between the Lower Huronian and the Upper Huronian deposits, for it is only close to shore lines that discordance between formations is to be expected.

The ferruginous slates are dark-blue or dark-gray, heavy, sandy-looking rocks that sparkle with reflections from the faces of innumerable little hematite crystals that are scattered uniformly through their masses. These slates grade into lean ores, from which they differ merely in per cent of hematite present. They occur at only a few places, notably at the Traders mine, where they can be plainly seen on the east side of the large open pit.

Microscopical and chemical.—The argillaceous slates of the Traders member are, for the most part, confused aggregates of small kaolin spicules, larger ones of a greenish muscovite, and a few of greenish-brown biotite, a few flakes of light-colored chlorite, many sharp-edged grains of quartz, enlarged here and there by the addition of quartz material, and numerous small round masses of limonite and irregular accumulations of magnetite, all lying in a matrix composed of quartz grains with indefinite outlines and a few masses of cloudy material stained red by hematite and limonite dust. The cloudy material may be decomposed feldspars. Here and there, scattered through this aggregate, are long columnar masses of limonite, which look as though they might be the alteration products of biotite or hornblende, and small needle-like crystals of zircon. In some places these components are arranged in such a manner as to suggest that they may have been derived from a fairly coarse-grained fragmental rock, but in the greater part of the sections no original structure is discernible. It is evident that most of the present constituents are secondary and that the rock has been subjected to silicification processes. Kaolin is by far the most abundant component after quartz. Its proportion with respect to the latter varies in different specimens, but in all specimens both these constituents predominate largely over all others. In a few specimens there are no other minerals present except the small grains of limonite and an occasional mica flake.

An analysis of a purplish-pink slate from the dump of an old shaft near the center of sec. 5, T. 39 N., R. 29 W., about on the contact of the Traders formation and the Randville dolomite north of the Norway mine, gave Mr. E. T. Allen, of the Survey laboratory, the result exhibited below in Column I. The corresponding molecular ratios are printed in italic.

Analyses of slates of Traders member.

	I.	II.	III.
SiO_2	67.04	67.76	47.85
	1.119		
Al_2O_3	15.01	14.12	18.13
	.147		
Fe_2O_3	3.54	.81	6.14
	.022		
FeO	3.18	4.71	.10
	.044		
MgO	2.11	2.38	14.51
	.052		
CaO	.19	.63	Tr.
	.003		
Na_2O	.29	1.39	.21
	.005		
K_2O	4.00	3.52	2.91
	.043		
H_2O at 105°	.67	.23	....
H_2O above 105°	3.73	2.98	[a] 9.96
	.207		
TiO_2	.69	.71	....
	.009		
P_2O_5	.03	.07	....
S	.02	(FeS_2) = .22	....
Cr_2O_3	Tr.	(CO_2) = .40	....
MnO	Tr.	.10	....
BaO	Tr.	.04	....
Total	100.50	100.07	99.81

[a] Loss on ignition.

In column III is the analysis of a purple fissile slate from beneath (north of) the ore on the fifth level of the Chapin mine. Between the laminæ are slickensided surfaces covered with talc. The analysis was made by Mr. E. E. Brewster, chemist of the Pewabic mine, to whom great obligations are acknowledged for the favor of publishing this and other analyses furnished by him. In column II is quoted an analysis of a sea-green roofing slate from West Pawlet, Vt.[a] The analyses show clearly that the argillaceous phases of the Traders slates are composed largely of the débris of granitic rocks, such as those forming the northern area of the Archean. The high magnesian content of the rock from the Chapin mine is plainly due to the presence of the talc which infiltrated along the fissile planes in solutions emanating from the dolomite.

The mineral composition of the first slate calculated from its analysis in Column I is approximately 47 per cent quartz, 20 per cent kaolin, 5½ per cent muscovite, 8.8 per cent orthoclase, 6 per cent penninite, and 2½ per cent limonite.

The quartzose phases of the slates differ but little from the argillaceous phases just described. In these much of the quartz is in round or oval grains that are usually homogeneous. Sometimes the original grains are broken up into mosaics of small grains, the outlines of the mosaic aggregates corresponding to the outlines of the original grains. Nearly all the grains are crossed by strain shadows. The matrix in which these are embedded differs little in its character from that of the argillaceous slates. Quartz and kaolin constitute its principal constituents. Sometimes this is traversed by irregular streaks rich in small flakes of brown biotite, and scattered indiscriminately through it are occasional large wisps of muscovite or sericite. The usual limonite grains and some hematite particles are also present.

The ferruginous slates differ markedly from the argillaceous and quartzose phases described above. They consist of nearly equal parts of opaque hematite in individual crystals and groups of crystals and a colorless matrix composed of small clastic quartz grains, wisps of muscovite, cloudy masses of some decomposed feldspar, a little light-green chlorite, and a considerable quantity of crystallized quartz cementing the other

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[a] Bull. U. S. Geol. Survey No. 168, 1900, p 278; also Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 3, 1899, pp. 232 and 243.

components. The hematite is the most noticeable constituent. Its groups sometimes consist of a very few grains aggregated in an irregular manner, and at other times they comprise a great number of grains united in such a way as to form aggregates that are much longer in one direction than in any other. There is thus produced a slight schistosity in the rock, which is accentuated to some degree by the tendency of the muscovite to arrange itself in a direction parallel to the elongation of the hematite groups. These slates, like the argillaceous phases, are mechanical sediments. They, however, have had deposited in them a great quantity of hematite and much silica. Thus they are, in a way, intermediate forms between the argillaceous slates and the jaspilites.

CONGLOMERATES AND QUARTZITES.

Macroscopical.—The conglomerates and quartzites are usually at or near the base of the member, in some places resting immediately upon the Randville dolomite, and at other places separated from the dolomite by one or more beds of the shaly slates just described. They vary in thickness from a few inches to 20 feet or more. They contain fragments, usually small but occasionally large, of quartzite, jasper, colorless and white quartz, and rocks that make up the Archean complex.

The more massive phases have the appearance of coarse, dark-colored quartzites composed of fragments of the above-mentioned rocks, usually varying in size from 4 to 10 millimeters, lying in a dark-purple or brown groundmass made up of small, colorless, brilliantly glistening quartz grains in what appears to be a homogeneous matrix of a dark color and a dull luster. In this rock bands filled with large fragments alternate with others free from them. Further, some of the former contain an abundance of sharp-edged pieces of jasper, while others contain none. Much of the rock is more or less schistose, but never is it as schistose as the more ferruginous phases described below. With increasing schistosity the quartz and other fragments become more and more elongated and the jasper fragments are rotated to a position parallel to the schistosity.

In many cases the conglomerate contains so much hematite and jasper that it is an ore-and-jasper conglomerate or quartzite. In these instances the ore and jasper are sometimes in fragments embedded in a quartzitic matrix like that above described, but more usually the ore is in small grains scattered through the matrix in which larger fragments of jasper are embedded. Often the hematite constitutes such a large portion of this matrix that to all appearances it is a comparatively pure ore.

These varieties are nearly always strongly schistose. On the cleavage surfaces of the less schistose phases the ore fragments appear as little shining oval plates up to 8 mm. in length and little shreds from 1 to 5 mm. long. The jasper fragments are smaller and sometimes have angular outlines, but usually these, too, are oval in shape. They are often of the same dark-purple color as the matrix in which they are embedded, and so are difficult to distinguish. On surfaces that lie across the schistosity the ore particles appear simply as lines parallel to the schistose structure, while the jasper particles are much elongated ovals.

Typical occurrences of the quartzose phases of these conglomerates and coarse quartzites are found near the base of the Vulcan series in the open pit of the Quinnesec mine and in the ledges bordering the south side of the little valley at the Brier Hill mine. They occur also in similar positions in many of the mines, and fine specimens may be found on their dump heaps. The ferruginous types are especially abundant at the Traders, the Cuff, the Millie, and the Pewabic mines and in many of the exploring pits north of the Curry and West Vulcan mines.

As the quantity of hematite in the quartzite increases, the rock tends to lose its fragmental character and to assume a schistose structure. 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.

When in this form the rocks are typical jaspilites. These are well represented in the exposures forming Hughitt Bluff, east of Iron Mountain. Here the jasper-bearing quartzose layers have given rise to purple-mottled jaspers and the ferruginous layers have yielded specular ore bands. All gradations are represented at this place between rocks that still retain evident clastic characteristics and those in which no trace of fragmental material remains. The finer the original grain of these rocks and the more schistose their present structure the more homogeneous are the resulting bands and the more difficult is it to distinguish in them any distinct evidence of their original clastic character. At the west end of Hughitt Bluff the original sediments were fairly coarse; hence the rocks, although very schistose, still yield proofs that they were originally fragmental. In the most fragmental phases the distinction between quartzose and ferruginous layers is not marked. The former are lighter colored than the latter, a little more siliceous, and a little more granular. The latter, on the other hand, contain more hematite and are therefore more schistose and less granular.

In some localities, more particularly at the Traders and Cuff mines, the conglomerates, together with the banded ores and jaspers, have become brecciated through mashing, so that the most apparent structure is the brecciated one. Long, flat, lenticules of jasper and ore are interwoven in such a manner as to give the rock the appearance of a conglomerate. At first sight this pseudo-conglomeratic structure may be taken for a true conglomeratic structure, but a careful examination of the ledges will show that there is a definite and regular alternation of jasper lenses with ore lenses in such a manner as can be explained only on the supposition that they represent the shattered portions of what were originally continuous bands of quartzose and ferruginous materials. Moreover, the rocks are strongly schistose, with the schist planes cutting the bands at all angles. Where the schistosity is highly inclined to the banding the jasper bands are dissected by occasional cracks and their dissevered portions are rotated into positions tending to conform with the schistosity (see fig. 23). Thus the individual bands may be made up of large numbers of lenses with their longer axes lying athwart the direction of the bands, but parallel to the direction of the schistosity. Their ends frequently fit the ends of the next adjacent lenses. The true conglomeratic structure of the rock is recognized only upon very close inspection of some of the jasper lenses. These, when examined carefully, are seen to be composed of fragments of jasper inclosed in a fine-grained matrix of jasper, sand, and hematite flakes. Under the microscope the fragmental character of all the jasper bands is quite plain.

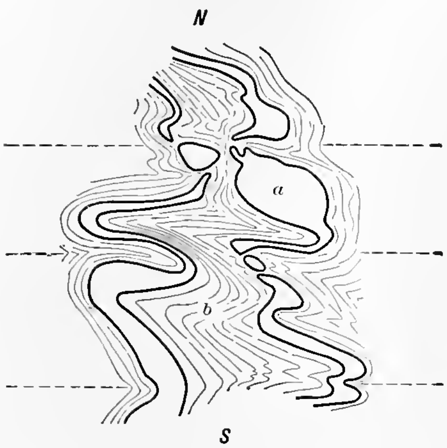

FIG. 23.—Sketch of contortions in jasper bands, west side of Clifford pit, illustrating production of breccias. *a*, Jasper; *b*, schistose hematite. Dotted lines show direction of schistosity. Area figured, about 5 by 3 feet.

Microscopical.—Most of the coarse quartzites or fine-grained conglomerates at and near the base of the Traders member are composed of large rounded grains of quartz and small pebbles of the same mineral, often enlarged by the addition of quartz material in optical continuity with the surrounded nucleus, and elongated sharp-edged or subangular fragments of jasper lying in a groundmass consisting essentially of quartz and hematite (see Pl. XIX, *A*, *B*). The quartz is in small polygonal grains, interlocking with one another to form a mosaic in which the hematite and other rarer components of the groundmass are embedded. No indications of the presence of clastic quartz can anywhere be detected in this mosaic. The quartz must have formed in situ, replacing completely the original cement by which the pebbles and large quartz grains were united. The hematite usually occurs in two distinct forms, but occasionally a third form is observed. The greater portion of the mineral is in irregular-shaped, angular masses that are apparently aggregates of small crystals. Another, but much smaller portion, is in large, well-developed crystals scattered here and there irregularly through the quartz mosaic. Occasionally one of these crystals is half within a large quartz grain, the other half projecting outward into the quartz mosaic. The third form is in little curved streaks, outlining oval areas or forming a ring or several concentric rings surrounding areas constituted exactly like the mosaic of the groundmass. These, for reasons that will be given later (see p. 344), are believed to be pseudomorphs of concretions in a ferruginous sediment. Their presence indicates that the groundmass of the conglomerates contained originally a considerable quantity of a chemically deposited ferruginous carbonate or silicate which was later replaced by silica and hematite. Further, the entire quartzose groundmass is dotted with a dust of tiny grains of transparent hematite.

In those beds in which the proportion of hematite present is very great, the hematite, in addition to the forms described above, occurs also as occasional fragments intermingled with the enlarged quartz grains. Here and there through the crystalline quartz matrix are also little rounded jasper grains that are peripherally enriched by concentric bands of ore, and ramifying between the quartz and ore fragments are small stringers of very dense hematite, which looks as though it were infiltrated in the form of veinlets after the rock had become silicified. Scattered through the matrix a few wisps of biotite are sometimes observed in the sections and occasionally there is present a shred of muscovite, but usually the only constituents of the rocks are quartz and hematite.

In the few localities where the formation is not much disturbed, as, for instance, near the center of the northeast quarter of sec. 9, T. 39 N., R. 29 W., where the flat lying Traders member is overlain by the Lake Superior sandstone, the fragmental character of the rock is very apparent. Here the ore and the jasper are in distinctly angular pieces and the matrix is a well-defined quartzite made up of enlarged quartz grains. This matrix, however, passes gradually into a finer-grained matrix composed of interlocking grains in which no distinction between nucleal and added quartz can be made out. The fragmental grains seem to have been replaced in parts of the sections by secondary material.

Usually the only evidences of the clastic nature of these rocks is the presence in them of the abundant rounded quartz grains and of a few jasper and ore fragments. Moreover, this evidence is often obscure, for nearly all the beds except the coarsest ones exhibit schistosity, and this structure, even in its less marked stages, is peculiarly effective in obliterating the fragmental character of the constituents, especially in those cases in which a considerable portion of these consist of ore grains. When the quartzites are interbedded with layers very rich in hematite the latter are always much more schistose than the former, often resembling in appearance the typical specular ores of the Marquette district. Where this is the case all evidences of the presence of ore fragments in these bands have disappeared, though the fragmental origin of much of the material in the quartzitic bands interbedded with those bands may still be apparent. When the quartzitic layers become sheared these too lose their clastic structure. The smaller quartz pebbles and the jasper fragments break up into mosaics and the ore pebbles are drawn out into long narrow streaks. In this manner beds of interlaminated quartzite and hematite pass into well-characterized jaspilites that are sometimes indistinguishable from those derived from chemical sediments.

Thus the whole aspect of the quartzites and fine-grained conglomerates is that of a sediment composed of many coarse ore and jasper fragments and fine quartz sand, which has been thoroughly silicified by the deposition of silica between the larger grains and the entire replacement of the cementing material by this substance. In one or two instances that have been observed it has seemed probable that the replaced cement was mainly fragmental quartz sand which had been almost completely dissolved and redeposited before the rocks became schistose, but in most instances no such process is indicated. The structure of the mosaic is identical with that of the jaspers, and it may well be that in the present case, as in the case of the jaspers to be discussed later, the silica has replaced a ferruginous carbonate or a silicate. If this is so the original deposits were composed of a mixture of chemically deposited substances and detritus from an older jasper and ore formation. At the very base of the formation the detrital portion was in great excess and the resulting rocks were mainly coarse quartzite and fine-grained conglomerates. Interstratified with these at little higher horizons, beds of almost pure jasper now occur, and these were originally beds of chemically deposited carbonate and silicate with no admixture of fragmental material. The mottled jaspers described above must have been composed of ferruginous compounds containing more or less abundant sand grains and small pebbles.

Although the quartzites and conglomerates have been subjected to deformation stresses usually sufficiently intense to cause mashing of the smaller quartz pebbles, nevertheless, in only a few instances have these caused any evident crushing of the larger pebbles or the production of strain shadows in them. In the conglomerate bed at the base of the ore formation in the open pit of the Quinnesec mine, however, the effects of pressure are very marked. In the hand specimen the rock is like the coarse quartzites elsewhere, with the exception that it is distinctly schistose. In thin section the small pebbles, when revolved between crossed nicols, are seen to be crossed by strain shadows which are differently oriented in different portions of the same pebble. In the interior of the grains the areas characterized by the different shadows are physically continuous. Near their peripheries, however, minute cracks develop between neighboring areas. These widen, and, at the borders of many of the grains, particles become entirely separated from the main portion of the grain, forming a granulated zone around it. With the separation of these parts the stresses in them seem to be relieved somewhat, for many of the dissevered particles are free from strain shadows while the neighboring portions of the unbroken grain exhibit them in great perfection. This process of granulation has proceeded so far, especially in the case of the fragments that were originally sharp edged, that the entire area of the original grain is now a mosaic of little grains, each of which is divided by tiny cracks into several portions, all of which, however, are crossed by a uniform shadow. Often these granulated masses retain the outline of the original fragment, but usually they are drawn out into long narrow strings or very flat curved lenses which strongly accentuate the schistosity of the groundmass. This latter is made up of large and small, apparently fragmental, quartz grains free from strain shadows, occupying areas of various elongated shapes and interspersed with these are streaks of interlocking quartzes forming well-defined mosaics. The quartzes in the mosaics are filled with the usual hematite dust, while those in the fragmental aggregate contain practically no inclusions. About a third of the rock consists of hematite. This is present in dense, opaque lines that run nearly parallel to the schistosity, in long lenticular streaks of massive ore, and in comparatively large isolated crystals within the quartz matrix and sometimes lying partly within this and partly within the areas of the granulated masses supposed to result from the crushing of quartz pebbles. The dense, massive ore appears to fill narrow crevices opened up in the rock parallel to its structure. The crystals were formed after the material of the rock was deposited, but before it was completely silicified and made schistose. The ore streaks, the lines of hematite crystals, and the long narrow lenses of the crushed quartz flowed around the large pebble-like quartz areas in a way known only in rocks of clastic origin that have been made schistose by pressure.

The rock of the Traders mine presents some peculiarities that warrant at least a brief special mention. In the ledge the rock is apparently, as has been stated, a sheared conglomerate or breccia composed of large jasper-like pebbles in a matrix of specular ore. Under the microscope the apparent pebbles are themselves seen to be made up of fragments from some older jasper bed, and the rock, as a whole, is discovered to be a brecciated series of fragmental beds. The ore matrix presents no unusual features. It is an aggregate of crystals, streaks, and flattened masses of hematite inclosing numerous grains of quartz. The appearance of the jasper sections is strikingly like that of many tuffs. In natural light, under low powers, they exhibit the usual features of individual and grouped crystals of hematite lying in a colorless matrix of quartz containing numerous small red inclusions. Under medium powers, however, the nature of the inclusions is seen to be quite different from that of the inclusions of the more normal jaspers. Without exception, they are the fragments of a colorless substance, that seems to be quartz, filled with very fine, red dust that resembles earthy hematite. The fragments vary in their largest dimensions from 0.03 to 0.06 mm., and are extremely variable in shape. Some are rod-like, others rounded, and yet others irregular in outline with sharp corners. The majority, however, are in general triangular or quadrangular, with curved bounding surfaces. In other words, these fragments have the same shapes as the glass splinters in many volcanic ashes. If present in a rock of another character than this, they might be cited as evidence of its volcanic origin. In the present instance there can be no doubt that the rock is a sediment. The fragments are probably fine splinters forcibly broken from a jasper, which, like all rocks with a conchoidal fracture, yielded flakes with curved surfaces. The fragments lie in all positions within and between the grains of the quartz mosaic, the linear dimensions of which are from three to four times as great as those of the fragments. A few sericite shreds occur here and there between the quartz grains, otherwise the mosaic is like that in all the other jaspers of this district.

The rock was probably originally composed of small, sharp-edged fragments of jasper and round ore fragments in a matrix that was subsequently silicified.

JASPILITES.

Macroscopical.—With increasing distance from the base of the formation the conglomerates and quartzites pass upward into cherty or jasper-like rocks, the former gray and the latter dark red or purple in color. The gray cherty rocks are exceedingly rare in the Traders member, being found at only a very few places in the formation and at these places in subordinate amount.

These siliceous rocks occur in layers that vary in thickness from a fraction of an inch to 18 inches or 2 feet. They are always interlaminated with hematite layers, forming the banded rock known as jaspilite. 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 jasper, which in some cases they are believed to be. The former are often mottled by red and purple blotches that appear to be due to the presence of red jasper grains in a ferruginous quartzose matrix. In the greater number of instances 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 jasper 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 jasper[a] (secondarily deposited) present, but apparently the former is the more abundant in many specimens, and it may predominate in most. In a few instances the structure of the siliceous layers is clearly fragmental. This is beautifully shown in a specimen obtained from the north end of a trench crossing the iron formation just east of the Cuff mine. The rock has a reddish-purple color. Through a purple jasper groundmass are scattered a great many small, irregular-shaped, brilliant-red jasper fragments with sharp edges. Because the rock is not sheared the fragments are easily recognized. Such a rock, if made schistose by mashing and shearing, would no doubt give rise to a mottled variety, like the mottled jaspers referred to in the preceding paragraph. A second type of fragmental texture is well exhibited by some of the siliceous bands in pit No. 2, north of the Curry mine. The dark-purple jasper is dotted with little irregular grains of a gray hematite lying in all possible positions within the bands. These are plainly fragmental. Together with a considerable number of small jasper fragments they constitute large portions of the rocks. In places the ore particles become larger and more numerous, merging into well-defined bands. At the same time the structure becomes

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[a]In this discussion the term "jasper" is applied to the nonfragmental aggregate of cherty quartz and hematite flakes associated with the hematite layers in the iron formations. The term "jaspilite" is applied to the banded rock composed of alternating layers of jasper and hematite. It is true that the latter term was first proposed by Wadsworth to designate the jaspers, on the assumption that the jasper associated with the Marquette rocks is an eruptive rock "more acid than the rhyolites." (Notes on the geology of the iron and copper districts of Lake Superior: Bull. Mus. Comp. Zoology, vol. 7, 1880, p. 76.) But when it was shown that the jaspers are sedimentary in origin the employment of the term in Wadsworth's sense was no longer applicable. Van Hise then suggested that the term be retained as a convenient one to designate the "rocks consisting of alternating bands composed mainly of finely crystalline, iron-stained quartz and iron oxide." (Mon. U. S. Geol. Survey, vol. 28, p. 362.) In this sense the term is used as a convenient descriptive one in this volume. In the preliminary report on the Menominee district (Geologic Atlas U. S., folio 62, U. S. Geol. Survey, p. 4) the discrimination between the terms jasper and jaspilite was not always made, nor in the monograph in which the term "jaspilite" was redefined was this term always used in the newly defined sense (cf.: "The hard-ore jasper or jaspilite," a few lines above the definition quoted above). In the present monograph all the siliceous material in the iron formation which is now composed entirely or largely of interlocking quartz grains (whether originally clastic or not) will be called jasper, and rocks composed of alternating bands of jasper and hematite will be designated jaspilites.

dense and the individuality of the constituent grains is lost. Even without the aid of the microscope it is clear that there has been a secondary deposition of ore material between the fragments, welding them into a homogeneous mass.

These distinctly fragmental types grade into the mottled jaspers, which are sheared phases of the same rock, and these in turn pass gradually by the loss of their mottlings into the aphanitic, flinty jaspers with a wax-like luster.

The ferruginous layers associated with the conglomerates and the quartzites become more numerous as the latter grade into jaspers, and the alternations of the siliceous and ferruginous materials become more regular. These associated iron oxides usually occur in beds no thicker than the quartzose layers. At various places, however, especially in the basins produced by the folding of the dolomites, they rapidly thicken and replace the quartzose layers along their strike, forming ore deposits, which may be sufficiently large to warrant mining.

The thin-bedded ores are usually gray specular varieties, strongly resembling in appearance the Marquette specular ores from the Ishpeming formation. The readjustments due to folding occurred mainly in the soft ferruginous bands between the harder siliceous ores, and as a result the former have been sheared and the hematite rendered micaceous. In some cases the shearing was so severe that it affected the jasper and ore alike and both became schistose. On fractured surfaces along the schistose planes of the ores, especially when these surfaces have been slightly weathered, there is noticeable a peculiar texture that possesses considerable significance. On such surfaces a distinction can be made out between a fine-grained matrix and numerous comparatively large oval or lenticular areas. The latter give uniform reflection from their entire surfaces, while the matrix reflects from many small surfaces. The appearance thus produced is that of a number of large flattened grains in a groundmass composed of small grains. This texture is characteristic of fragmental sediments. Considered in connection with the fact that ore fragments are known to be present in some of the jaspers (cf., p. 308), the texture is regarded as indicating that many of the ore layers are composed largely of fragmental material.

The ore bands interstratified with the siliceous ones are not always schistose, nor have they always the mottled appearance of the typically fragmental ores. In many cases the interbedded ore is a dense black variety, almost aphanitic in texture, but striped parallel to the bedding with narrow lines that look like lines of sedimentation. The ore of this kind is mainly secondary, having been deposited along the planes between contiguous jasper layers or along bedding cracks that may have been opened within original ferruginous layers. In these cases there is usually a sharp contact line between the ferruginous and the siliceous layers, and the borders of the former are often denser and harder than their interior portions, which are composed principally of original material. In the case of the bands that consist largely of granular or micaceous hematite, the transition from these layers to the siliceous ones is more frequently gradual. The jasper near the ore is highly charged with hematite. Moreover, near the borders of the bands narrow seams of the siliceous material are interlaminated with the broader ferruginous ones. These become more numerous and broader, predominating over the ore bands and finally exceeding them altogether. In many instances ore bands that at first sight look homogeneous are found upon close inspection to be made up throughout of minute interlaminations of hematite and jasper.

Like all other fragmental sediments, the ores contain a variable quantity of impurities. Much of this impurity consists of quartz grains and of the constituents that are usually found in slates. Sometimes the proportion of such substances is so great that the ores are not marketable. They are then known as slates. The blue or dark-gray slates occurring under the ore at the Clifford pit of the Traders mine and in the dump heaps of the Cuff and Indiana mines are of this character. They are ferruginous sediments in which the proportion of ore grains is not sufficiently great to warrant working. On their cleavage surfaces these slates look like fine-grained specular ores, but on cross fractures they have a dull luster and are marked by obscure bands due to sedimentation. Moreover, they have a distinct argillaceous odor and are noticeably lighter in weight than the merchantable ores. With a lens the constituents can easily be made out to be ore particles and grains of a dull yellowish-white mineral.

The distinction between ore and slate at the Traders mine is mainly based on economic considerations. The boundary line between the two oscillates with the demands of the ore market. At the present writing, however, those deposits in which the impurities are distinctly visible as yellowish-white grains disseminated through the mass are unmarketable. The marketable ores are confined to those in which the impurities are jasper fragments or secondary silica aggregated into narrow bands. The guaranteed quality of the Traders ore is: Fe=41.00 per cent, P=.020 per cent. Cargo analyses of the ore shipped in 1899 averaged as follows:

Average analysis of ore from Traders mine.

Fe	41.01
SiO_2	39.10
P	.014
Mn	.09
S	.003
Al_2O_3	.97
CaO	.49
MgO	.29
H_2O above 105°	2.55

The surface surrounding the mine has been exhaustively test-pitted and the contents of the pits have been carefully tested for iron and phosphorus. The results of these analyses exhibit well the gradual transition between ore and slate. The numbers are those given to the different pits on the mine plats. Of these the first four pits are regarded as in slate, the balance as in ore. The arbitrary division between slate and ore is at 35 per cent Fe.

Iron content of rock taken from test pits north of the Clifford open pit.

	No. 6.	No. 3.	No. 12.	No. 1.	No. 7.	No. 13.	No. 11.	No. 8.	No. 9.
Fe	29.70	31.50	33.019	33.30	35.10	39.10	44.20	45.30	49.40
P	.011	.008	....	.011	.011	.040	.009	.008	.022

The rocks constituted by the alternations of the siliceous and ferruginous bands often resemble very closely the jaspilites of the Marquette district. The brilliant red banding of the Marquette rock is, however, noticed at only a few places in the Menominee district. The prevailing color of the Menominee jaspers is dark purple or brown. In a few instances, especially where the siliceous bands contain very little fragmental jasper, the red color may be marked, as in the case of some of the bands in the Quinnesec open pit and in the ledge northwest of the Curry shaft No. 2, which has already been referred to as illustrating the character of the jaspilites of the Negaunee formation (p. 275). On the weathered surfaces the siliceous bands frequently take on a deep-red color, and on the surfaces of joint cracks druses of brilliant-red quartz crystals often cover the ends of the bands, but the color in both instances is only superficial. It rarely penetrates the rock to any great depth.

In most cases, except where the rock is brecciated, the bands are continuous, with a uniform thickness for long distances. Occasionally the bands wedge out, and when this occurs it is without exception the siliceous ones that so disappear, the ferruginous ones wrapping around their ends and coalescing. The result of this is the appearance of lenticular masses of jasper embedded in schistose ore (see Pl. XX, *B*). Sometimes the lenses are small and numerous, measuring one-fourth or one-half inch in their long diameters; sometimes the dissevered masses are spherical rather than lenticular. In both cases the resulting schist is knotty, resembling in general appearance micaceous schists that are studded with staurolite or garnet crystals. Well-marked phases of lenticular and brecciated jaspers are to be seen in the rock piles of the Traders and the Cuff mines and in the pits lying along the contact of the Vulcan formation and the Randville dolomite and stretching from the Norway mine to the West Vulcan mine. These all exhibit the structure on a large scale. They are plainly nearly all brecciated jaspilites. At other places, notably west of Iron Mountain, the typical lenses occur, and these, so far as can be learned, are not connected with brecciation.

Where folded the siliceous bands are often crossed by cracks and fissures, on the walls of which are druses of quartz or calcite and hematite crystals. Veins of quartz, of calcite, and of dense hematite also traverse the ore and jasper bands indifferently, and not infrequently hematite veins are intercalated in the ore bands parallel to their bedding. The vein ore is always denser and more granular than the surrounding ore, and from the fact that the vein material often lacks schistosity when the intruded ore is schistose it follows that the former must have been deposited after the period of readjustment, during which folding occurred.

Where the rocks are folded the ore bands usually thicken and the ores take on a character very different from that of the ore in the thin beds. They lose their specular habit and their steel-gray color and become granular in texture and dark blue or black in color. This change is noticed to occur particularly at the ends and in the troughs of folds and in places where the rocks have been crushed or jointed. In these places the water that is constantly circulating through the rocks has removed silica and deposited hematite (see pp. 352, 395), thus producing the ore deposits of the district. New hematite has built out the plates of the original ore into grains. At the same time it has filled or partly filled with ore the openings that were produced during the crushing and jointing of the rock. Where the crushing was considerable the ore may present a porous aspect and all joint cracks may be lined with druses of hematite crystals. In other instances the thickening of the ore beds is, in part at least, an original effect and not one due to secondary causes. Some places along the original shore lines were more favorably situated for the accumulation of the ferruginous sediments than others. Here the deposits settled in greater abundance than elsewhere and made thick beds. The ore bodies thus produced may pass gradually along the strike into ferruginous jaspers, whereas when the change is due to secondary enrichment the passage may be comparatively sudden. The ore deposits are thus exceedingly variable in thickness, in some places measuring only a few inches, in others reaching 200 feet or more.

Microscopical.—When viewed under the microscope the jaspilites are found to be in most instances thoroughly crystalline. Even those specimens which in the hand specimen show a distinct mottling exhibit, only in a few cases, a fragmental structure when studied in thin sections. Those which exhibit this structure best are the jaspilites of Hughitt Bluff.

Sections of these rocks show both ore and jasper fragments in a matrix resembling that of the homogeneous jaspers described in succeeding pages. The ore fragments consist of long oval or lenticular masses of a very fine aggregate of quartz grains and tiny hematite flakes. Streaks of a coarse-grained and dense ore penetrate these masses in a direction parallel to their long axes, and usually their peripheries are bordered by zones of the same dense ore. The lenses are also traversed by quartz veins, the structure of which is much coarser than that of the quartz mosaic in the fragments. On the other hand, their material seems to be identical with that of the matrix in which the fragments lie. In reflected light those fragments with least of the dense ore in them have the bright-red color of jasper, while those in which there is much dense hematite are opaque and black. The distinction between the jasper and the ore pebbles is thus due solely to the quantity of hematite in them and to its character.

The groundmass in which these larger fragments are embedded consists of smaller oval and lenticular fragments of the same kind as the larger ones, cemented together by the usual matrix composed essentially of interlocking quartz grains materially larger than those in the jasper fragments. A few of these present the appearance of enlarged clastic particles, but by far the greater portion were clearly formed in place. Tiny nests of a ferruginous carbonate are also noticed here and there. In a few cases zones of coarse quartz border the large jasper and ore fragments and separate them from the mosaic matrix. Carbonate nests also occur frequently in the jasper pebbles and fragments, where it is clearly secondary.

The sections of many specimens, especially of the more schistose phases of the rocks, are mottled with large patches of quartz, many grains of which are granulated on their peripheries. These patches are traversed by broad veins of crystalline quartz like that composing the mosaic which cements the granulated patches together. These rocks look very much as though they had been crushed and shattered and, after shattering, had been healed by deposits of silica. Within the patches, in addition to the quartz, there are often large quantities of a yellowish, probably ferruginous, carbonate, partly in granules and partly in nests, and a great number of small particles of hematite. The cementing mosaic, on the other hand, is free from carbonate and also practically free from hematite dust, though an occasional speck of the mineral may frequently be detected in it, and here and there a bunch of fibrous chlorite.

The more distinctly schistose these rocks the less well preserved is their fragmental structure. The larger fragments in most schistose phases are flattened almost into shreds, and the components of the groundmass mosaic into distinctly lenticular grains. Wisps of muscovite are also developed in the groundmass, and with them is nearly always associated a little calcite or other colorless carbonate. A few little nests of the ferruginous carbonate remain. Coarse-grained quartz veins cut through this schistose groundmass, and occasionally it is crossed by a small vein of dense hematite. The ore bands differ from the jasper bands mainly in the presence of

PLATE XIX.

PLATE XIX.

PHOTOMICROGRAPHS OF ROCKS IN THE VULCAN FORMATION.

FIG. *A*.—Schistose ferruginous quartzite at base of Traders member, west end of Quinnesec open pit. Sand grains are inclosed in a matrix composed of smaller grains and narrow lenses of quartz intermingled with hematite dust and distinct crystals of the same mineral. Some of the hematite crystals are partly within a quartz fragment and partly in the matrix. The schistosity of the hand specimen is due to the wrapping of the quartz-hematite matrix around the large quartz sand grains. Ordinary light, ×23.

FIG. *B*.—Less ferruginous phase of the quartzite at the base of the Vulcan formation. The sand grains are surrounded by a matrix composed of small grains and masses and crystals of hematite. The fragmental character of the rock is very plain. Between crossed nicols all the quartz in the matrix possesses the crystalline character of that in typical jaspers. Ordinary light, ×15.

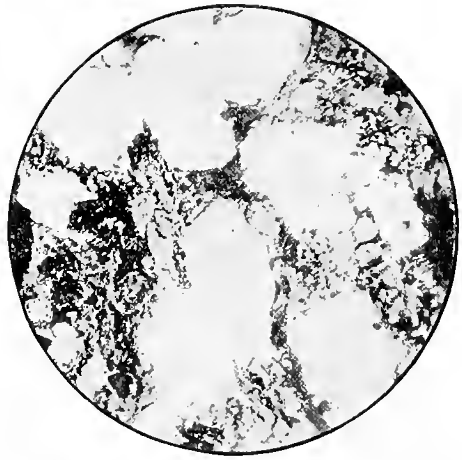
FIG. *C*.—Jasper band in jaspilite, south side of Curry member, in northwest quarter of sec. 13, T. 39 N., R. 29 W. The section shows a finely crystalline quartz aggregate (which appears homogeneous in ordinary light) crossed by curved and concentric opaque bands, composed of little crystals of hematite. These mark the outlines of what were nodules, which have otherwise entirely disappeared. Ordinary light, ×23. Compare with photograph of ferruginous chert derived from greenalite. Mesabi district, Mon. U. S. Geol. Survey, vol. 43, Pl. XV, *A*.

FIG. *D*.—Specular siliceous ore from test pit in the northwest quarter of sec. 13, T. 39 N., R. 29 W., Curry member. The section is made up of elongated nodules of hematite and of jasper in a homogeneous mosaic of fine-grained crystallized quartz. The opaque nodules are hematite. The cloudy ones are jasper, composed of hematite dust in a fine-grained quartz mosaic. One nodule shows a concentric arrangement of the quartz and hematite, characteristic of nodules derived from siderite. Ordinary light, ×23.

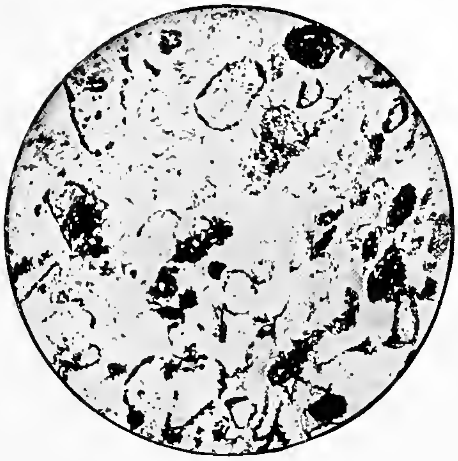
FIG. *E*.—Spotted jasper from jaspilite, on railroad west of the Verona mine. This jasper consists of nodules of hematite and quartz and sharp-edged fragments of an older jasper in a groundmass of cherty quartz. The particles that are uniformly colored by hematite may be fragments of an old jasper. Those with accumulations of hematite toward their centers are probably nodules. All particles are surrounded by narrow rims of hematite grains that must have been deposited after the rock had practically assumed its present character. Ordinary light, ×23. Compare with photograph of ferruginous chert derived from greenalite. Gogebic district, Mon. U. S. Geol. Survey, vol. 43, Pl. XVI, *B*.

FIG. *F*.—Same section. Under crossed nicols the entire field of view breaks up into an aggregate of finely crystallized (cherty) quartz. The outlines of a few of the nodules can be dimly discerned, but on the whole the section becomes a uniform mosaic, typical of the jaspers in general. Crossed nicols, ×18. Compare Pl. XV, *D*, Mon. U. S. Geol. Survey, vol. 43.

(A)



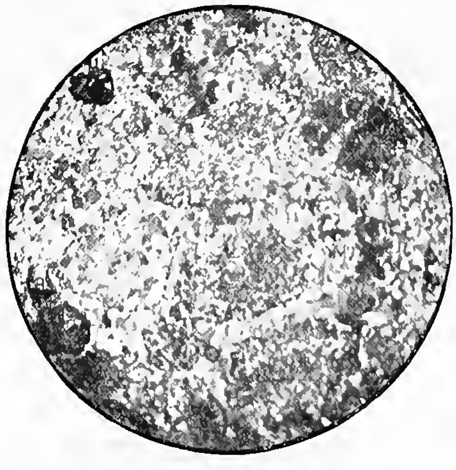
(B)



(C)

(D)

(E)



(F)

MICROPHOTOGRAPHS OF ROCKS IN THE VULCAN FORMATION

a larger proportion of very much flattened ore fragments and partly in the presence of subsequently deposited hematite in the form of stringers or narrow veins. The proportion of the latter to the former can not be determined, but in some instances the newly deposited ore is present in large amount.

The majority of the mottled jaspilites differ from those of Hughitt Bluff in containing no distinctly characterized pebbles of either jasper or ore. Occasionally, when the sections are viewed in natural light, there can be seen in the siliceous layers obscure traces of round or oval quartz masses that look something like pebbles. Sometimes the center of each mass is occupied by a little irregular nucleus clouded red by minute particles of hematite. This is surrounded by a zone of quartz in optical continuity with the nucleus and meeting the peripheries of other grains in interlocking sutures. Although there seems to be no sharp line of demarcation between clouded nucleus and clear periphery, nevertheless the appearance is as though the former were sand grains that had been enlarged by the addition of new material. Again, in some sections the distribution of hematite grains is such as to outline areas of quartz free from ore particles in the midst of an aggregate of quartz and ore, or the hematite is aggregated into small spherical and lenticular masses in which the ore is intermingled with a little quartz or borders a little quartz area. In the first case the sections seem to be composed of colorless pebbles in a crystalline aggregate of quartz and hematite. In the second case the apparent pebbles are probably pseudomorphs of concretions originally present in the sediments. These are much more common in the jaspers of the Curry member, in the discussion of which they will be referred to again. Between crossed nicols the fragmental structure of all sections disappears, or, at any rate, it becomes very obscure. The entire section in each case breaks up into a practically uniform mosaic of interlocking quartz grains speckled with opaque dots and ovals of hematite and occasional crystals of magnetite (compare Pl. XIX, *E* and *F*). In a few of the lenticular areas outlined by the ore the texture of the mosaic varies a little from that of the rest of the section, but only a very little.

The ore layers of these rocks differ from the siliceous ones mainly in the greater quantity of ore present. Most of it is scattered in little irregular masses between grains of quartz like those in the mosaic composing the essential part of the jasper layers, but much of it is in long narrow stringers that may be flattened pebbles or infiltrations along cracks.

Most of the true jaspilites exhibit no evidence of any kind of having ever contained fragmental detritus. Their jasper bands consist of a mosaic of slightly elongated quartz particles crossed by streaks of opaque hematite running in the same direction as the elongation of the quartz grains. The quartz grains are all small, their dimensions varying between 0.07 mm. and 0.14 mm. along their shorter diameters and 0.18 mm. to 0.22 mm. along their greater diameters. The ore streaks are made up of lines of small crystals or aggregates of crystals that seem to lie indifferently between quartz grains and inclosed within them. Besides the ore inclusions the quartz contains also a few liquid inclusions, a few indeterminate cloudy masses, some small independent crystals of hematite, and a quantity of fine dust-like particles that may also be a form of iron oxide. The hematite and quartz look as though they were deposited contemporaneously, the rocks in their microscopical features being identical with the jaspers of the Marquette district.

Occasionally in some sections small round lenticular areas of fine-grained quartz mosaic are distinguishable from a surrounding area of coarse grain, and often these are bounded by a thin zone of ore. In other sections there are lenticular and long, narrow, acicular masses composed of a mixture of quartz and limonite lying in the usual quartz mosaic. Of course these phenomena may indicate the former presence of pebbles in the original sediments, but the bodies are more probably concretions. They are, however, by no means as distinct as those in the conglomerates (see p. 303) or those in the Curry jaspers.

In some of the layers the microscope shows that the jasper consists of bands of the usual quartz mosaic interlaminated with others in which there is an abundance of a cloudy, red substance, which appears to be quartz stained by a thin layer of some iron hydroxide. Occasionally the red matter is in little plumose masses radiating inward from the peripheries of the stained areas, indicating plainly its secondary character. In other specimens round, cloudy areas are in reality portions of several quartz grains filled with tiny liquid inclusions. Between crossed nicols these areas break up into aggregates of grains each of which comprises two parts, one of which is filled with inclusions and the other entirely free from them.

Neither of these phenomena can be regarded as indicating the former presence of pebbles.

The most typical jaspers—those which can not be distinguished macroscopically from the typical jaspers of the Marquette district, except by their more purple tinge—differ from the siliceous bands above described mainly in possessing a much finer grain. The grains of their quartz mosaic rarely measure more than 0.03 mm. by 0.04 mm. They constitute a uniform aggregate of interlocking particles thickly peppered with small, irregular flecks of ore and uniformly dusted with minute opaque hematite grains, which under high powers of the microscope are resolved into little rods, tiny oval and irregularly shaped bodies, usually transparent in red and yellow colors, and small, sharp-edged particles that resemble very small fragments. The ore flecks are ragged-edged opaque masses with many sharp projections that look very much like the corners of little crystals extending beyond a compact aggregate of crystals.

The distinction between jasper layers and ore layers in all varieties of the jaspilites is due solely to variations in the relative proportions of quartz and hematite present. Those layers in which hematite is in excess are the ore layers. Those in which quartz predominates are jasper bands. The transition from jasper to ore is usually accomplished in one of two ways. In some cases the dust particles, which have been referred to as being uniformly distributed through the quartz mosaic, become aggregated into streaks and bands. Toward the borders of the jasper layers these grow thicker and thicker and more and more numerous until the hematite exceeds the quartz in quantity and the layer loses its siliceous character and passes into an ore bed. In the second and more frequent type of transition the gradation is plainly the result of a secondary deposition. Mention has been made of the fact that the quartz mosaic of the jasper bands is often dotted with large, isolated crystals of hematite. Through the layers, which in the hand specimen are recognized as jasper, the crystals are sparsely scattered without any definite arrangement that can be detected. As the ore layers are approached, however, the crystals become numerous and on the borders of the bands they merge into groups of crystals with irregular outlines, but usually with their longer axes parallel to the directions of the bands. In the densest portions of the ore layers these aggregates exclude nearly all of the quartz, leaving just enough remaining to enable one to detect the presence of the aggregates.

The ore layers in all the jaspilites thus differ from the jasper layers merely in the presence of a greater quantity of hematite of the same character as that existing in the jasper. The structure of both bands is the same, although the quartz in the ore bands is usually freer from hematite dust than that in the jasper layer. Although there is usually a gradation from jasper to ore, nevertheless in some cases the ore layers are rather sharply separated from the jasper layers by a distinct line. Sometimes there may be a gradation on one side of an ore bed and a sharp contact with the neighboring siliceous bed on the other side. Again, a quartz vein may intervene between the two, in which case, of course, their separation is complete.

All the jaspilites, whether of the homogeneous or of the mottled kind, are without exception schistose. The elongation of the individual grains of the quartz mosaic, the trend of the ore laminæ, and the position of the long axes of the pebble-like masses in the few specimens exhibiting them, are all in the same direction, which is also parallel to the banding. Moreover, the tiny quartz veins that here and there ramify the siliceous bands usually tend to follow this same direction, and thus to accentuate the schistosity.

BRIER SLATE.

DISTRIBUTION.

The Brier slate lies immediately above the Traders member and is practically coextensive with it. Wherever the ground which is geologically just above the ore-bearing Traders member has been explored the Brier slates have been uncovered. Where its distribution has not been complicated by faulting and profound folding, the slates occupy a continuous belt about 200–400 feet across, lying between the Traders ore belt on one side and the Curry ore belt on the other. In a few places faulting has caused the slates to disappear from the surface, and in other places folding has increased their apparent thickness, but in those stretches in which the rocks have not been affected by disturbances other than those which produced the major folding of the entire sedimentary series the belt maintains a nearly uniform width.

Along the north side of the Huronian trough there are no natural exposures of the Brier slates, and explorations that have been made in the belt of country immediately south of the northern dolomite belt have nowhere encountered the slates except at the Loretto and the Appleton mines, in the extreme eastern end of the district. In sec. 14, T. 40 N., R. 30 W., pits have been opened up in an iron formation which is believed to belong in the Curry member. The Brier slates should be north of these, but drift hills cover the surface, and this drift has not been penetrated by exploring pits or shafts. Therefore nothing is known of the nature of the rocks intervening between the ore pits near the center of the section and the dolomite outcrops near its north quarter post. On the map (Pl. IX) this area is colored to indicate that the underlying formation is not known. The same conditions exist for the entire belt between the pits just referred to and the Loretto mine in sec. 7, T. 39 N., R. 28 W. If the Brier slate occurs along this border of the trough it is as a narrow strip in the area colored for "Formation not determinable" (see legend of map, Pl. IX).

At the Loretto and Appleton mines the Brier slate has been encountered in the underground workings, in diamond-drill holes, and in numerous pits (see pp. 404–406) scattered over the surface between the shafts of the two mines. East of the Appleton mine exposures of the Vulcan formation are unknown. Its presence in this area is indicated by the existence of a strong magnetic line (see p. 286), but whether one or all of its members are present under the drift is unknown.

The distribution of the Vulcan formation around the central dolomite belt has been described (pp. 286–287). At the Traders and Clifford pits of the Traders mine the Brier slate is exposed under the stripping just above the beds that have yielded the merchantable ore. It has been discovered again by drilling south of the Indiana mine between the ore-bearing Traders member, which has been exploited from the Indiana shaft, and a magnetic ore formation farther south. At the Forest mine, in the southwest quarter of sec. 25, T. 40 N., R. 30 W., several drill holes, located between the main iron formation in which the mine shaft is sunk and a second ore formation about 400 feet south of this shaft, penetrated a dark slate, the position of which corresponds to that of the Brier slate elsewhere. East of the Forest mine for some little distance the Algonkian beds are covered by the Lake Superior sandstone, hence the eastward extension of the Brier member can be followed no farther. But somewhere between the Forest mine and Iron Hill, where the Hanbury slates are approximately in contact with the Randville dolomite, it disappears entirely with the rest of the Vulcan beds.

The best exhibition of the Brier member is south of the belt of the Traders member lying on the south side of the southern dolomite belt. It is exposed for nearly the entire length of the district from Waucedah in the east to the Menominee River in the west. At Waucedah (Pl. XXXVI) it has been exposed for nearly a mile through the north portion of sec. 22, T. 39 N., R. 28 W., by ledges and a series of pits, the most numerous of the latter lying a short distance to the northwest of the Emmett mine. Between this point and the Sturgeon River, a distance of about 2 miles, no ledges of the Vulcan formation have been found, nor has any test pitting been done. A magnetic line passes through secs. 17 and 18, T. 39 N., R. 28 W., and gives evidence of the presence of the Vulcan formation beneath the sands that cover the rocks in this portion of the district. Since, however, the Brier slate is found both at Waucedah and on the west side of the Sturgeon River in sec. 13, T. 39 N., R. 29 W., there is no reason to suppose that it is not present in the stretch of country between these two points. The evidence of its existence in the northwest quarter of sec. 13 is the presence of slates in two pits about 100 paces apart. North of the northern slate pit are other pits in an ore formation which has many of the characters of the Traders member elsewhere, and south of the southern pit is a trench and a line of pits exposing about 270 feet of an even-bedded iron formation in the position of the Curry member. The Brier slate at this place must be between 250 and 300 feet in width. At the Verona mine, and beyond it as far west as the Aragon mine, the slate is so well developed by pits, ledges, and the underground workings of the mines that there is no question as to its continuation throughout this distance as a distinct and well-characterized belt between the Traders and the Curry ore beds. At several points the direction of the belt changes to conform with the folding of the Traders member. At the Norway and Cyclops mines the slate is exposed at a great number of places in the large open pits of these mines and in numerous small test pits. Its thickness is increased by the several folds that produced the Norway and the Aragon basins and by several minor folds superimposed upon these (Pl. XXXI). The presence of the belt in sec. 6, T. 39 N., R. 29 W., and in the eastern half of sec. 1, in the next township west, is doubtful (see p. 459). Near the center of sec. 1, however, the entire Vulcan series is known to disappear in consequence of an overlap. It reappears again at Quinnesec near the line between secs. 2 and 3, in T. 39 N., R. 30 W. In the Quinnesec fold the

Brier slate is again met with in several belts, due to repetition of the member by close folding. Beyond Quinnesec the Vulcan formation is exposed by drill holes, test pitting, and open mine pits as far as the Pewabic mine, but in this stretch, so far as known, it consists of but two members—an iron-bearing member to the south and a slate member between this and the dolomite to the north. The iron-bearing member is probably the Curry. The slate member seems to vary in thickness, but it never quite disappears. There is always a thin selvage lying against the dolomite, and this has the characteristics of the light-colored slates between the Traders member and the underlying dolomite. Where thicker, the upper portion of the slate seems to resemble more nearly the typical Brier slate so far as can be determined from the meager evidence at hand. These facts suggest that the Brier slate in places, like the Traders member throughout this portion of the district, has disappeared and that only where the slate belt is thickest does any of it reach the present surface. The mapping is in accordance with this view (see map, Pl. XXXVIII). West of the old Keel Ridge mine, in sec. 32, T. 40 N., R. 30 W., is a fault, and northwest of this fault the entire Vulcan formation again appears with its three members. From this point to the west end of the Chapin property the Brier slate has been exposed at many places, not only in the mine workings, but also by test pits on the surface. West of the Ludington mine the Vulcan formation is known to occur as far as the end of the bluff in the center of sec. 26, T. 40 N., R. 31 W., and many pits have penetrated it; but no series of openings exhibits an entire cross section of the formation; therefore it can not be stated definitely whether the Brier slate occurs here or not. On the dump heaps of many of the pits slates are found which in many respects resemble strongly some of the weathered phases of the Brier member, but not enough confidence is felt in their identification to warrant their mapping as such in this portion of the district.

From the fact that the Brier slate has been recognized in all portions of the Vulcan series where this has been exposed from the Hanbury slate on the one side to the dolomite on the other, it is believed that the formation is a constant one, and that under normal conditions it will be discovered everywhere between the Traders and Curry member, when exploration has been sufficiently thorough to open up the ground between them.

LITHOLOGY.

Macroscopical.—The Brier slates, in their freshest and most typical phases, are heavy, black, dark-gray or dark-purple, very ferruginous rocks, with a dull, earthy luster quite different from the glistening luster of similarly colored slates belonging in the Hanbury formation. The dull luster is most noticeable on the cleavage surfaces, which are nearly always parallel to the bedding. On joint surfaces inclined to the bedding there can often be detected a little sheen, due to the shearing of hematite particles. Though a few specimens exhibit no bedding bands, the great majority present a very even and fine banding in consequence of the presence of layers richer than the average in iron oxides or of beds containing varying quantities of chloritic or other dark pigments. This banding, which is inconspicuous on fresh surfaces, is strongly emphasized by slight weathering, and consequently, since the slates are very susceptible to weathering influences, it is a characteristic feature of most exposures. With slight weathering the bands become gray and yellowish-gray, the yellowish-gray bands being very narrow, often not wider that the thickness of a sheet of writing paper, and the gray ones measuring on the average about one-fourth inch in width. At the same time the texture becomes sandy, and it is discovered that a large proportion of the rock consists of quartz grains. When the weathering is more profound, red ocher is formed and the slate becomes an alternation of narrow bands of varying shades of yellowish pink, red, and black. Where the weathering has progressed very far, however, the slates are stained an almost uniform red color, in which form they are often indistinguishable from certain phases of similarly stained Hanbury slates. Usually, however, the Brier slates are much the heavier and possess a darker tinge.

It has already been intimated that the Brier slates split easiest along their bedding planes. This tendency is greatly increased by weathering. The rocks open between the layers, become very shaly, and yield an abundant talus at the bases of all cliffs in which they are exposed. While rarely exhibiting schistosity, in many places, especially where folds have been developed, they are crossed by joints inclined to the bedding, along which they break readily, leaving fairly smooth surfaces. Often the joints are close together, and in two systems intersecting at angles of about 70°. Consequently the talus fragments are not infrequently small, flat blocks, diamond shaped in cross section and wedge shaped in vertical section, like the combination of the prisms and basal planes in the triclinic crystal system.

Reference has also been made to the fact that the joint surfaces are sometimes made lustrous by shearing. Movement along these planes has drawn out some of the hematite constituents and produced a thin coating of flat scales, which cover the surfaces like a thin layer of graphite. This phenomenon is not common, and even when it occurs the luster produced is usually not more noticeable than would be the case had the dust from a lead pencil been lightly rubbed over the surfaces. In a few instances the coating is much more marked, causing the rocks to look very much like graphite slates, similar to some of those in the Hanbury formation. The coating is easily recognized as hematite, however, by the red color of its scratched surface. Moreover, the slate may be distinguished from the Hanbury graphite slates by the fact that the coating is not along the main cleavage surfaces, but is on the surfaces of crevices that are inclined to the cleavage at large angles. In other instances the joint surfaces are covered by a dense deposit of crystalline hematite, which before the rock is fractured forms little veins. These usually run in straight lines for long distances corresponding to the direction of the joints, but occasionally they fork, the branches occupying the places of small gashes in the rock or ending in what were little cavities, but which now are minute bodies of ore. In a few instances quartz was deposited in the joint cracks, and in exceptional cases the joint surfaces are covered by druses of small calcite or dolomite crystals.

The typical slates above described grade in several ways into others that present quite different features. All phases, however, exhibit the characteristic fine uniform banding produced by the alternation of thin layers of different compositions. By increase in the quartz the slates may become sandy in texture and lighter in color. Alternate bands may be gray and white, with occasional narrow lines of red separating adjacent bands, due to the production of ocher along the divisional planes between the layers. On the other hand, the earthy components may increase in quantity. The slates thus become less competent to resist strain, and hence slight shearing may occur and the slate may become schistose. In this case the schistosity is nearly always parallel to the bedding.

A third distinct phase is produced by the development of many small plates of glistening mica. The slates of this type are usually of a nearly uniform gray color, without very distinct banding. They are more granular than the normal type, and because of the luster of the tiny mica plates they look like fine-grained quartzites.

The most prevalent of the intermediate types are those that connect the normal slate with the jaspilites of the Curry member. The normal Brier slate is a fairly dense, earthy banded rock, containing a large quantity of hematite. In the gradation phases there is a more or less perfect separation of the iron oxides and the quartz and an accumulation of these constituents in distinct bands, as though they had been more perfectly sorted by water than in the deposition of the normal rock. The layers in which the hematite was concentrated thus became lean ore beds and those in which the quartz accumulated are impure quartzites. In the latter a siliceous cement was deposited, which increases in quantity with nearness to the Curry beds and produces a rock that more and more closely resembles jasper, until finally the fragmental quartz disappears entirely and true jasper results. Many specimens are so completely intermediate in their character that they can not with confidence be placed either in the Brier or the Curry member, except when their environment is known.

Microscopical and chemical.—Under the microscope nearly all sections of the Brier slates exhibit practically the same features. Small, sharp-edged, fragmental quartz grains, with a diameter of about 0.1 mm. and well-formed crystals of hematite with about the same dimensions, are embedded in a matrix composed of smaller quartz fragments and crystals of hematite lying in a still finer aggregate of quartz and a cloudy substance which appears to be a decomposition product of some aluminous mineral, probably feldspar. The matrix contains a few spicules of kaolin, a little chlorite, and some secondary quartz. Its cloudiness is due to the presence of innumerable hematite particles. A comparatively few large flakes of biotite and of muscovite are scattered here and there through this matrix and strewn through it in greater numbers are fragments of some mineral stained red by clumps of red ocher. The banding is caused by the greater or less abundance of the cloudy hematitic matrix in the different layers.

The different phases of the rock noticed in the hand specimens are mainly due to the varying proportions of the chlorite and magnetite present, and the wide variations in the quantity of small quartz grains and cloudy material in the matrix. Where the latter is in excess the chlorite and kaolin are also abundant. Their flakes are frequently arranged in a parallel position which is as often inclined to the bedding as parallel with it. In this way a slight schistosity is produced which is inclined to the bedding, but it is not sufficiently marked to be noticed macroscopically, partly because the quantity of the micaceous constituents present is always small and partly because of the great abundance of crystallized hematite which serves as a bond to hold together the components of the individual layers and prevent easy fracture across them. Consequently splitting takes place more easily between the layers than across them in the direction of the schistosity. When the slight schistosity is parallel to the bedding the rocks naturally break especially easily in this direction.

Nearly all types of the normal slate present the features described above. In a few places the feldspathic component was originally so abundant that the rocks are now practically clay slates, containing only here and there an isolated quartz grain. These are usually more schistose than the more quartzitic slates. The ferruginous compounds are mainly earthy hematite or brown ocher, and this constituent is in very flat lenses and in numerous small oval bodies.

In weathering, ocher is abundantly produced, as has already been related. The chlorite and cloudy material of the matrix appears to yield most freely to the alteration processes, and as a result the rock becomes a mass of granular ocherous material, in which are embedded hematite crystals and quartz fragments. Where the hematite crystals are surrounded by the decomposed matrix they are often attacked by the weathering agencies, with the production of a peripheral zone of ocher. Adjacent crystals, in contact with quartz only, remain unaltered. Consequently, it frequently happens that the slates are banded in dull-red and black bands, the former representing layers in which there was originally much clayey or chloritic substance and the latter layers particularly rich in quartz.

In the last stages of alteration the smaller hematites and all the micaceous and feldspathic minerals have been altered to limonite, and the rock now consists of large crystals of hematite and clumps, grains, and rods of brown ocher scattered through a colorless groundmass, which under crossed nicols is resolved into fragments of quartz in a matrix of crystalline quartz; or, if the ocher is in great excess, the rock is now composed of fragmental quartz grains in a slightly granular or an almost homogeneous mass of ocher.

A second type of the rock contains considerable carbonate. Specimens of this type can not be distinguished by the eye from the siliceous types. Under the microscope, however, it is at once noticed that the matrix often consists of a carbonate in place of quartz and feldspathic material. The crystals of hematite and the quartz fragments are less abundant than in the siliceous types; nevertheless they are both present, usually in considerable quantity. The hematite crystals only rarely retain their sharp forms. Their outlines are rather ragged, and brown ocher or green chlorite nearly always borders them. The appearance suggests that the crystals were altered and that their ragged outlines are due to corrosion, which resulted in the production of the chlorite and ocher. Hematite grains and chlorite also occur in aggregates forming irregular masses embedded in the carbonate. The latter mineral is a pale-yellow, untwinned variety, which, together with small flakes and shreds of chlorite, forms a matrix surrounding the hematite and quartz grains. The carbonate is in small grains, some of which are distinct rhombohedrons, forming a crystalline aggregate. It is probable that it is all a secondary infiltration from some outside source. Sometimes it occurs in rather small quantities between the fragmental grains of quartz, plagioclase, and altered orthoclase in a manner that leaves no doubt as to its secondary character. At other times the fragmental grains are very sparse and the chlorite-carbonate aggregate makes up the principal portion of the rock, with the ocher and hematite thickly strewn through it, often in isolated grains, masses, and crystals, but frequently, also, in narrow stringers and flat lenses.

The banded character of these slates, like that of the siliceous kinds, is due principally to the accumulation of the hematite in certain layers and its absence from others.

An analysis of the carbonate, separated by solution in nitric acid from 1 gram of the black slate occurring in the open pit north of the Curry shaft, gave Mr. Allen, of the Survey laboratory, the following result: MgO, 0.0579; CaO, 0.0810, and CO_2 in about the proportion necessary to saturate the two bases. The molecular proportions of the two bases are as 1 : 1, and the carbonate is therefore a typical dolomite, containing 0.12159 gram $MgCO_3$ and 0.14474 gram $CaCO_3$, or a total of 0.2663 gram dolomite in 1 gram of the rock. Thus 26.63 per cent of the slate consists of the dolomite cement and 73.37 per cent of insoluble components.

The carbonate-bearing beds seem to be only locally developed. They are more noticeable in the neighborhood of the Curry mine and the No. 3 shaft of the East Vulcan mine than elsewhere. In the former place the overlying ore formation is cut by veins of a ferruginous carbonate that are unquestionably secondary. At the East Vulcan locality there is close subordinate folding of the slates and the associated rocks.

The gradation phases between the typical fragmental slates and the jaspilites of the Curry member do not exhibit such features as would readily enable one to trace the former into the latter. The most fragmental varieties differ from the typical Brier slates principally in being finer-grained and in the possession of considerable crystallized (i. e., interlocking) quartz between the finer débris forming the cement uniting the larger grains. Here and there are large cloudy areas of light-green chlorite, kaolin, and quartz, probably representing decomposed feldspar grains, and scattered all through the section are large and small crystals of hematite. Very small, dust-like particles of hematite are disseminated throughout the crystallized quartz, and tiny irregular opaque masses, that may be this mineral or magnetite, occur in the chlorite. In some of the sections there is a quantity of a micaceous mineral in small flakes, filled with a dark-brown, earthy, ferruginous compound. This is apparently a biotite. The texture of these rocks is very fine and in the hand specimen they appear very like a highly siliceous clay slate. It is probable that these phases contained a greater proportion of clay than most of the rocks of the Brier member and that it is by the decomposition of this substance that the biotite originated. In these phases, also, much of the hematite is in linear masses, which are apparently the cross sections of platy aggregates that developed along the bedding planes. In other cases large, irregular masses of a semitransparent red hematite occur here and there through the section. In some places these seem to have resulted from the decomposition of a mineral that has now disappeared. In other cases, however, the masses show a concentric arrangement of layers around numerous centers like the concentric arrangement of opal in many agates. In this form the mineral appears to occupy little cavities in the rock. It is unquestionably an infiltration.

In the most jasper-like phases of the slates the grain is very fine. All traces of a fragmental component have disappeared and the rock is now a mass of interlocking quartz surrounding an occasional cloudy mass, probably representing a decomposed feldspar, and the usual crystals of hematite. In the hand specimen the rocks are finely and evenly banded and exhibit close relationship with the slates. In thin section the specimens resemble very closely some of the jaspilites except that the iron oxides are not so dense and the quartz is less clear. Its cloudiness is due mainly to the presence of little flakes of kaolin, shreds of muscovite, particles of hematite, and a host of tiny dust grains of various kinds, too small to be satisfactorily identified.

Two analyses of Brier slates follow. The first is of a specimen from the cut along the railroad north of Curry shaft No. 1, sec. 9, T. 39 N., R. 29 W. It was made by Mr. E. T. Allen in the Survey laboratory. The second is an analysis of the foot slates on the fifth level of the Chapin mine. This was furnished by Mr. E. E. Brewster.

Analyses of Brier slates.

	I.	II.
SiO_2	50.15	54.13
	.8303	*.8962*
Al_2O_3	6.55	13.53
	.0642	*.1326*
Fe_2O_3	33.80	21.23 (Fe₂O₃ and FeO together)
	.2112	
FeO	.94	
	.0131	
MgO	.94	4.24
	.0233	*.1052*
CaO	.16	
Na_2O	.31	.03
	.0050	
K_2O	4.38	3.29
	.0466	*.0350*
H_2O at 105°	.81	[a] 2.95 (H₂O at and above 105° together)
	.0450	.1639
H_2O above 105°	1.43	
	.0794	
TiO_2	.52	
P_2O_5	.08	
S	Tr.	
Cr_2O_3	Tr.	
	100.07	99.40

[a] Loss on ignition.

From these two analyses it is seen that the Brier slates differ materially from the Traders slates in the higher percentage of silica present and greater abundance of ferrous iron. The former must be ascribed to quartz and the latter to hematite. The potash and most of the alumina are probably in orthoclase or its decomposition products, kaolin and muscovite. These constituents, together with the silica present in the remaining ones, make up about 94 per cent of the slate, the composition of which is given under I, leaving only 6 per cent to be distributed among the biotite, chlorite, and other minerals present. Of the silica present about 30 per cent must be in the form of quartz.

CURRY MEMBER.

DISTRIBUTION.

The iron-bearing Curry member lies immediately above the Brier slate, completing the series of beds comprehended in the Vulcan formation. It is probable that it is more widely spread over the district than either the Traders member or the Brier slate, though it can not everywhere be definitely identified. Wherever the Brier slate has been recognized, except where it occurs as small remnants preserved from erosion on the top of Traders beds, the Curry member has been discovered closely associated with it and always between it and the Hanbury slates. Moreover, in several belts of country from which the Brier slates are absent, but in which some of the Vulcan formation is present, this member is believed to be the Curry member. However, the continuity of the Curry beds is not so well established as that of the lower members of the formation for the reason that it has not been as thoroughly explored. Fewer valuable ore deposits have been discovered in it than in the Traders member, and consequently it has not been thought worth while to explore it as carefully.

On the north side of the Huronian trough the only places at which the Vulcan formation is known to occur are in sec. 14, T. 40 N., R. 30 W., and at the Loretto and Appleton mines, in sec. 7, T. 39 N., R. 28 W. In the first-mentioned locality the rock is exposed only in pits, but since the character of the material on the dumps is more like that of the Curry member than like that of the Traders member where this has been seen elsewhere, the underlying iron-bearing series is thought to be the Curry. At the Loretto and the Appleton mines there are few outcrops now visible, and none of these are of rocks belonging with the Curry beds. Pits and drill holes have exposed siliceous slates like those belonging in the Brier member, underlain by an iron-bearing series closely resembling the beds of the Traders member. The slates are the youngest Huronian rocks yet disclosed in this vicinity. They are now at the surface; the Curry member, which overlies these stratigraphically, has been removed by erosion.

Since the Loretto beds are in an eastern-pitching syncline and a southern-dipping monocline, the Curry member may still exist to the east of the Appleton mine and to the south of this and the Loretto mine, but if so, there is, as yet, no evidence to this effect, as the country to the east and south of these mines has not been explored and there are no natural outcrops of the Vulcan formation in either area. Near the mine the surface is covered with sand, and, farther away, by a thick layer of sandstone.

In the center of the trough the Curry member exists at the Traders and the Old Indiana mines, but it has not been encountered elsewhere. At the Traders mine (Pl. XXIV) there are two pits in an iron formation north of the compressor at the end of the trestle extending from the Traders mine pit, and between these and the main ore deposit of the mine is a belt over 200 feet wide in which are pits of Brier slate. Moreover, at 320 feet west of the compressor, on the north side of the railroad running into the Clifford pit of the same mine, is a small exploration that uncovered graphitic slates belonging at or near the bottom of the Hanbury formation. In this interval there is scarcely room for the full development of the Curry member, but since the graphite-slates must be very near the eastern limit of the Hanbury formation at this place, it seems necessary to assume that the Curry beds occupy the space.

The presence of the Curry member at the Old Indiana mine is shown by drill holes south of the slate member south of the Indiana ore beds. At this place the Curry beds are magnetic.

At the Forest mine exploration has not proceeded far enough at this writing to warrant a statement as to the absence or presence of the Curry member, but since a belt of slates 350 to 400 feet wide is known to exist between two belts of ore-bearing beds it is probable that the southern of these is of Curry age.

The best development of the Curry member is in the belt lying south of the southern dolomite belt. At Waucedah it is exposed in the Emmett and Breen pits (Pl. XXXVI), and it has been traced by test pits and ledges westward for a distance of about three-fourths of a mile. It has again been uncovered by a trench and test pits in sec. 13, T. 39 N., R. 29 W., and has been opened up by exploring pits and mine workings as far west as the Aragon mine. For a short distance beyond this point only one ore-bearing series has been found. It was traced to the west side of sec. 6, T. 39 N., R. 29 W., where it gradually disappears by the overlap of the Hanbury slate, which has buried the entire Vulcan formation in sec. 1, T. 39 N., R. 30 W. On the Cundy, the Pewabic, and the Chapin properties there is abundant evidence of the presence of the Curry member, not only in the underground workings of the respective mines, but also in the surface pittings and occasionally in ledges. Between the Cundy and the Pewabic mines and between the Ludington mine and the Menominee River only one iron-bearing horizon has been detected. It is true that in these two stretches the explorations are mainly limited to the lower portion of the Vulcan formation, but here and there test pits and drill holes show that the ore-bearing horizon is narrow, and that there is not sufficient room between the known position of iron-bearing series that has been located and the slates regarded as Hanbury slates to the south to admit of the occurrence between them of the Brier slates and the Curry beds. The iron-bearing series in these two portions of the Vulcan belt is therefore placed provisionally in the Curry member, the underlying Brier slates and the Traders beds being considered as having disappeared by overlap. If the southern slates are not members of the Hanbury formation, but are Brier, then the iron-bearing series would have the position of the Traders bed (see pp. 456–457).

LITHOLOGY.

Macroscopical.—The rocks of the Curry member comprise even-bedded jaspilites and quartzose slates and irregular-shaped ore deposits intersecting the bedded series more commonly at or near their base than elsewhere. There are present also locally developed interbedded cherts and hematite layers. These are much more common than they are in the Traders member, nevertheless they are greatly subordinate to the jaspilites, from which they seem to differ principally in the color of the siliceous component. Of the jaspilites two distinct varieties are recognizable. The first resembles strongly the corresponding rocks in the Traders member. These are even-banded, dark-purple, sometimes almost black varieties, consisting of interlaminated layers of jasper and ore. The former are in beds that vary in thickness from a small fraction of an inch to nearly 2 inches. The jasper is dark purple in color, a little denser and more flinty than the greater portion of the jasper in the Traders member, and very much like the dense variety near the base of the member. Occasionally this jasper has the granular appearance characteristic of the major portion of the Traders jasper and rarely it exhibits the spotted appearance so noticeable in this rock—a structure which, in the Traders jaspers, was regarded as indicating the presence of fragments of jasper derived from some preexisting source. The ore bands are usually much thinner than the jasper layers, though occasionally they reach a considerable thickness through the replacement of the jasper by hematite. More commonly the individual ore bands are not more than one-tenth inch thick, the apparently thicker bands being made up of a great number of laminæ of the thickness of a sheet of writing paper. Between them are equally thin layers of jasper. Because of their composite character nearly all the hematite layers of this variety have a stratified appearance. In all cases the stratification is parallel to the banding produced by the alternation of ore and jasper. The material of the ore bands is a hard, dense, flinty, steel-gray hematite without definite structure. It resembles closely the dense black ore forming the small veins in the Traders beds.

None of the jaspilites of this type present any evidence of the intense shearing to which the Traders jaspilites have been subjected. This may be due to the fact that the Curry beds are at a greater distance from the contact plane between the Lower and the Upper Menominee series.

The second and more common form of the Curry jaspilites differs considerably from the form just described and has practically no counterpart in the Traders member. This type, although distinctly banded, has not usually the definite clear-cut banding characterizing the first type, nor is the contact between siliceous and ferruginous bands as striking. The materials are more or less thoroughly intermingled, the jasper bands containing a large proportion of hematite and the ore bands containing much silica. Where the two kinds of material are most distinctly differentiated the siliceous bands can be made out to be long, flat lenses, overlapped at the ends by the ferruginous material. Toward their edges and ends the jasper passes over gradually into ore. The jasperized bands are sometimes dark red or purple, but more frequently they are dark pinkish-gray and cherty looking. In some places the siliceous bands are well-characterized chert of a light gray or nearly white color, but, as before stated, these varieties are only locally developed. In other places narrow seams of the white chert penetrate the jasper and the ore bands along their bedding planes, and sometimes they occur between the ore and the jasper. In the latter case the chert seems to be a vein filling; in the former cases it is similar to the normal jasper in all respects save color.

In every instance the siliceous material is granular looking, as though it were composed largely of sand grains. In some specimens this texture is so marked that the rock resembles closely a fine-grained quartzite or a dense sandstone.

The ore associated with the jasper is also sandy looking, as though it were mixed with an appreciable quantity of sand grains or were itself a mass of small fragments. Upon close inspection it is found to consist of many little plates of hematite lying in one direction, which is the same as that of the banding of the jaspilites, and innumerable little crystals of the same mineral, with glistening surfaces. On cleavage surfaces the ore sometimes presents a micaceous appearance, but the plates are small and the structure is therefore by no means as marked as in the micaceous ores of the Traders member. More frequently the surface is slightly rough and granular, like that of a poorly cleavable clay slate. The splitting appears to have taken place between two sedimentary layers which had not been moved with respect to one another. In some specimens the arrangement of the little ore particles is so regular that the rock appears to be schistose throughout, and this structural feature is often emphasized by the occurrence within the ore of many small lenses of jasper with their long axes in the plane of the apparent schistosity. Usually, however, the ore presents no appearance of schistosity but is a dense, fine-grained, lusterless aggregate of small grains of hematite with occasional flakes of a light-colored micaceous mineral, which the study of thin sections shows to be muscovite. Like the ore bands of the first kind, those of the sandy texture are also very frequently laminated, the laminæ sometimes consisting of alternating thin layers of jasper and ore and sometimes of light- and dark-colored ore.

Mention has been made of the fact that the banding of the sandy jaspilites is not as distinct as that of the denser variety, because of the gradation of the siliceous into the fer uginous layers. In some few cases, however, the banding is quite definite, especially where the siliceous layer consists of gray chert in place of purple jasper; but this definiteness is usually more apparent than real. The borders of the chert layers are often stained by dark-red iron oxides or they are bleached to a white color. Where the alteration has proceeded inward to a uniform distance a sharp line of demarcation occurs between the altered and the unaltered chert, and thus a definite band of gray chert between white borders is produced, or a gray band with a uniform thickness for some distance is bordered by narrow dark-red bands that grade off gradually into the black ore. In either case the siliceous bands seem to be regular and continuous, but when closely inspected in large hand specimens and in the ledge they may be seen to wedge out at each end, i. e., to be large flat lenses.

The flinty and the sandy jaspilites grade into one another both through the ore bands and the jasper layers, but more commonly through the latter. The gradation phases of the ore are identical in appearance with the mottled ores of the Traders member. On fresh cleavage surfaces little dots of glistening micaceous ore are interspersed through a less brilliantly reflecting mass of the same mineral. In the jasper layers a distinct mottling is also apparent. Little oval particles of a bright-red or dull-purple jasper are thickly strewn through a dark-purple or purplish-gray matrix, in which lie also minute lenses of ore measuring one-half millimeter or less along their larger axes. With the increase in the number of inclosed particles of jasper in the siliceous bands and of ore particles in the hematite bands these assume more and more the characters of the flinty jasper and the micaceous ores until finally, with the entire disappearance of the matrices, the rocks pass over into the typical flinty jaspilites.

Although rarely schistose to any great extent the Curry jaspilites are jointed and gashed in a few places. Hematite has sometimes entered the cracks thus formed and veinlets of ore have resulted. When parted along these joint cracks their surfaces are found to be coated by druses of tiny hematite crystals. At the angles between intersecting joints the jasper is sometimes crushed to a fine breccia and the fragments thus produced are cemented together by quartz or hematite. In other instances the cracks and open spaces in the rock are filled with a yellow clay-like ocher, or with druses of yellowish-brown calcite crystals. Small veins of quartz and of calcite also traverse the rock in divers directions, and narrow seams of white chert are interposed between the ore and jasper bands, or penetrate the ore and the jasper bands parallel to their bedding. In either case they seem to have insinuated themselves between the laminæ, which separate readily in many instances, especially in the ores, and give these a platy structure. In other cases larger open veins of crystallized calcite occur cutting through the ore bands approximately, but not quite parallel to their lamination. The laminæ are cut across obliquely, showing that the openings were made, not by separation of laminæ, but by solution. The ore bordering the veins is saturated with calcite for a distance of about one-half an inch from the borders of the veins and the walls of the openings are lined with druses of small white or brown-stained crystals that are modified rhombohedrons. Here and there the vein widens and large vugs partially filled with crystals are developed. These veins are quite distinct from the veins of granular red carbonate cutting the rocks in the neighborhood of the Curry mine (see p. 339). These phenomena indicate that the Curry member has suffered considerable fracture since its deposition. Its deformation by this process was, however, by no means so severe as that of the underlying Traders member. It will be observed later that its folding was likewise less severe. The reason for this is probably that the Curry member lies above a slate belt which absorbed most of the stresses to which the formation was subjected while the Traders member lay between these slates and an underlying very competent dolomite bed that transmitted the stresses almost unimpaired.

The interbedded quartz-slates and ores differ markedly from the jaspilites described in the foregoing paragraphs in the fact that they are not definitely banded in distinct jasper and ore bands, but, on the contrary, are made up of a regularly interlaminated series of thin ferruginous and siliceous layers forming a rock with nearly uniform characteristics throughout. In many instances, it is true, the siliceous layers predominate through a thickness of one-fourth to 1 inch, and these are followed by a thickness of the same extent in which the ferruginous laminæ predominate. Thus a certain sort of a banding is produced, but the contrast between the contiguous bands is very slight, since each is composite, being made up of laminæ of the same materials but in slightly different proportions. As may be inferred from what has been stated, these rocks are all beautifully laminated, and because cleavage takes place so readily between the laminæ they are often platy in structure. In many places the layers are so rich in iron oxides that they almost constitute lean ores. Where enriched by a secondary deposition of hematite, as at the Curry mine, they furnish an ore of considerable value.

In their general aspects the quartzose slates and interbedded ores look very much like the more ferruginous forms of the Brier slate. They are found most frequently at or near the base of the Curry member, passing below into the slates by gradual transitions through the increase in number and size of the siliceous layers and upward into the banded jaspilites by the aggregation of the ore laminæ into layers and the gradual passage of the siliceous layers into jasper layers, partly through the withdrawal of the more highly ferruginous laminæ and the further silicification of the remaining material by the deposition of secondary quartz. The resemblance of some of the rocks to the Brier slates is so striking that it seems necessary to infer that they were formed by the gradual replacement of the slates by ferruginous material. All these rocks are dark brown or black and very fine grained. Some of the layers occasionally have a greenish tinge because of the presence of chlorite, but this is rare. Occasionally there are also met with a few layers of a pinkish-gray, fine-grained quartzite and sometimes a layer or vein of gray chert interlaminated with the more usual type.

None of the beds are schistose, but in some of them the ore and other particles are platy, with their long directions lying in the plane of the bedding, and in these cases the cleavage surfaces parallel to the bedding are somewhat lustrous.

At the Klondike shaft of the West Vulcan mine, in the northwest quarter of the southwest quarter of sec. 10, T. 39 N., R. 29 W., there is intimately associated with the ore in the dump a light-gray calcareous cherty rock quite different from the usual cherts of the formation. This occurs in bands or layers one-half inch or less thick, interlaminated with a dense black ore. The ore appears to grade into the chert and to cut it in numerous tiny veins. Although dense as a rule, the chert contains some open cavities, and on the walls of these are druses of crystallized hematite. A rock resembling this in its external aspects has also been found on the south side of the Curry ore beds on the fifteenth level of the Vulcan mine, about 1,200 feet below the collar of the shaft. Here it is distinctly laminated parallel to the bedding, and is crossed by at least four systems of joint cracks, most of which are filled with a dark-green earthy chlorite. On the thirteenth level of the same mine, about 400 feet east of the locality on the fifteenth level and about 140 feet above it, the same rock seems to have been met with again. At this place it is more massive and less distinctly stratified, and is extremely rich in pyrite, which is uniformly distributed through it in small grains and irregular masses rather than in veins. These rocks will be referred to again in the descriptions of the West Vulcan ore deposits (p. 439).

In the neighborhood of the Curry mine the rocks of the Curry member are traversed by coarse-grained veins of a dark-pink dolomite. Some of the narrower veins and a few of the coarser ones cross the beds diagonally, but most of them run parallel to the bedding and preferably along the contact between neighboring beds. The same carbonate occurs also disseminated as small crystals through the ore, and in some beds it forms a matrix in which ore particles and small masses are scattered. In this form the ore looks like a granular aggregate of hematite and carbonate. In other places certain of the ore bands, which upon casual inspection look no different from the contiguous ones, are found upon closer study to be saturated with carbonate. This reveals itself only in broken cross sections when the bands fracture along the cleavage planes of the carbonate and consequently reflect uniformly from large surfaces. Often a narrow layer will reflect evenly for distances of 2 inches or more, while the neighboring bands are completely devoid of such reflecting surfaces. The rocks seem to be well impregnated with carbonate, but this appears to have selected for saturation certain definite layers. These carbonated ores are gray when fresh and brown where weathered.

Microscopical.—The flinty, or more typically cherty, jaspilites of the Curry member differ very little from the corresponding rocks of the Traders member. In the siliceous layers quartz predominates, though ore particles are often present in great numbers. The majority of these consist of hematite in small opaque crystals and in minute transparent plates. Another portion, and a much larger portion than in the Traders jaspers, consists of large crystals of hematite and of magnetite. These ore particles are often disseminated through the quartz grains, but more frequently they lie between them. For the most part they are distributed uniformly, but in nearly all sections it is observed that the hematite especially, and sometimes the magnetite, is arranged along lines that run in the direction of the rock bedding. Besides these two iron oxides there is also present in a large number of sections an abundance of brown ocher which is usually in small irregular masses between the quartz grains. The latter interlock in the usual manner characteristic of the jaspers. Liquid inclusions containing bubbles, some of which are movable, are common in them and strain shadows are almost universal, more particularly in those specimens in which the grains are elongated. Besides the minerals mentioned, the jaspers of this kind often contain also small plates and wisps of a light-green chlorite, an occasional shred of kaolin or sericite, and little grains of a highly refractive, light-yellow, transparent substance that yields ocher by decomposition. This was at first thought to be siderite, but since it is not attacked by hydrochloric acid it can not be a carbonate. An undoubted carbonate, which from its color is supposed to contain some iron, is present in little nests here and there through the rock. This is plainly secondary.

The banding of these jaspilites, like that of the Traders jaspilites, is due to layers alternately richer and poorer in hematite. In structure and composition the ferruginous bands are not essentially different from the siliceous ones except as influenced by the greater proportion of hematite present. This is commonly in the larger grains and crystals, although there are intermingled with them some of the small transparent plates. In the richer bands the hematite is practically in solid masses of snugly compacted granules. In many instances these bands are so narrow, so uniformly parallel, and so close together that it seems as though the ore must have been infiltrated along bedding cracks. Indeed, in some sections there are visible cracks into which ore has penetrated, and vein-like streaks of a very finely granular quartz along the sides of which are narrow borders of hematite and limonite. Sometimes the veins enlarge and inclose small cavities, on the walls of which there are likewise thin coatings of hematite. In the wider ore bands the ore is usually denser on the sides than in the centers, but even in this case the ore is rarely sharply defined from the jasper through which it cuts, since each grades into the other in consequence of the increase in the quantity of one of their constituents and the diminution in the quantity of the other.

Some of the specimens, which appear homogeneous when examined megascopically, are found to be minutely brecciated when viewed under the microscope. The fractures caused by the brecciation are healed by quartz. Veinlets of the same substance also traverse unbrecciated specimens in different directions, but most frequently parallel to the bedding, and small veins of calcite and hematite are also common. In the straighter portions of the quartz veins the grain of the vein filling is nearly of the same size as that of the surrounding jasper, but in curved portions, and particularly in the triangular areas between the fragments of the brecciated jaspers, the grain of the quartz filling is much coarser. From the great abundance of these veins it is clear that the jaspilites have been subjected to silicification processes subsequent to the silicification which gave rise to the jasper.

The granular or sandy jaspilites are more varied in character than the flinty varieties. In some of them the layers of jasper seem to differ little from those of the flinty jasper except in the presence of a few apparently fragmental quartz grains and of a small number of jasper fragments. The greater part of the rock consists of the usual aggregate of interlocking quartz grains, hematite particles, and here and there a scattered magnetite crystal. In natural light the quartz mosaic appears entirely uniform in structure, but between crossed nicols it often breaks up into many oval or rounded areas composed of aggregates of a few or many small grains which are distinctly marked off from the surrounding matrix by differences in the size of their grains. In some cases the components of these areas interlock, while in other instances they are in crushed fragments. Although no definite evidence is at hand to confirm the view, it nevertheless seems probable that these areas represent original sand grains in a sedimentary rock. Nearly all the quartz grains, whether in the rounded areas referred to or in the surrounding matrix, contain great numbers of small hematite plates. The greater part of this mineral is, however, in little crystals and irregular masses between the grains. In nearly all respects the iron oxides are in the same forms and they exhibit the same relations with the quartz as was noted in the case of the ores in the flinty jaspers. As in the latter case, the ore bands are simply layers in which the proportion of hematite is largely in excess of silica. Sometimes magnetite is present in considerable quantities, in certain instances in sufficient quantity to impart to the whole rock a recognizable magnetism. Occasionally a fragmental grain of zircon is observed. Besides the constituents already mentioned there is noticed in not a few specimens a finely fibrous aggregate of a light-green, very feebly polarizing mineral.

It occurs as little nests scattered between the quartz grains in the jasper bands and between the hematite grains in the ore bands. It also occupies the central portions of many quartz veins, and forms rather large masses where these widen out. This mineral, which is probably serpentine or some nearly allied species, is undoubtedly an infiltrated substance introduced after the rocks had assumed nearly their present character. Calcite is present also in little isolated nests, more frequently in the jasper layers than in the ferruginous ores, and much more frequently in both than in the corresponding rocks of the Traders member. In some specimens a little earthy green chloritic substance is also observable. Quartz, calcite, and hematite veins cut both ore and jasper.

The greater number of the sandy jaspilites possess a very beautiful oolitic or nodular structure, which is much more distinctly apparent in the jasper layers than in the ore bands (Pl. XIX, *C*, *D*). It is due partly to the prevalence of this structure that these rocks are more granular than the other jaspilites of the district. The nodular structure has already been referred to in the description of some of the beds of the Traders member (p. 303). It is, however, so very much more common in the Curry jaspilites than it is in the corresponding Traders rocks that it may well be considered the characteristic structure of the former. Only rarely can the structure be recognized in the hand specimen and then only when the concretions are composed of ore lying in a matrix of jasper. In thin section, however, it is seen in great perfection. Of course, all traces of the original material of the concretions have disappeared, but there remain as proofs of their former existence a great number of beautiful pseudomorphs composed of quartz and hematite. In some specimens these are sparsely scattered through a groundmass with the features of the nonoolitic jaspers; in others they are closely crowded together, constituting more than three-fourths of the rock visible. In the majority of cases, however, the nodules are present only in certain bands separated from one another by bands devoid of them, as though the rock had been composed of alternating layers of oolitic and nonoolitic material.

The nodular structure is best studied in natural light. As already related, the original material of the concretions has entirely disappeared. It is now represented by the same constituents as those forming the matrix in which they lie, viz, quartz and hematite. The quartz is usually identical with that in the surrounding matrix. It is in interlocking grains filled with hematite dust and abundant liquid inclusions. As a general thing the coarseness of the grain is the same in the nodules as in the matrix (see Pl. XIX, *F*), but occasionally the nodules are a little finer grained. The characteristic feature of the concretions is the arrangement of the hematite. This mineral usually occurs in one or several concentric lines producing circles, ovals, or other curved forms, inclosing a quartz mosaic, which, as has been said, is identical with the mosaic outside of the lines (Pl. XIX, *C*, *D*). Sometimes the lines are continuous and thin, often they are thick, and occasionally the ore occupies nearly the whole area of the nodule (Pl. XIX, *E*). In other cases the hematite is in little crystals, arranged along a curved line indistinctly outlining an area.

When viewed between crossed nicols the entire field of view of an oolitic band is resolved into an aggregate of small quartz grains, broken here and there by opaque ore masses. The general impression produced is that of a practically homogeneous rock. When viewed in natural light, however, the appearance of the section is strikingly different. The concretions stand out plainly against a nearly colorless background and give the impression that the rock is composed of a great number of black-bordered sand grains of a uniform shape and size lying in a quartzitic groundmass. It is only when the nicols are crossed and the interiors of the supposed grains are discovered to be composed of an aggregate indistinguishable from the surrounding matrix, and many of the grains of this aggregate are found to be continuous with grains in the surrounding mass, that this view is dispelled and the ovals, circles, etc., are recognized as sections of concretions.

Within some of the bands the concretions are elongated and arranged indiscriminately with their longer axes in any direction, but usually the elongated forms lie with their long directions in the plane of the bedding. In schistose phases, in which all the components are elongated, the nodules are much flattened and drawn out to several times their normal lengths, and often their quartz components, as well as the corresponding constituents of the groundmass, are also slightly elongated and are crossed by strain shadows. The ore masses are also often drawn out to great lengths, appearing as lenticular stringers or thin bands woven in and out between composite lenses of quartz.

Many of the concretionary masses are identical in all essential respects with the ore concretions observed by Van Hise and Irving in the Gogebic and Gunflint Lake rocks, and by Van Hise in the Marquette jaspilites.[a] Others are like those observed by Leith in the ferruginous cherts of the Mesabi area. The concretions in the Gunflint Lake beds are shown to have been without doubt originally nodules of siderite in a ferruginous cherty carbonate, and most of those in the Gogebic and Marquette rocks have almost as certainly been shown to have originated in similar concretions. The nodules in the Mesabi cherts were derived partly from siderite, but principally from granules of a magnesium iron silicate which Leith calls greenalite. Some of the structures in the Menominee jaspers are identical with those pictured in the report on the Penokee series,[b] but the concretions differ from most of those illustrated in the Penokee monograph in the fact that no original siderite or other ferruginous carbonate has been detected in them. A single quotation from a description of the jaspers in the Marquette district will reveal the close similarity in appearance between the concretionary structure in these rocks and that in the Menominee jaspilites. In his account of the microscopical features of the Negaunee jaspers, Van Hise writes:[c]

> In the jaspers * * * is also a beautiful concretionary structure exactly similar to that of the ferruginous cherts of the Penokee district. The concentric zones of red hematite, separated by a greater or less distance, appear as if painted upon the quartzose background, the grains of which seem in no way to be affected by the hematite. * * * In some slides the concretions are decidedly flattened by pressure.

Except for the statement that the hematite is red, this description will apply word for word to many of the Menominee jaspers. In these, however, the hematite is generally opaque.

Most of the nodules in the Menominee jaspers are, however, more like those described by Leith as characteristic of altered greenalite rocks. Some of the illustrations published by this author[d] might easily be duplicated in photographs of Menominee jaspers.

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[a] Irving, Roland Duer, and Van Hise, Charles Richard, The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 200–209 and 260–265. Van Hise, Charles Richard, and Bayley, William Shirley, The Marquette iron-bearing district of Michigan, with atlas, including a chapter on the Republic trough by Henry Lloyd Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 373, 376.

[b] Mon. U. S. Geol. Survey, vol. 19, 1892, Pl. XXII, figs. 1 and 2, Pl. XXVI, figs. 1 and 2, Pl. XXVIII, fig. 2.

[c] Mon. U. S. Geol. Survey, vol. 28, 1897, p. 373.

[d] Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, Pls. XIV and XV, *A*, *C*, and *D*.

Besides the masses of concretionary origin there are also present in many of the Curry sections quartz ovoids that are not outlined by rings of ore. These are distinguished from the surrounding matrix by the fact that they are very fine grained and that their material is filled with minute particles of dust. They are thought to be small jasper fragments that were intermingled with the sediments in which the nodules were formed. A few small fragments of quartz with the usual peripheral enlargements are also met with in some specimens. The fragments are usually composite, though occasionally a homogeneous one is discovered. The composite character of most of these shows conclusively that the entire rock in which they occur has been silicified, and that even the quartz of which these fragments probably consisted was dissolved and new quartz like that of the main body of the rock was deposited in its place. Although in some instances fragments and concretions are found in the same layer, they usually occur in different layers, separated, perhaps, by a thin seam of ore. One layer may consist almost exclusively of concretions embedded in a sparse matrix, while the next layer, distant only a small fraction of an inch, may be made up of many round and oval quartz grains greatly enlarged by additions of quartz in optical continuity with them, some homogeneous, others composite, and all embedded in an abundant fine-grained jasper. The conditions of deposition must have varied rapidly to give rise to such a marked difference in sediments within such short vertical distances.

In the ore bands the oolitic structure is likewise in evidence, but here the material is opaque and the structure is much more difficult to recognize, especially if the ore is very dense. In the less dense bands the ore borders around the ovoids are much thicker than those around the concretions in the siliceous bands, and in many instances entire concretions consist of ore. Moreover, ore crystals abound within the concretions, and a great deal of ore occurs in the interspaces between them. A sparse quartz matrix containing an occasional jasper fragment lies between the ore masses. In the dense ores the entire matrix is replaced by hematite; but even in these a nodular structure is revealed on the edges of the section where the grinding has caused the ore to split along curved lines into round and oval masses like the concretions in the jaspers.

The slaty varieties of the Curry member do not differ as much from the flinty and sandy or granular varieties as might be inferred from an examination of hand specimens alone. In composition and structure they are gradation phases between the Brier slates and the normal phases of the more siliceous portions of the jaspilites, always approaching more closely the jaspers than the slates. Some of the samples which in the hand specimen present the appearance of only slightly altered slates are found to be entirely changed to jaspers. In spite of the fact that they retain in great perfection the definite banding and the characteristic texture of the slates, they have been very completely silicified. All fragmental material has disappeared and the rocks are now completely crystalline. Many of the specimens afford excellent illustrations of the manner in which a rock may be entirely changed by the replacement of its original components, while still retaining its fundamental structures.

The most jasper-like varieties of these rocks differ but little from the normal jaspers in their essential features except that they contain more chlorite. The varieties most like the Brier slates differ from these rocks in possessing a groundmass of crystalline quartz in place of the fine fragmental groundmass of the slates. Moreover, the smaller fragments have been entirely replaced by a fine-grained aggregate of interlocking quartz.

The intermediate phases present a greater individuality, though even these do not differ markedly from the jaspilites. They are characterized by the presence of a great abundance of light-green chlorite in plates and in aggregates of tiny fibers in the jasper layers, and by the presence of plates and small flakes of a darker-green chloritized biotite in the ore layers. The chlorite occurs in the interspaces between neighboring quartz grains and the biotite plates between the magnetite grains and usually attached to them. The small biotite flakes are scattered through the quartz grains. In most specimens a brown or reddish-brown ocher is also very common. It appears as an irregular coating on the quartz grains, as small masses between them, and as little radial groups sometimes within and sometimes between them. It is especially abundant in some of the hematite layers, constituting a large proportion of the mass in which the ore particles are embedded. In all instances it seems to be a decomposition product of chlorite.

The ore bands are usually not unlike the siliceous bands except in the possession of a large quantity of hematite and in the presence of a chloritized biotite in place of the chlorite of the jaspers. In a few distinctly slaty ores the rock is practically a sandstone with a quartz-hematite cement.

It consists of numberless enlarged quartz grains, a few cloudy masses that look like decomposed feldspar fragments, and a few small masses and plates of chlorite surrounded by an aggregate of opaque and transparent hematite and quartz. In this cement the hematite predominates to a very large degree over the quartz, the latter seemingly occurring merely as a filling of little spaces in a porous aggregate. Many of the quartz grains show strain shadows.

In the preceding paragraphs repeated reference has been made to the fact that many specimens of the Curry rocks contain calcite or some other carbonate. Usually the mineral is uniformly distributed in small quantities between the quartz grains of the jasper bands, but sometimes it occurs in very considerable masses both in the jasper and the ore, and occasionally in series of little nests nearly, but not quite, connecting with one another along lines parallel to the bedding. Distinct calcite veinlets are also sometimes met with The characters and distribution of the mineral leaves no doubt that its origin was subsequent to that of the major portion of the rocks. It was infiltrated after the rocks attained approximately their present condition and crystallized in pores and crevices that already existed, or that were made by the removal of some other component. No original carbonate has been found in any of the Curry rocks. The material that was referred to as original siderite in the preliminary report on the district, upon closer study is discovered to be a secondary carbonate.[a]

The rocks containing carbonate in greatest amount are those in the workings and the immediate vicinity of the Curry mine. In addition to the large masses and veins of red dolomite that have already been mentioned as being conspicuous in the Curry ores and jaspilites the rocks contain also dolomitic material which is revealed only by the microscope. In these phases of the rocks the carbonate has almost completely replaced the quartz. Nearly all the silica that was probably once present has disappeared and in its place is a coarse aggregate of dolomite in which magnetite crystals and hematite plates and grains are embedded in the same manner as they exist in the siliceous ores and jaspilites elsewhere. In most specimens much of the entire portion of the section in the field of view at any one time is occupied by a continuous mass of carbonate that polar-

[a] Geologic Atlas U. S., folio 62, U. S. Geol. Survey, 1900, p. 5.

izes uniformly. In the cases where the beds are brecciated the carbonate cements the fragments together. In extreme cases both fragments and cement are carbonated. The brecciated structure remains, but all the original components except the ores have been replaced by the carbonate. In some portions of a few sections the ore is in round and circular masses and in concentric rings that look like pseudomorphs of nodules; but these also are carbonated, nothing remaining of their original components but the ores.

It is quite evident that these rocks have been completely permeated by carbonate-bearing solutions, and that these solutions have carried off all the silica and chlorite that was originally in the rocks and deposited a dolomitic carbonate in their place. That none of this carbonate was an original component of the rock in its present position is apparent without discussion.

The identification of the carbonate as dolomite is confirmed by analyses of the ore from the Curry mine furnished by Mr. F. A. Janson, engineer of the Penn Iron Mining Company. Analysis I is of the ore obtained from the Curry member, and II that of an ore taken from the Traders beds.

Analyses of carbonated ores from Curry mine.

	I.	II.	
Fe_2O_3	73.41		68.04
Al_2O_3	.62		1.41
MnO_2	.89		1.04
SiO_2	3.42		11.72
$CaCO_3$	11.59	CaO =	4.91
$MgCO_3$	10.61	MgO=	5.41
		CO_2 =	7.31
Total	100.54		99.84

In the first sample the calcium and magnesium carbonates constitute about 22 per cent of the ore, and in the second about 15 per cent. In the first the two carbonates are nearly in the proportion demanded for typical dolomite of the formula $(CaMg)CO_3$, which would require 12.63 per cent of $CaCO_3$ to 10.61 per cent MgO. If all the CaO in the second analysis is present as $CaCO_3$, the proportion of the two carbonates in the ore is 6.59 $MgCO_3$ and 8.77 $CaCO_3$. Typical dolomite would require 7.36 $MgCO_3$ to

8.77 $CaCO_3$. It is therefore quite certain that the carbonate which replaces the silica in these rocks, like that which saturates the Brier slates near by (see p. 328), is almost a pure dolomite of the type $CaCO_3 + MgCO_3$.

RELATIONS BETWEEN THE MEMBERS OF THE VULCAN FORMATION.

Where no marked disturbances exist between the Traders member and the Brier slates, the first grades into the second by diminution of the amount of ferruginous material and increase in the proportion of slaty material. At the same time there is a diffusion of the quartzose component and the gradual disappearance of the distinctively quartzose layers. The silica, moreover, changes from the crystalline variety characteristic of the jaspers to the plainly clastic quartz characteristic of slates. When the ferruginous material is much reduced in quantity and the fragmental components are correspondingly increased, the ore-bearing Traders bed becomes the Brier slate. This gradation occupies only a very short vertical range, so that the line between the Traders member and the Brier slate is usually determinable within a few feet.

Where marked disturbances have occurred, as in the vicinity of Norway and eastward for several miles, 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 often to be a plane of differential movement. At the open pits of the Norway and the Cyclops mines and those north of the Curry mine, and between this mine and the West Vulcan, the Traders rocks are in places pseudoconglomeratic. The Brier slates also may be brecciated (Pl. XXI, *A* and *B*). 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 the relations between the dolomite, the Traders member, and the Brier slates were originally normal, i. e., the ore-bearing beds were principally detrital material lying upon the dolomite, and that the Brier slates were conformable deposits upon the ferruginous beds. At the time of folding slipping occurred along the contact between the Upper Menominee series and the Lower Menominee series, 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 instances the lower portions of the Brier slates were likewise included within the zone of movement and were fractured and brecciated. Talc and serpentine were developed along the slickensided surfaces and were deposited in joint cracks and openings made in the rocks, and, later, the breccias were enriched by the deposition of hematite and other iron compounds. Thus both the Traders member and the lower part of the brecciated Brier slates became sufficiently ferruginous to warrant mining. This line of contact is marked by large open pits in the southeast quarter of sec. 5 and the northeast quarter of sec. 9, T. 39 N., R. 29 W. The ore belonging to the Traders member was taken from them some years ago. But it was not until the summer of 1899 that the demand for lean ores was so great that the ferruginous phases of the Brier slates could be mined with profit. In this year, however, some of the Norway mine product consisted of this material.

From the descriptions of these pits given in the Tenth Census reports[a] it may be inferred that at the time the pits were visited (1880) the relations of the breccias to the ores now mined out could be easily seen. The entire Traders member was evidently not brecciated, for there were distinct bands of specular and slaty ores near the foot walls of pit No. 3 (West Vulcan), and at various places in the Perkins, the Saginaw (afterwards north portion of the Perkins pit), the Norway, and the Cyclops pits. Since the rock forming the walls of the pits is brecciated on the strike of the material that has been removed, which was presumably ore, it seems probable that pockets of nonbrecciated ore actually existed in the midst of the breccias. They may have been finely comminuted breccias which were so completely ferruginized that all of their original components disappeared, and which later, by slight movements, became schistose and lost their brecciated structure. In other words, the same conditions seem to have controlled the deposition of the ore in the breccias as elsewhere. While the entire brecciated zone was enriched, certain portions of it, being more crushed than others, gave rise to the richest ores.

The change from the Brier slates to the Curry member proceeds in the opposite manner from that of the Traders member into the Brier member. The argillaceous constituent diminishes, the quartzose component becomes aggregated into bands and at the same time loses its fragmental character and becomes crystalline or cherty, ferruginous

[a] Reports of the Tenth Census, vol. 15, 1886, pp. 441–447.

material is introduced, and hematite increases in abundance and becomes segregated into distinct layers. Sometimes the gradation is sudden, occupying but a foot or more; sometimes it is more gradual. Jasper layers appear in the slates 10 feet or more from the fully developed beds of the Curry member. These increase in number and thickness as higher horizons are reached. The interlaminated slates grow more ferruginous and lose their fragmental texture, hematite is introduced along their bedding planes, and finally the slaty layers are transformed into lean ores. Thus typical jaspilites are produced. The transition can be seen at a number of places on the surface and at many more in the underground workings of the mines. In the mine workings the transition is often so sudden that there is no difficulty in drawing a sharp line between the two sets of beds. On the surface the case is somewhat different, since weathering oftentimes masks the characteristic features of the slates and causes them to resemble the Curry rocks. At the Curry shaft No. 1, in the southwest quarter of the northeast quarter of sec. 9, T. 39 N., R. 29 W., the transition is seen to occur laterally as well as vertically. At this place is an excavation in the hillside exposing the upper portion of the Brier slates and the lower portion of the Curry member. The north side of the excavation is bordered by slates. On its west side the vertical gradation between the slates and the iron-bearing beds can be profitably studied. It exhibits the gradation by means of the interposition of jasper bands described above. On its east side, only 200 feet distant from the west side, the rocks are principally well-defined beds of the Curry member. Since no evidences of folding except slight plication can be detected in any of the rocks, and since the jaspilites are on the direct strike of the slates on the west side of the cut the inference that there is also a horizontal gradation here is unavoidable.

At one or two places the contact between the two series is extremely sharp, no transition of any kind being observable. In most of these instances there is plainly a small fault between the two sets of beds. Such are the conditions on the fourth level of the Pewabic mine, on the sides of some of the pits of the Cyclops, Curry, and West Vulcan groups of excavations, and more particularly in the dividing wall between the pit in which No. 4 shaft of the West Vulcan mine is situated and the pit to the west of this one (see map, Pl. XXXIII).

No stratigraphical break has been discovered anywhere within the Vulcan formation.

GENESIS.

From the descriptions of the various members of the Vulcan formation that have been given it is evident that this formation comprises a series of sediments laid down in water in successive beds from bottom to top. The bottom layers are slates and coarse quartzites or conglomerates, composed largely of waterworn quartz grains and fragments of jasper and ore. Plainly these layers are mainly fragmental sediments derived from a pre-existing land surface. The slates were laid down at some distance from the shore line and were derived from a land surface which at the time of their deposition consisted largely of dolomite. The quartzites and conglomerates were deposited nearer the coast. They were derived from a land surface composed partly, at least, of jaspilites, quartzites, and crystalline rocks. The absence of coarse conglomerates indicates that the deposits now exposed were formed at some distance from the shore line rather than along beaches. Currents or waves caused a sorting of the sediments and produced interlaminations of hematitic and quartzose layers. The crystalline quartzose cement in the quartzites and the conglomerates, and the nodules of ore in the latter rocks suggest that there was deposited with the fragmental material some of the ferruginous carbonate and greenalite[a] nodules which at higher horizons gave rise to the jaspers of the jaspilites. If this is so, as it seems to be, the Vulcan epoch was ushered in by conditions favorable to the accumulation of fragmental sediments at the bottom of a sea or bay that was depositing a cherty ferruginous carbonate or silicate, or both. Thus, in the lower portion of the Traders member clastic and chemical sediments were intermingled, with the former largely in excess. In the course of time, probably after the district was folded, the slates were altered and much talc and serpentine were deposited in them, partly by circulating waters emanating from the underlying dolomite and probably partly in consequence of changes set up in the dolomitic material of the slates themselves. The cherty ferruginous cement of the quartzose layers was changed to a crystalline quartz and hematite and the layers were enriched by deposits of hematite between the original grains. With deepening of the water in which the deposits were being laid down these became finer grained. The proportionate quantity of the ferruginous compounds precipitated was increased and the series of mixed mechanical and chemical

[a] For theory as to deposition of greenalite see Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 247–259.

sediments grew to a considerable thickness. In some places and at certain horizons the deposits were almost purely chemical. At other places the mechanical sediments were in great excess. In most places the two kinds of sediments were precipitated together. There thus resulted the Traders series of beds, consisting of alternating layers of carbonates, greenalite, ferruginous and quartzose sands, and mixtures of the three.

The conclusions as to the existence of original carbonate and greenalite in the Vulcan formation is based principally on the analogy that exists between the character of the iron-bearing beds in the Menominee district and that of similar beds in the Marquette, the Gogebic, and the Mesabi districts, which have been shown to have developed either from cherty ferruginous carbonate or from deposits of greenalite. The conclusion is confirmed by the presence of hematite and jasper pseudomorphs after concretions and nodules in the rocks of the Traders member, and more particularly in those of the Curry member of the Vulcan series, and by the existence of the ores in the Menominee district in just such situations as are demanded by the assumption that they were concentrated by descending waters (see p. 396).

Since the steps in the theory that derives the jaspilites from a ferruginous carbonate were worked out mainly by Van Hise in his studies on the Gogebic, the Gunflint Lake, and the Marquette districts, we can do no better than quote his statements concerning the origin of the jaspilites in general, as explaining the mode by which the iron-bearing beds in the Menominee district finally came to have their present characters. With respect to the origin of the iron in the carbonates, he writes:[a]

When the individual districts are taken up, it will be seen that a greenstone, often ellipsoidal, in many places porous and amygdaloidal, in many places schistose and rich in iron, is the most characteristic rock of the Archean, and that similar rocks occur abundantly in the Huronian. Where these igneous rocks were adjacent to the seas they would be leached by the underground water and the iron transported to the adjacent seas. It is possible that to some extent this leaching process also went on below the waters of the sea. The iron was probably transported to the water mainly as carbonate, but to some extent as sulphate. The carbonate would there be thrown down by oxidation and hydration as limonite, and the sulphate in part as basic ferric sulphate. Much of the sulphate was probably directly precipitated as sulphide by the organic material. The limonite would be mingled with the

[a] Van Hise, C. R., The iron-ore deposits of the Lake Superior region: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 319–322.

organic matter, which was undoubtedly present, as shown by the associated carbonaceous and graphitic shales and slates. When deeply buried the organic matter would reduce the iron sesquioxide to iron protoxide. By the simultaneous decomposition of the organic matter carbon dioxide would be produced, which would unite with much of the protoxide of iron, producing iron carbonate. The sulphate of the basic ferrous sulphate would be reduced to the sulphide by the organic material, thus producing the pyritic carbonates. Where the iron was brought to the water mainly as sulphate, the direct reduction of this salt by organic matter would form iron sulphide with little or no carbonate. Simultaneously with the production of these substances chert was formed, probably through the influence of organisms.[a] Some of this silica would unite with a part of the iron protoxide, producing ferrous silicate. More or less mechanical sediment would also be laid down. Thus the original rocks—the cherty iron carbonates, the ferrous silicate rocks, and the pyritic cherts—would be produced. * * *

The alterations of the original rocks of the iron-bearing formations have been along two general lines, depending upon whether the iron-bearing carbonate or ferrous silicate or pyrite, when altered, was at the surface or at considerable depth. Where the rocks were altered at or near the surface, so that oxygen-bearing waters were abundant, ferruginous slates, ferruginous cherts, and ore bodies were produced. * * *

The formation of the ferruginous slates and ferruginous cherts from the iron-bearing carbonate is usually a process of liberation of carbon dioxide and of oxidation and hydration of iron. Where oxidation takes place with little hydration, jaspilites may be formed. * * * Ordinarily the rearrangement of the iron and chert emphasized the original sedimentary banding. * * *

For the development of jaspilite further alterations are commonly required. The first stage ordinarily forms ferruginous slate or ferruginous chert at or near the surface, as above described. These rocks, when later deeply buried by sedimentation and subsequently folded, are altered in the deep-seated zone in which dehydration is one of the characteristic reactions. The hydrated iron oxides of the ferruginous slates and ferruginous cherts are changed to hematite. This gives the rocks the blood-red appearance of jasper. The jaspilites therefore differ mainly from the ferruginous slates and the ferruginous cherts in the nonhydrated condition of the iron oxide.

During any of the above processes of alteration the iron oxides may be more or less concentrated. The concentration may result in bands of nearly pure iron oxide between the leaner portions of the rock. It may result in the concentration of the iron oxide in veins. It may result in the concentration of the iron oxide in large masses under peculiar conditions, as fully explained below, and thus produce ore bodies. The ores are mainly somewhat hydrated hematite, but limonite and anhydrous

[a] Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 246–253. Walcott, C. D., Fossil Medusæ: Mon. U. S. Geol. Survey, vol. 30, 1898, pp. 17–21.

hematite (either earthy or specular) occur plentifully. Magnetite is also found, but is very subordinate in quantity. The great mass of the iron ore of the Lake Superior region is iron sesquioxide.[a]

After the Traders beds had been laid down to a thickness of several hundred feet, conditions again changed, the cherty carbonate and greenalite ceased to be precipitated and the deposits for a time consisted exclusively of mechanical detritus from the neighboring shores. This was comparatively fine grained, and consequently must have accumulated at some distance from land. It consisted of the débris from crystalline rocks, among which were many that were basic. What the nature of the change was that determined the cessation of chemical precipitation can not be told. Changes in the water level may have contributed to the result. Depression of the land may have reduced the rate of erosion of the basic rocks considered by Van Hise to be the source of the iron salts and, consequently, the amount of ferruginous material leached from them.

At the end of Brier time the conditions that prevailed during the latter part of Traders time returned and the chemical precipitates were again deposited, this time without much admixture of fragmental detritus. The abundance of concretionary ore in the Curry beds shows that some of these consisted largely, if not almost exclusively, of the chemical precipitate, interbedded perhaps with a few thin layers of quartz and hematite sand.

In the course of time the ferruginous precipitates were changed to hematite, the silica was rearranged, and jasper was formed. Where the iron compounds were in beds of notable thickness the resultant jasper is important. Some new hematite was deposited in thin layers along the bedding planes. Another portion of the newly formed hematite remained or was deposited along the grains of the detrital ores, thus enriching them, especially in the bottom of the folds and in areas of disturbance. In spite of the enrichment of the Curry member in iron oxide, its ores are nevertheless not profitably worked at as many places as are those of the Traders member. The ferruginous detritus in the Curry beds is usually not so rich in iron oxide as that found at the Traders horizon. Where folds exist in the member, furnishing favorable situations for rich deposits, the ore bodies may be large enough and rich enough to warrant mining, but for the greater part of its extent the member yields only lean ores.

[a] For a discussion of the chemical changes that resulted in the production of jaspilite from greenalite, see Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 255–259.

FOLDING.

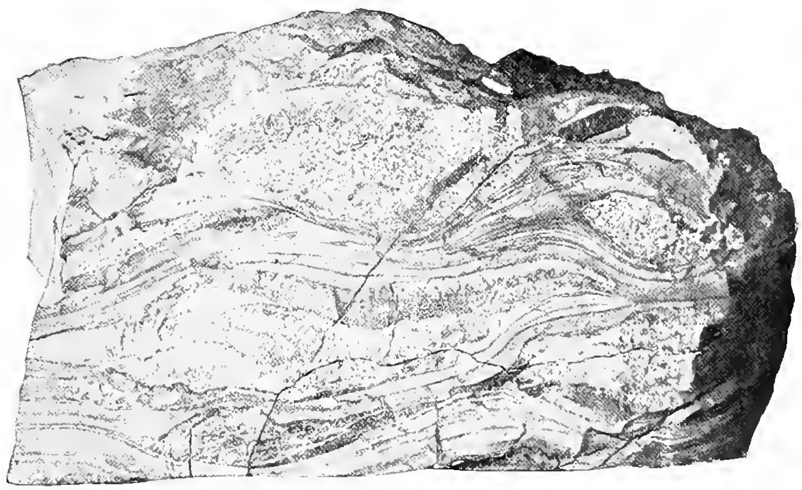
FOLDS OF LOWER ORDERS.

The Vulcan formation, where it is known to exist, 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 (see p. 237). Within the formation there are, moreover, numerous still smaller folds of the third order, which, because of the hardness of the rocks and the perfection of their 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, on which they are superimposed, but the strikes of their axes may diverge slightly. Usually these folds are directly related to folds of a corresponding order in the dolomite, as in the Aragon mine and in the Norway syncline, but often they are apparently independent of the folding in the underlying rock. The minor folds are extremely important guides to the discovery of ore bodies. The folds of the second order determine the general position of the ore bodies, while the folds of the third order determine in many cases their more exact positions within the larger folds. The folded slates of the formation are relatively impervious, and where not shattered often furnished troughs into which the circulating waters were conveyed and the ore deposits formed. In exploring operations it is important to determine the strikes and dips of the axes of the minor folds, not only because they indicate the direction of the pitch and strike of the larger folds, but also because they direct attention to those places at which ore bodies are most apt to exist.

FOLDS OF HIGHER ORDERS.

In addition to the three orders of folds above referred to, there may in many places be discovered still smaller folds. These 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 in the jaspilites appear as a series of crinklings or flutings, with heights of from one-quarter inch to 5 or 6 inches from trough

(*A*)



(*B*)

FOLDS IN JASPILITES OF THE VULCAN FORMATION.

A, Pitching fold in jaspilite; *B*, lenses of jasper inclosed by layers of schistose hematite.

to crest (Pl. XX, *A*). In some cases the cross sections of these have smooth and flowing contours with rounded turns, and in other cases they have straight limbs with sharp, angular turns, their shapes depending largely upon the shapes of the larger folds upon which the smaller ones are superposed. In some places the folds are open and at other places they are greatly compressed. In the sharper folds the rock in the turns, i. e., at the axes of the crests and the troughs, is often crushed to a breccia, the fragments being cemented together by deposits of dolomite or siderite or of ore. In other cases the siliceous bands at the turns are replaced by ore into which the jasper passes gradually both vertically and transversely.

While the folds of the high orders are most noticeable within the troughs of the dolomite folds, they are by no means limited to these situations. Many minor folds are found also in those portions of the formation where there are no visible folds of larger dimensions, and even in comparatively small specimens of jaspilites there may be gently folded layers included between considerable thicknesses of other layers in which there is no evidence of contortions of any kind. In nearly all instances the folded layers are more richly ferruginous than the uncontorted ones, and in some instances they have been changed completely to ore, while the straight layers are practically pure jaspers.

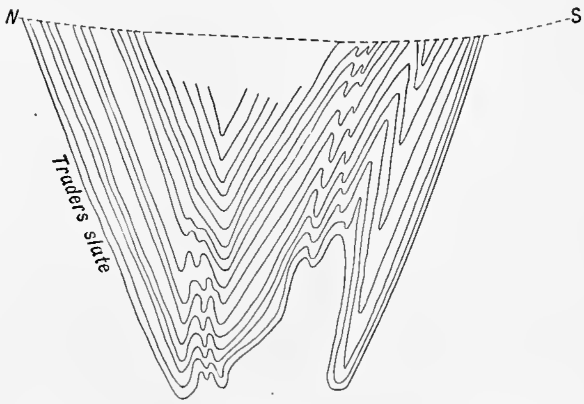


FIG. 24.—Diagrammatic sketch illustrating folding in the iron formation on east side of pit at old Keel Ridge mine. Area about 20 feet by 20 feet.

Much of the thickness of the iron formation in some portions of the district is due to the repeated recurrence of the same layers in consequence of the minor folding. The east side of the old Keel Ridge pit in sec. 32, T. 40 N., R. 30 W., exhibits this effect in a fine manner. The pit has been abandoned for some time and its walls are partly covered by fallen material, but enough of the surface can be seen to show the presence of folds of two orders (see fig. 24). Folds of tertiary and higher orders are well seen also on the stripped surface of the Traders jaspilites at the west end of the

Clifford pit of the Traders mine (see fig. 25), and those of the third order can again be seen on the wall of the pit immediately under the plan shown in fig. 25 (see also Pl. XVII, *B*). The Brier slates, as would be expected, were much more subject to minor folding than the two more rigid series of jaspilites between which the slates are included. Small folds and crinkles are therefore much more frequently noticed in the slate member than in the iron-bearing members. Indeed, there is scarcely a single slate exposure of large size that does not exhibit distortions of some magnitude. Sometimes the distortion takes the form of a slight change from the normal in the dip of the slate beds, indicating the presence of a very open, gentle fold; frequently it takes the form of a sudden monoclinal bend in the bedding, and many times it appears as a series of crinkles,

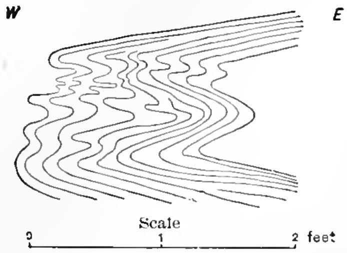


FIG. 25.—Sketch illustrating puckering in jaspilite on stripped surface, west end of Clifford pit, Traders mine, 1899.

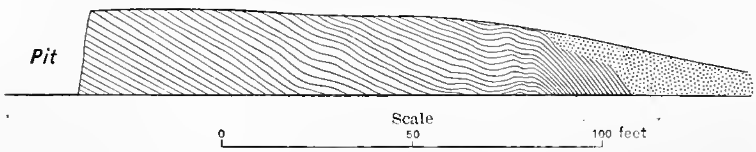


FIG. 26.—Sketch illustrating folding in Brier slates, on wall of trench from No. 2 pit extending south, West Vulcan mine.

flutings, or puckerings in the strata without affecting their dip as a whole. The general character of the minor folding of the slates is well shown on the east side of the trench extending south from the large pit near the center of the southeast quarter of the northeast quarter of sec. 9, T. 39 N., R. 29 W., just west of No. 4 shaft of the West Vulcan mine (see fig. 26), and again on the west side of the excavation at the Curry shaft No. 1 (fig. 27).

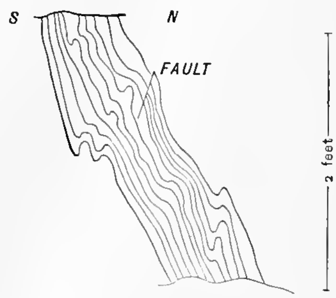


FIG. 27.—Sketch illustrating puckering in Brier slates, west side of cut at Curry shaft No. 1.

SECONDARY STRUCTURES RESULTING FROM FOLDING.

Wherever folding is observed within the iron-bearing formation, it is noticeable that it 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, as may well be seen on the surfaces forming the west side of the Traders open pit. In the siliceous layers this is the only secondary structure observed, while in the ores there is present in addition a schistose structure nearly parallel to the bedding plane, unless this has been obliterated by the deposition of new ore material. Frequently, however, the conditions were not favorable to the production of cleavage in the brittle jaspers, while eminently favorable to the production of schistosity in the ores. The jasper layers are then folded into sharp folds. They are thick and thin alternately, and in some places are broken across at intervals, making a breccia of jasper fragments in a schistose ore matrix (fig. 23). The banding in the resulting breccias may be either in the direction of the bedding, when the detached fragments have not been moved far from their original positions, or it may be in a direction transverse to the bedding when they have been moved appreciable amounts; for in the latter case they have been rotated into the plane of the motion and taken positions corresponding to that of the cleavage in the ores. The rocks of the Traders and Clifford pits are principally breccias of this character. Because of the rounding of the edges of the jasper fragments, the rocks look very much like conglomerates (see plan of Clifford pit for relations between folding and schistosity at this place, Pl. XXIV, and p. 407, for descriptions of the brecciated rocks).

THICKNESS.

A number of sections offer opportunities for determining the thickness of the separate members of the Vulcan formation, but only a few present opportunities for determining its total thickness.

All along the south side of the southern dolomite belt, from the Aragon mine eastward to the 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 member to the top of the Curry 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 its thickness is about 675 feet.

The thickness of the individual members comprising the formation is easily estimated at a number of places. The Brier slates have 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 member have not yielded such concordant results. In the first place, its thickness probably varies widely, as should be expected of a formation composed largely of detrital deposits laid down near a shore line. Moreover, only a few sections reach as low as the dolomite; consequently 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.

Favorable opportunities for accurate determinations of the thickness of the Vulcan formation in the southern iron-bearing belt west of Norway and in the central iron-bearing belt north of Lake Antoine are very poor. In both of these areas folding is more prominent than it is in the southern belt east of Norway, and where folding is not prominent exposures are lacking. In the Pewabic mine a measured section along a drift in the first level under shaft No. 1 gave 232 feet for the Traders member and 265 feet for the Brier slates. Near the center of sec. 6, T. 39 N., R. 29 W., the measured width of the Curry member is 350 feet. The dip of the jaspilites is not known, but it is about 75°. The thickness calculated on this dip is over 325 feet. At the Traders mine 195 feet of the Traders member are exposed, but because of close folding and lack of exposures no estimate of the thickness of the remaining members of the formation is hazarded. At the Indiana mine the measured thickness of the entire Vulcan formation is about 550 feet. At the Forest mine, in sec. 25, T. 39 N., R. 29 W., a drill hole penetrated about 130 feet of the Traders member.

An interesting feature of these figures appears when we compare the estimated thickness of the Brier and the Curry members with the total thickness of the two. In almost every case 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 slates vary between 240 feet and 360 feet, and nine estimates for the Curry member vary between 112 feet and 325 feet, measurements of the total thickness of the two vary only between 400 and 530 feet. The apparent greater variation in thickness of each of the members than the two combined may be partly explained as due to the gradation between them and the consequent difficulty of fixing upon 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 member, where it is fully developed, 150 feet; Brier slates, 330 feet; Curry member, 170 feet—i. e., the two ore-bearing members combined about equal in thickness the intervening slates. Of course it is understood that by overlapping, one, two or all the members of the formation may disappear from the surface, though they may exist with their full thicknesses at some little depth beneath it.

RELATIONS BETWEEN THE VULCAN AND ADJACENT FORMATIONS.

The relations between the Vulcan formation and the underlying dolomite have been repeatedly discussed in the preceding pages. It seems unnecessary to repeat the statements already made concerning these relations. Under the present head the facts discovered that throw light on them, and the conclusions to which these facts lead, are summarized, and a few additional facts are described which explain the absence of the iron formation from some portions of the district where it would naturally be expected to occur.

The iron-bearing Vulcan formation, except in very limited areas, is known to rest upon the Randville dolomite. Where they can be seen the lower layers of the upper formation appear to lie conformably upon the older one, usually with an extremely sharp line of definition between them. In some places the upper part of the Randville formation is a dolomite. In other places it is a talcose schist derived from the dolomite. Where the Vulcan formation rests on the dolomite or talcose schist its basal member is either a thin bed or series of beds of slate, a quartzite which often contains ore and jaspilite fragments, or an ore and jasper conglomerate containing large and small pebbles of ore. In some cases the slate is absent, but in every case the quartzite or conglomerate is present either at or very near the base of the formation. The fragments in the conglomerates must have been derived from an older iron formation that originally rested upon the dolomite, but which was eroded at the time the Traders member was laid down. In one case, at least, the dolomite itself yielded bowlders to the overlying beds, for on the seventh and eighth levels of the Chapin mine, at a point just south of shaft "C," several large rounded fragments of the dolomite were found embedded in the iron-bearing formation. If there was originally a slight discordance in bedding between the two formations, it has been obliterated by the movements along the contact plane that took place during the folding of the district. The Traders member thus appears to be conformable in attitude with the underlying dolomite, which remained practically undisturbed during the long interval which succeeded its deposition and preceded the deposition of the Traders member.

Along the north side of the Norway syncline and in the belt north of the Curry and the West Vulcan mines in sec. 9, T. 39 N., R. 29 W., the movements along the contact plane were so vigorous that they caused brecciation in the rocks on both sides of it. On the dolomite side of the contact the rock is affected by the brecciation only to a limited depth. For a short distance beneath its upper surface it consists of a mass of large fragments and bowlders of dense dolomite embedded in a soft, sheared matrix composed of serpentine, talc, and an earthy substance often colored slightly by limonite. On the upper side of the contact the brecciation has affected the entire Traders member and a portion of the Brier slates (Pl. XXI, *A*), causing them in many places to resemble strongly true conglomerates The resemblance of the ore breccia is so strikingly like that of the Ishpeming conglomerate at the base of the Upper Marquette series that at first glance it was taken to represent a basal conglomerate at the bottom of the Upper Menominee series. It contains large bowlder-like masses of ore and jasper in a schistose, or specular, ore matrix (see Pl. XXII, *A*) exactly like the conglomerate above the Negaunee formation in the Marquette district. When traced upward, however, the rock in some places is seen to pass into a slate breccia in which the matrix is a serpentinized slate and the bowlders or fragments, either slate or ore, or an intermingling of both. In the Norway syncline the brecciation extends far upward into the Brier slates, in some places crushing them throughout their entire thickness.

PLATE XXI.

PLATE XXI.

FIG. *A*.—BRECCIATED BRIER SLATES. In Norway pit, near the contact of the slates with the underlying ores of the Traders member.

The surface photographed was a portion of a wall bounding a mass of the slate near the center of the pit. This mass was left in the pit because it was not quite rich enough in iron to warrant mining. Other portions of this same breccia had been mined and shipped as lean ore (1899).

FIG. *B*.—BAND OF BRECCIATED BRIER SLATE CROSSING DEFINITELY BEDDED SLATES TRANSVERSELY TO THEIR BEDDING. In Norway pit.

The bedding of the unbrecciated slate is from right to left. The breccia band truncates the layers. In this breccia the fragments and matrix originally had the same composition, but the finely comminuted texture of the latter afforded favorable conditions for the deposition in it of ferruginous and talcose materials. Consequently the matrix is now softer than the fragments, and hence is more easily eroded, and at the same time it is more highly ferruginous.

A. BRECCIATED BRIER SLATES IN NORWAY PIT.

B. BAND OF BRECCIATED BRIER SLATE CROSSING DEFINITELY BEDDED SLATES TRANSVERSELY TO THEIR BEDDING, IN NORWAY PIT.

The fragments are nearly all sharp edged (see Pl. XXI, *A*). If there were any doubt as to the true character of the rock, the existence of brecciated bands crossing the rock transversely to its bedding would effectually remove it (see Pl. XXI, *B*). The lack of sharp contacts in this area between the dolomite and the members of the iron formation and the complexity of their mutual relations is thus plainly due to brecciation of the beds bordering the contact planes, and not to any confusion in their stratigraphical positions. Here, as elsewhere, the Vulcan formation was deposited upon the Randville dolomite and was followed conformably by the Brier slates. Movement in a zone near the contact plane crushed the rocks and produced brecciation and schistosity. The motion must have taken place sometime after the deposition of the Brier slates, but before the deposition of the Lake Superior sandstone which overlies the breccias in horizontal layers. It was probably contemporaneous with the folding.

The relations between the Vulcan formation and the overlying Hanbury slates are also those of conformity. The contact is usually very sharp. Little difficulty is experienced in defining the upper limit of the iron-bearing formation where exposures are plentiful. The slates, however, are often so very schistose on the upper side of the contact that their bedding planes can not be recognized. In most places the overlying slates are strongly graphitic and often very fissile. Where not graphitic they are light silvery schists from which all bedding traces have disappeared. The bedding of the iron-bearing formation, on the other hand, is still almost perfectly preserved, and is parallel to the contact. In one or two places the iron-bearing beds are separated from the slates by narrow bands of a soft earthy green rock containing remnants of plagioclase and a mass of green chloritic products such as usually result from the decomposition of a basic eruptive. The green rock has the appearance of a dike, which it probably is, that intruded the bedded series along the contact plane. Dikes of this kind are common in the Hanbury slate area, but are rarely seen in the Vulcan formation. The best preserved example of one of these contact dikes is that on the east wall of the large pit at shaft No. 1 of the West Vulcan mine. Here the dike, as far as it can be traced, follows the contact between the Curry jaspilites and the gray schistose slates of the Hanbury formation.

At a few other places, as, for instance, in the neighborhood of the

Pewabic mine, faults may intervene between the iron-bearing formation and the overlying slate. They are apparently of little importance from a structural point of view, but have not yet been sufficiently exposed to warrant any very definite statements as to their extent or position with reference to the adjacent rocks. The fault in the Pewabic mine separates the Traders quartzite from the Brier slate where it is best exposed, but it probably extends to the west, where it must pass between the Curry and the Hanbury beds unless it terminates suddenly (see map, Pl. XXVIII and fig. 35).

The relations between the Hanbury slate and the formations older than the Vulcan formation should perhaps logically be considered under the Hanbury slate rather than in this place. However, these relations are so connected with the relations of the Vulcan formation that the subject is here introduced. A further reason for this treatment is that the relations of the Hanbury slate have an important bearing upon the possible distribution of the beds of the Vulcan formation, which carry the iron ores.

At only one point has the actual contact between the Randville dolomite and Hanbury slate been seen. This is in a trench about 10 feet long in graphite-slates near the east line of sec. 2, T. 39 N., R. 30 W., a few rods west of the Bryngelson shaft. A careful examination of the relations between the dolomite and slate was made, with special reference to their bearing upon unconformity and faulting It was found that the dolomite projects slightly into the slates halfway up the exposed portion of the contact, and recedes from them both above and below this point. The surface of the dolomite is minutely irregular, small projections and reentrants occurring throughout the entire line of contact. The slates, which are strongly graphitic, are interlaminated with cherty bands. They contain small fragments of the dolomite and are badly shattered. A slate breccia is thus formed, which might be a fault breccia or a brecciated conglomerate. There can be no doubt that there has been movement along the contact zone, for the bedding of the slate has been much disturbed for a distance of 8 feet or more from the dolomite. Whether or not the movement was along a fault plane which cut out the Vulcan formation was not determinable from the exposures. The dolomite along the contact plane is not slickensided, nor is the rock near the contact greatly mashed, so far as could be observed. This may be thought to indicate that the movement was of slight

PLATE XXII.

PLATE XXII.

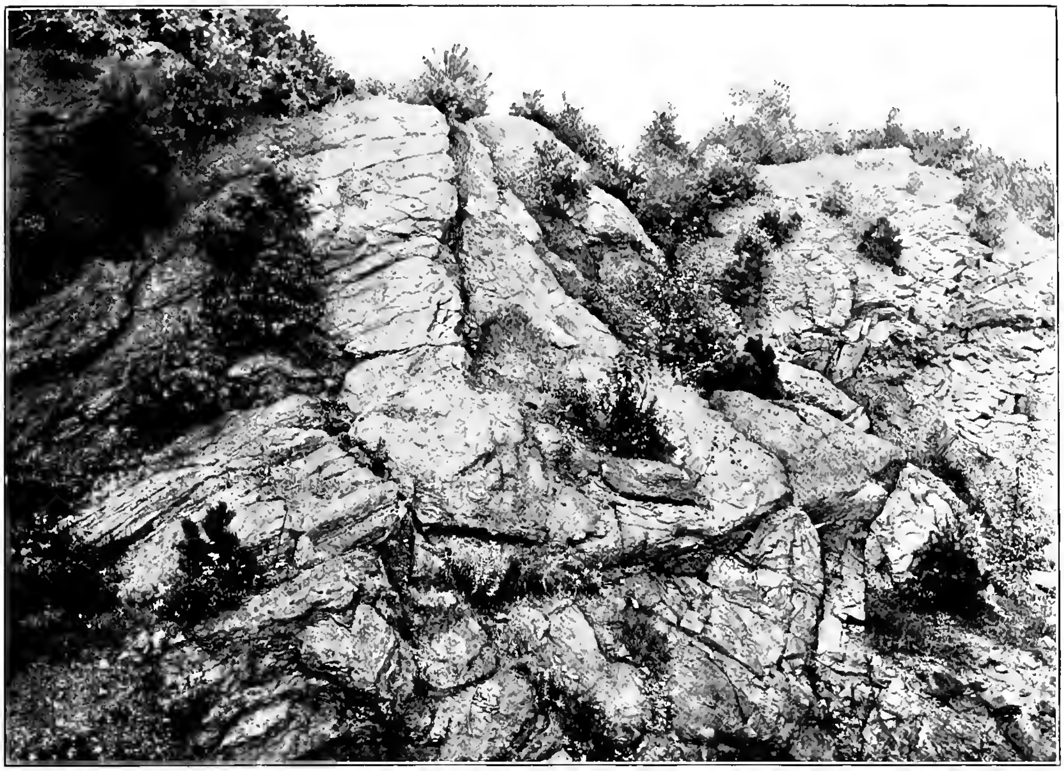
FIG. *A*.—SURFACE OF ORE BRECCIA. Near contact of the Traders member with overlying Brier slate, No. 3 pit, Curry mine, southwest quarter of northeast quarter, sec. 9, T. 39 N., R. 29 W.

The brecciated rock was a banded jaspilite. The surface shown is the surface of a band of specular hematite. The large lenticular fragments of jasper embedded in the schistose ore matrix make their presence known by causing projections and depressions in its surface. To the right, in the background, distinctly bedded, unbrecciated jaspilites can be seen.

FIG. *B*.—CONCENTRATING WORKS AT THE PEWABIC PIT. Photograph by J. J. Eskil.

The rough ore used is the conglomerate at the base of the Lake Superior sandstone. This is crushed, and the hematite is separated from the sand by washing.

To the left of the building is a cliff of cherty dolomite.



A. SURFACE OF ORE BRECCIA NEAR CONTACT OF THE TRADERS MEMBER WITH THE BRIER SLATES, NO. 3 PIT, CURRY MINE.

B CONCENTRATING WORKS AT PEWABIC PIT.

magnitude, and that it was more in the nature of a differential movement of the slates near the contact than of faulting across the beds. If the absence of the iron-bearing beds between the Hanbury slate and the dolomite is due to overlapping of the slates rather than to faulting, the lower layers of the slate should be coarse detritus, since the relation of the slates to the underlying rocks are those of a younger sedimentary series to an older series upon which the younger series is unconformable. The breccia between the slate and the dolomite referred to above may be a mashed conglomerate of this kind.

At Iron Hill, in sec. 32, T. 40 N., R. 29 W., the Hanbury slate is believed to lie immediately upon the Randville dolomite, although no contact between the two is seen (see Pl. XLII). The dolomite ends in a number of small knobs having steep faces toward the south. At the bases of the little cliffs is a swamp about 300 feet wide, and upon the opposite side of the swamp, on the north slope of a slight elevation, are several exposures of slate. The intervening swamp area has been tested at a number of places by auger borings, as has already been related, and has been found to be underlain by slates.

The uppermost layers of the dolomite formation consist of white cherts, and these are beautifully brecciated. Below these in some places lies a conglomerate containing numerous large rounded bowlders of dolomite, subangular fragments of chert, and an occasional pebble of quartzite in a matrix composed mainly of dolomite and chert débris (see Pl. XVI, *B*). Many of the pebbles are mashed and faulted, showing that the district was deformed after the conglomerate was laid down. When the conglomerate is traced eastward to the end of the set of dolomite ledges, the relations between this rock and the chert are found to be very complicated. The conglomerate apparently grades into a breccia, and this in places is between beds of dolomite or layers of the chert. At one place the conglomerate looks as though it were a breccia formed by crushing of the chert and dolomite; at other places it appears to be a layer of true conglomerate between layers of massive dolomite, and in other places it strongly resembles a conglomerate composed of fragments of the dolomite and chert lying above the dolomite. The conglomerate may be an intraformational conglomerate (one originally produced during the deposition of the formation, and therefore an integral part of it), whose complex relations to the remainder of the Randville dolomite are due to crushing and close folding; or, on the other hand, it may be a true conglomerate at the base of the Hanbury slate, made to appear like an intraformational conglomerate by repeated close folding at the end of an eastward-pitching anticline on which are superposed several minor folds. The latter is thought to be the probable explanation. If this be correct, the difference in composition of the conglomerate from the normal slates is explained by its being the first deposit along a shore line composed of dolomites and cherts. But the relations of the various rocks at this place are so exceedingly complicated that no unprejudiced observer would be willing to declare without reservation that the conglomerate is not a member of the dolomite formation, rather than the basal member of the Hanbury slate (see also pp. 256 and 481 for fuller descriptions of the relations at this place).

EXPLANATION OF THE DISTRIBUTION AND RELATIONS OF THE VULCAN AND HANBURY FORMATIONS TO THE UNDERLYING FORMATIONS.

Two possible explanations suggest themselves to account for the facts of distribution of the Vulcan and Hanbury formations, their relations to the adjacent formations, and the character of their basal members, faulting and unconformity.

For a time it was thought that faulting near the contact plane between the Hanbury slate and the older rocks might explain the phenomena. Thus the absence of the Vulcan formation east of Quinnesec could be explained by the hypothesis that the Hanbury slates had been thrust over the lower formation of the Upper Menominee series so as to rest upon the Randville dolomite. The absence of the Vulcan formation between the Hanbury slate and the dolomite at Iron Hill might similarly be explained, only here it would be necessary to believe that after the faulting occurred close folding took place, else the manner in which the Hanbury slate wraps around the eastern 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, those in the Pewabic mine being the only ones of sufficient magnitude to be mapped on the mine plat. Moreover, it is clear that the crushed zones of the Traders and Brier beds at the Norway, Curry, and West Vulcan locations are due to faulting. Further, there have been marked movements of accommodation between the different formations at their contacts, which might be called faulting. In all of these instances, however, the faults are local, and in none of them is the displacement of the faulted beds great. These few minor faults, which are easily recognized, certainly would not warrant the assumption of such numerous and extraordinary faults as would be necessary to explain the relations above described. Furthermore, the faulting theory does not explain the conglomeratic and quartzitic character of the Vulcan formation where it is in contact with the Randville dolomite, nor does it explain the apparent conglomerates found at several places at the base of the Hanbury slate.

The second explanation which suggested itself is founded on the belief that an unconformity exists between the Lower Menominee and the Upper Menominee, such as exists elsewhere between the Upper Huronian and the Lower Huronian in the Lake Superior region. The order of events producing the unconformity must have been somewhat as follows: After the deposition of the Lower Huronian series, consisting of the Sturgeon quartzite, the Randville dolomite, and the iron-bearing Negaunee formation, the area was raised above the sea. Denudation continued for a long time. Upon the southern side of the Menominee trough these formations, if deposited, were entirely removed. In the central and northern portions of the district denudation extended to a sufficient depth to remove the Negaunee formation in the larger part, if not all, of the area, and to cut into the Randville dolomite. Probably the folding accompanying this uplift and erosion was very moderate. After erosion had long continued, there was slow subsidence of the Lower Menominee land. During the early stages of the encroachment of the sea upon the land the Vulcan formation was laid down. As shown by the character of this formation, it consists largely of detrital ore-formation material. This was derived from the Lower Menominee Negaunee formation, which during the course of the erosion had practically all disappeared. However, at the end of Vulcan time the sea had not yet wholly overridden the land, for at some places certainly, and perhaps for extensive areas, the Vulcan formation is not present. After Vulcan time the subsidence of the land continued during the deposition of the Hanbury slate. In places where the Lower Menominee series was below the sea at the beginning of Vulcan time the Hanbury slate rests upon the Vulcan formation. Where the Lower Menominee series was above the sea at the beginning of Vulcan time, but was depressed beneath the sea at the end of this period, the slate overlapped the underlying Vulcan rocks and now rests directly upon the Lower Menominee series, as, for instance, at Iron Hill and at the locality east of Quinnesec to which reference has been made.

The theory of unconformity with overlap thus fully and satisfactorily explains every fact of distribution and every known relation between the Upper Menominee, the Lower Menominee, and the Archean rocks. The presence of a great quantity of detrital ores, of quartzites, and of ore and jasper conglomerates near the base of the Vulcan formation is fully explained. The absence of the Vulcan formation from various parts of the district also presents no difficulty, these being areas which were still above the sea during Vulcan time. The disappearance of the Traders member first among the Vulcan beds and its absence from strips of country in which the Curry member is to be found, and the gradual approach of the base of the Hanbury slates to the Lower Huronian at such places are likewise made clear.

It is therefore with great confidence that the second theory is proposed to explain the structural phenomena of the district—the theory of unconformity between the Lower Menominee and the Upper Menominee series, with a gradual advance of the Upper Menominee sea, the deposits of which slowly overlapped the earlier deposits and gradually buried the higher lands composed of the Lower Menominee rocks.

According to this theory there are in the Menominee district all the evidences of a great unconformity between the Upper Menominee and the Lower Menominee—an unconformity like that found in the Huronian of the Marquette district and other districts of the Lake Superior region, except that in the Menominee district there is no marked discordance in strike and dip between the upper and lower series. This lack of discordance does not in the least invalidate the conclusion that a great time gap separates the two series. It has been shown by Van Hise,[a] that an apparently minor unconformity may mark as great a time interval as the most startling discordance. The relations of the two series in the Menominee district are very similar to those existing in the Penokee district between the cherty limestone of the Lower Huronian and the Upper Huronian quartz-slate member.

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[a] Van Hise, C. R., Principles of North American pre-Cambrian Geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1894.

THE ORES.

LITHOLOGY.

PHYSICAL CHARACTERS.

The ores occurring in the Vulcan beds have been incidently referred to repeatedly in the preceding paragraphs, and the characteristics of some phases of them have been described. Under the present head a general description of the ores is presented and a few statements are made concerning their composition, without respect to their position in the formation. In general, the Traders and the Curry ores are not very different, though there are some varieties in the lower member that have not yet been discovered in the upper member, and there are others that are peculiarly characteristic of the upper member. Under the term ores is included not only the material now being shipped, but also that which, in the near future, must be drawn upon to meet the demand when the richer supplies have become scarcer or exhausted. The character of the ore varies from year to year in the smaller mines, as old deposits are worked out and new ones are exploited, and also, to some degree, in accordance with the condition of the ore market, which may enable ores to be profitably worked in certain seasons which in other seasons would not begin to pay the cost of mining.

A rough division of the ores of the district is into siliceous ores and rich ores; and these classes may be subdivided into different grades, based partly upon their chemical and partly upon their physical characters.

The siliceous ores are, in part, simply very rich portions of the iron formation, retaining its original physical characteristics, and in part portions of the formation in which some of the jasper of the jaspilites has been replaced by ferruginous material. In the latter class the physical aspects of the jaspilites have suffered great modifications. These two classes of ores pass into one another and into typical jaspilites too poor in hematite to warrant mining at present, and the second class grades into rich ore, from which practically all the silica has been extracted. In both classes the original banding of the jaspilites is often preserved with great perfection. This banding extends without disturbance from ore to jaspilite, the passage between the two being accomplished both by lateral and by vertical gradations. The difference between the two classes is mainly one of degree of alteration. The ores of the first class retain more nearly their original character than those of the second class. The former are but slightly changed phases of the original deposits, to which some hematite has been added by alteration of their original ferruginous component, while the latter are largely replacements of the original materials through the removal of quartz by solution and the deposition in its place of derived hematite.

In those cases in which the ores consist of enriched portions of the iron formation they possess the general aspects of the ferruginous bands in the original jaspilites. The ores may be even-banded bluish-black rocks composed of alternating thin layers of hematite and of very ferruginous jasper, with the hematite layers greatly in excess, or they may consist of thick layers of hematite separated by thin layers of jasper. Laminæ of dense black hematite sometimes run through the deposits parallel to their bedding, emphasizing this structure and making the ore very hard. When occurring in sheared portions of the formation, the ores are more or less micaceous and specular, as at the Traders mine, but none of the ores now mined are as typically specular as some of those on the Marquette range. The micaceous varieties are limited exclusively to the lower portion of the Traders member, and are thus in the same stratigraphical position as the corresponding ores in the Marquette district. The nonspecular lean ores have in general a rather dull luster and a texture that is dense or granular, according to the proportion of the dense, flinty, vein-like hematite in them or to the proportion of quartz grains intermingled with the ferruginous material. When the proportion of quartz grains is large, the ore takes on a gray tinge and becomes more or less friable or sandy. When the ores contain but little quartz and no vein-like hematite, they are very close grained, fairly hard, and finely granular, showing fine bedding laminæ and a slight schistosity parallel to the bedding. In the Cundy ore, which is of this kind, there is considerable magnetite intermingled with the hematite. For this reason it is much harder and denser than the other ones of this class and has a black, rather than a bluish-black, color. At the Keel Ridge mine the ore is platy and schistose. Thin layers of a denser black hematite alternate with thicker beds of a finely granular sandy ore in which there is apparently much silica in the form of sand grains. The sandy constituent has a slightly pink tinge, and since this is one of the principal components of the ore this too possesses a pinkish tinge. In the trade this ore is sometimes referred to as a red slaty hematite. It is, however, quite different from the soft red hematites of the Gogebic, the Mesabi, and the Marquette ranges.

The lean ores produced by the partial replacement of the jasper of the jaspilites by hematite are not so distinctly banded as those of the first class, although their banding is still very noticeable. Usually they are more lustrous than the latter, the newly deposited hematite being crystalline, causing the ores to sparkle with the reflections from the crystal faces. The ores of this class occur both in the Traders and the Curry members, particularly in those places where the formation has been deformed by folding or brecciation.

The brecciated ores consist of large and small fragments of ore and jasper in a matrix composed of small jasper and ore fragments and tiny ore grains cemented by a porous ore. Some of the ore mined at the Clifford pit of the Traders mine and much of the Cuff ore is of this character. In some cases, as in the Norway open pit, small pieces of dolomite are occasionally intermingled with the other fragments, and in the cement is a large proportion of talc or serpentine. This type of ore has usually a reddish or purplish tinge, though when the ferruginous cement is in large quantity the ore closely resembles in general appearance the porous crystalline ores of the better grades, exhibiting here and there mottlings due to the fracturing of ore or jasper fragments. A third type of the brecciated siliceous ore is a brecciated Brier slate, in which the comminuted slate cement, as well as the fragments, are partially replaced by brown earthy hematite. These ores are purplish brown and lumpy, and often present slickensides through the mass.

Nearly all the brecciated ores containing slaty material, and those banded ores with which are interbedded thin layers of slate, are coated on the weathered surfaces of their joint planes with thin layers of a yellowish-green substance having nearly the color of epidote. This is much more plentiful along the edges of certain layers than of others, and is sometimes limited to a single layer. When examined carefully a large portion of this coating is discovered to be a vegetable growth. Another portion, however, probably consists of an aluminous silicate[a] (see also pp. 385–386). It is found mainly on weathered surfaces or along the surfaces of joint cracks to

[a] Putnam, B. T., Notes on the samples of iron ore collected in Michigan and northern Wisconsin: Report on the Mining Industries of the United States (exclusive of the precious metals), with special investigations into the iron resources of the Republic, etc., by Charles Pumpelly. Reports of the Tenth Census, vol. 15, pt. 1, 1886, p. 449.

which atmospheric water has had access. In many instances the alteration has penetrated the slaty layers to some depth and has given their material a yellowish-green tinge.

All the ores of the classes described above contain both fragmental and chemically deposited material. Much of the hematite in the banded and the brecciated ores is of fragmental origin, but with it is a considerable quantity of newly deposited material. It is probable that none of these deposits in their original form would have warranted exploitation. By enrichment, however, their ferruginous component was proportionately increased, and in many cases is now in sufficient quantity to bring the deposits within the limits of merchantable ores. Since the deposit of iron oxide in these instances is dependent on the same processes that gave rise to the rich ores that constitute the most valuable deposits of the district, the laws governing the distribution of the lean ores is the same as that determining the positions of the rich deposits (see pp. 392–401). The lean ores, like the rich ores, are found in plunging synclines and in those portions of the ore formation that suffered brecciation, jointing, shearing, close folding, or other deformation that produced conditions which afforded opportunities for the entrance of ground water into the rocks. Thus the lean ores are usually found in the lowermost portions of the Traders member along its contact with the Randville dolomite (where slipping and brecciation has taken place), along the straight limbs of folds in both the Traders and the Curry members, and in the Curry member along troughs of synclines. The last two positions are favorable for ore concentration to some extent, but not sufficiently so, as a rule, for the production of rich ores like those found at the bottoms of troughs in the Traders member (see p. 393).

The rich ores of the district are confined, as far as our present knowledge goes, to the Traders member and to a very few exceptionally favorable situations in the Curry member. They occur in those portions of the Traders member near the contact with the underlying dolomite, especially where the two formations are separated by a layer of serpentine and talc, or by beds of impervious slates. The richest deposits are in the troughs of pitching synclines. In the Curry member they occur where folding and brecciation were both severe.

These ores are usually bluish-black, porous, friable, fine-grained aggregates of crystallized hematite. They crush easily and soil the fingers when handled. They are commonly called soft blue hematites.

In many cases the ores are entirely devoid of all evidences of bedding. These varieties are frequently penetrated by tiny seams of dense hard ore, and are cracked and gashed by openings that widen out into distinct cavities. All surfaces are covered with druses of minute hematite crystals, which reflect the light from thousands of sparkling faces. Usually, however, the ores are distinctly laminated. In these the drusy character is lacking. The ores are soft, and are earthy in luster except where they have suffered shearing. At such places they become more or less specular. Gradations between the laminated and the massive ores are common. In many of the ores dense laminæ and earthy or drusy ones alternate, producing an ore with a platy structure which, when not deformed, splits readily between the laminæ into flat, clinkery slabs. The dense laminæ are vein-like in character and appear to have been introduced after the earthy ones had attained their present features. At the Ludington shaft of the Chapin mine much of the ore is also platy. But in this instance the structure is due to the fact that laminæ of the soft, earthy, bluish hematite alternate with others composed very largely of calcite or dolomite. Between these separation occurs very readily.

At the ends of folds and at a few other places where the iron formation has been greatly shattered the ores are often brecciated and their fragments cemented together by a drusy mass of ferruginous calcite or dolomite or by a mass of porous, drusy hematite identical in appearance with the material of the drusy ores referred to above. The cavities still remaining in these breccias are often partially filled with earthy brown limonite, or their walls are coated by little crystals of red siderite. The material of the ore fragments in the hematitic breccias is like that of the hematite bands interstratified with the jasper bands in the jaspilites. Those in the calcareous breccias are fragments of the banded rich ores described in the preceding paragraph. In the latter the replacement of silica by hematite had practically been completed before the ore was brecciated, while in the former deposition of ore continued after brecciation.

The ore of the Curry shaft is so unlike any other ore of the district that it deserves at least another brief mention in this place (see also pp. 347–348). As it appears on the stock pile (1899) most of it is a dark-blue, dense, massive variety cut by veins of white and dark-red dolomite and containing here and there through it large and small nests of the same mineral.

Other pieces are mottled in gray, pink, and yellow colors. These varieties are minutely brecciated by ramifying veinlets of the carbonate. While these ores may be enriched to some extent by the deposition of hematite from solutions passing through a lean ore, their present value is due largely to the replacement of their original silica by carbonates.

CHEMICAL COMPOSITION.

The ores mined in the Menominee range during 1900 were all Bessemer, with the exception of one grade obtained from the Quinnesec mine and the ores of the Walpole and the Cundy mines. The Cundy ore contains a large proportion of magnetite, but the ferruginous component of all the other ores is almost exclusively hematite, although all contain magnetite to some extent. This varies in amount between 1.51 and 9.56 per cent[a] in the dried ores, of which complete analyses have been published. The purest hematite being shipped contains about 92 per cent of Fe_2O_3. In addition to the iron oxides all the ores contain varying amounts of SiO_2, Al_2O_3, CaO, MgO, CO_2, S, P_2O_5, and H_2O, and most of them also some manganese, K_2O and Na_2O. In a few ores TiO_2 and C have been detected.

The minimum silica reported in the ores of 1900 is 2.75 per cent. The average in the richer ores is about 4 per cent. The maximum limit of this constituent fluctuates with the ore market, since an increase in silica means a decrease in the metallic contents, and a consequent decrease in market value. In 1900 the maximum silica was 38.65 per cent in an ore containing 40.93 per cent Fe (equivalent to 58.46 Fe_2O_3). The Al_2O_3 varied between 0.61 per cent and 1.89 per cent, the CaO between 0.18 per cent and 1.58 per cent, and the MgO between 0.21 per cent and 3.35 per cent. Manganese was found in the averages of all the cargo analyses of 1900, in quantities between 0.08 per cent and 0.43 per cent, corresponding to 0.10 per cent and 0.55 per cent MnO, but in some of the specimens collected by the agents of the Tenth Census it was not detected, or, at any rate, it was not reported.

Sulphur and phosphorus are universally present, but neither exists in

[a] Fifteen complete analyses of Menominee ores are published in the Reports of the Tenth Census, vol. 15, 1886, pp. 437–453. While it is not pretended that these analyses represent exactly the ores shipped at present, nevertheless, they probably indicate the character, and, approximately, the degree of variation in the composition of these ores.

any considerable quantity. The former element is present between the limits 0.002 per cent and 0.028 per cent, corresponding to 0.0036 per cent and 0.05 per cent FeS_2, and phosphorus between 0.009 per cent and 0.135 per cent, corresponding to 0.02 per cent and 0.3105 per cent P_2O_5.

Records of the percentages of the other components present are not to be found in the recently published analyses. In those of the Tenth Census, however, they are given, and the determinations seem to have been made with great accuracy. In recent analyses the loss on ignition is specifically stated (it varies between 0.65 per cent and 3.24 per cent), but the proportion of this loss due to the escape of CO_2 is not recorded. In the Census analyses CO_2 was detected in every sample analyzed, in quantities usually varying between 0.08 per cent and 0.50 per cent. In one ore, however, that from the old Keel Ridge mine in the northwest quarter of the southeast quarter of sec. 32, T. 40 N., R. 30 W., the proportion was 7.12 per cent. No description of this ore is given in the report, but it was probably cut by veins of dolomite like the ore of the Curry mine, which contains 22 per cent of dolomite (see p. 348), or was an ore in which the quartz had been replaced by a carbonate, like some of the ore from the Chapin mine. The ores in which the CO_2 was present in small quantity probably contained the substance in calcite (0.18 per cent to 1.14 per cent) scattered through them in little nests (see p. 314)

Of the alkalies K_2O was found in 11 of the 15 samples analyzed and Na_2O in 5 of them, but since these constituents were sought for only in those cases in which the sum of the other constituents amounted to less than 100 per cent, it is probable that they occur in a larger proportion of the ores, if not in all. The K_2O was present between the limits 0.05 per cent and 2.29 per cent, and the Na_2O between 0.02 per cent and 0.30 per cent. Carbon was detected three times in small quantities, viz, 0.006 per cent twice and 0.01 per cent once, and TiO_2 in one sample to the amount of 0.075 per cent. It was present in several other samples as traces too small to be determined.

The specific gravity of the ores is dependent partly upon their composition and partly upon their physical structure. A large number of determinations were carefully made by the chemists of the Tenth Census.[a] These showed a very wide range, i. e., between 3.447 and 5.173, but their

[a] Reports Tenth Census, vol. 15, 1886, pp. 531–535.

value was in no wise comparable with the iron contents of the samples, as the following short tabular exhibit will affirm:

Density of Menominee ores compared with iron contents.

Mine.	Density.	Iron.	Mine.	Density.	Iron.
Breen	3.447	50.17	Curry	5.001	67.40
Cyclops	3.478	64.38	Quinnesec	5.006	63.49
Norway	3.830	59.72	Vulcan	5.036	67.62
Breen	4.590	59.79	Curry	5.173	67.53

The great variation in the structure of the ores is also responsible for great variations in their capacity for absorbing water and retaining it. The ore as it comes from the mine is saturated with moisture. That removed from the mine and protected from the rain for a long time becomes dry, and on analysis yields only a trace of water. That, however, which remains unprotected on stock piles, and ore in transit, absorbs such a great quantity of water that it is a matter for serious consideration whether it would not prove profitable to dry it before shipment and protect it during transportation to the furnaces. The average cargo analyses showed the ores in 1900 to contain in their natural state, i. e., before drying, percentages of moisture varying between 2.10 and 8.97, the lean ores as a rule showing less moisture than the richer ones, mainly because of their less porous character. In the table below the moisture contents of some of the ores are indicated. The figures do not represent percentage weights of the dry ores, the analyses of which are given above the moisture figures, but they are moisture percentages based on the weights of the natural ores, i. e., of the dry ores plus the moisture, and therefore are considerably smaller than they would be if calculated on the weights of the former. The shipments of one mine alone in 1899 contained over 58,000 tons of water in addition to that which was chemically combined in its constituents.

In the following table the average cargo analyses of some of the ores shipped in 1899 are arranged in the order of diminishing silica. While it is recognized that the composition of the individual ores varies from year to year, nevertheless the general features exhibited by their analyses remain practically the same. The figures for 1899 are chosen rather than those of later seasons, because the former correspond to the ores described in the foregoing paragraphs. The analyses are not so complete as those published by the Tenth Census, but they furnish abundant data for comparison of the different grades and give an excellent summary of their characters.

The results are calculated on the weights of samples dried at 212° F. The moisture figures represent the loss of weight in drying and are calculated as percentages of weight of the natural ores before drying. The iron is calculated as Fe_2O_3, although it is probable that in every instance some of it is in the form Fe_3O_4. Except where otherwise indicated, the analyses are taken with slight modifications from Mineral Resources of the United States, 1899, Twenty-first Annual Report U. S. Geological Survey, Part VI, pages 39–40.

Cargo analyses of Menominee iron ores, season of 1899.

	Clifford.[a]	Keel Ridge.	Pewabic, Genoa.[b]	Quinnesec, siliceous Bessemer.[c]	Toledo.[b]	Loretto.[d]	Walpole.	Chapin.	Pewabic.[b]	San Jose.[d]	Nimick.[e]	Millie
Fe	41.01	40.64	44.00	47.20	54.21	57.067	58.75	58.13	63.21	64.405	62 72	63.705
SiO_2	39.10	37.42	32.89	26.00	19.80	13.20	10.51	6.20	5.48	4.64	4.35	2.97
Mn	.09	.20	.09	.12	.11	.20	.13	.54	.11	.30	.22	.12
P	.014	.046	.007	030	.01	.0205	.120	.065	.009	.014	.071	.0275
S	.003	.006	.005	004	.004	.062	.002	.019	003	.027	.03	.008
Fe_2O_3	58.58	58.04	62 85	67 42	77.44	81.45	83 92	83.01	90.29	91.97	89.55	89.99
SiO_2	39.10	37.42	32.89	26.00	19.80	13.20	10.51	6.20	5.48	4.64	4.35	2.97
P_2O_5	.032	.106	.016	.07	.023	.047	.276	.15	.02	.032	.163	.064
FeS_2	.006	.011	.009	007	.007	.114	.004	.036	.006	.050	.055	.015
Mn_2O_3	.13	.29	.13	.17	.16	.29	.19	.78	.16	.43	.32	.17
Al_2O_3	.97	.90	1.10	1.02	1.20	2.12	1 30	1 41	1.04	1.24	1.25	.94
CaO	.49	1.35	.79	.27	.88	.32	.79	1.235	.86	.19	.65	1.14
MgO	.29	1.00	1.07	.32	1.08	.57	1 96	3.565	1.12	.39	2.24	1.49
Loss by ignition	.45	Undet.	1.18	2.80	1.20	1.59	1.22	3.22	1.20	.64	1.65	2.12
Total	100.048	99.117	100.035	98.077	101.790	99.701	100.170	99.606	100.176	99.582	100.228	99.899
Moisture	2.55	2.90	4.22	2.10	6.00	8.72	5.00	6.96	7.00	8.28	7.99	5.67

[a] From Traders (Antoine) mine.
[b] From Pewabic mine. Analysis of Genoa ore is an average analysis of shipments for season 1898. From Lake Superior Iron Ores, published by Pickands, Mather & Co., Cleveland, Ohio, 1899, p. 14.
[c] Analysis of shipments 1900. Mineral Resources, United States, calendar year 1900, Washington, 1901, p. 14.
[d] From Loretto mine.
[e] From Aragon mine.

Of the four analyses given below, the first, made from a sample of the Chapin ore, was furnished by Mr. E. E. Brewster. The second and third are analyses of two grades of "soft specular" Quinnesec ore, and the fourth of a "soft specular" blue ore from the Cornell mine. The last three analyses are taken from the Tenth Census Report. They, of course, do not represent the exact composition of any ores being mined at the present time, but they afford the best data we have for determining the mineral composition of the richer of the Menominee ores, and for this reason they are quoted. The second analysis was made from chips selected with special reference to securing a sample rich in the greenish-yellow incrusting mineral (see p. 375) that coats the ore-bearing rocks in many places.

Complete analyses of Chapin, Quinnesec, and Cornell ores.

	I.	II.	III.	IV.
Fe	60.54	55.58	65.63	57.03
Fe_2O_3	85.44	76.14	91.51	80.15
FeO	.47	2.87	1.97	1.10
Al_2O_3	1.33	4.69	1.53	3.88
Mn_2O_3	.76	....	....	....
CaO	1.26	.27	.36	.17
MgO	3.02	3.55	.21	.48
K_2O	.064	.99	.57	2.29
Na_2O	.066	.02	.03	.30
SiO_2	4.53	9.31	3.03	10.72
P_2O_5	.15	.021	.021	.074
S	.002	FeS_2= .110	.099	.146
CO_2	....	.30	.38	.08
H_2O (above 100°)	2.75	1.72	.27	.56
Total	99.842	99.991	99.980	99.950

In the course of the analyses of the Quinnesec and Cornell ores the insoluble components were determined separately, with these results:

Insoluble constituents of Quinnesec and Cornell ores.

	II.	III.	IV.
Total insoluble	12.02	4.61	16.45
SiO_2	9.31	3.03	10.72
Al_2O_3	1.61	.93	3.21
CaO	.09	.07	....
MgO	.09	.06	.08
K_2O	.93	.51	2.23
Na_2O	....	.03	.20
Total	12.03	4.63	16.44

MINERALOGICAL COMPOSITION.

MINERAL CONSTITUENTS OF THE ORES.

From the microscopical examination of the ores it is learned that they contain hematite, magnetite, quartz, calcite, dolomite, muscovite, and serpentine. The chemical analyses show, in addition, the presence of pyrite, apatite, and some manganiferous mineral. All of these minerals appear to occur in practically all the ores, but they are found in greatly varying amounts. In attempting to calculate their proportions in the ores, the analyses of which are given above, we are met by several difficulties which can not be entirely overcome. In the first place, no microscopical examination was possible in the case of any of the samples analyzed. Hence there is no knowing whether all the minerals mentioned above were in these samples or not; or, if all were present, which of the rarer ones were in excess. In analysis I there was no determination of CO_2 separately from H_2O, though it was known to be present. In sample II there was presumably present some serpentine in addition to the yellowish-green mineral, which is probably a soluble silicate of magnesia and alumina. But there is nothing to guide in the distribution of the Al_2O_3, MgO, and SiO_2 between these minerals, or in determining how much of the bases occur in them and what proportions are present as isomorphous mixtures in the hematite and magnetite. If we assign all the P_2O_5 to apatite, all the CO_2 to dolomite, all the FeO to magnetite, and the insoluble K_2O, Na_2O, and Al_2O_3 to muscovite, calculate the proportion of MgO necessary to unite with the available CaO in the formation of dolomite, and assign the balance to serpentine, the mineral composition of the first, third, and fourth of the above ores is as indicated below:

Mineral constituents of rich ores.

	I.	III.	IV.
Hematite ($Fe_2O_3+Al_2O_3$)	85.55	87.74	78.28
Magnetite	1.51	6.34	3.54
Muscovite	.54	2.62	9.45
Serpentine	6.49	.25	1.15
Dolomite	2.62	.82	.18
Apatite	.35	.048	.171
Pyrite	.004	.099	.146
Quartz (excess of SiO_2)	1.46	1.84	6.50
Manganite (?)	.85	....	....
Excess unaccounted for:			
H_2O	.48	.17	.32
K_2O	....	....	.06
Na_2O	....	.03	.10
Total	99.854	99.957	99.897

It is fully realized that the above estimates are only approximate. In the calculations all the CaO in excess of that required by the P_2O_5 to form apatite is assigned to the dolomite, and enough MgO in addition to saturate the CO_2. The remaining MgO is all considered as occurring in serpentine. If the dolomite is richer in MgO than it is assumed to be, the percentages of the serpentine in the ores are less than estimated and the percentages of quartz larger. Moreover, the excess of CaO which would then be unaccounted for would probably indicate the presence of some chlorite. Again, some of the magnesia may be in the form of talc, but that this mineral is present to any considerable amount is not probable, since talc contains less water than serpentine, and even on the assumption that all the MgO is in serpentine there is nevertheless some water unaccounted for in every analysis. Serpentine is an abundant constituent in some of the ores, as will be shown later.

If we exclude from consideration the MgO in analysis II and distribute the other oxides in the same manner as was done in the remaining three analyses, the calculated percentages of the mineral components become: Hematite, 69.77; magnetite, 9.24; muscovite, 4.55; dolomite, 0.64; apatite, 0.048; and pyrite, 0.110. This would leave 3.08 per cent Al_2O_3, 3.45 per cent MgO, 7.41 per cent SiO_2, and 1.61 per cent H_2O to be distributed among the serpentine or talc, quartz, and the yellowish-green incrusting mineral. If all the MgO is assumed to be present as serpentine, there would be required 3.72 per cent SiO_2 and 1.22 per cent H_2O to combine with it, leaving 3.08 per cent Al_2O_3, 0.39 per cent H_2O, and 3.69 per cent SiO_2 ($=2\ Al_2\ Si_2O_7+1\frac{1}{2}\ H_2O$) to represent the quartz and the yellowish-green incrustation. According to this calculation, however, the serpentine would be in an excessive amount, i. e., 8.39 per cent, which is not thought to be probable. Evidently the greenish-yellow mineral is a soluble aluminous silicate, but whether it contains much or little MgO can not be learned with the data at present in hand.

Of course the lean ores, since they contain a much higher percentage of silica than the rich ores, the analyses of which are quoted above, must, in consequence of this fact, contain smaller proportions of the other constituents. Moreover, since many of them are but slightly changed phases of the normal jaspilites, they contain but small proportions of talc, serpentine, calcite, dolomite, and other minerals that were deposited by the circulating waters by whose action the richer ore bodies were concentrated. Otherwise the lean ores are similar to the richer ones. Both kinds are composed of the same chemical elements, but they contain them in different proportions.

MINERALS ASSOCIATED WITH THE ORES.

All the minerals mentioned above as being constituents of the ores are occasionally visible in the hand specimens, with the exception of the apatite.

Quartz, dolomite, and calcite.—Quartz, dolomite, and calcite appear in veins cutting the ores, as has already been repeatedly stated. The quartz and calcite are nearly always in small veins, most of which are straight, marking the positions of joint cracks. The dolomite is also usually in small veins, but sometimes the veins are 2 or 3 inches in width. The smaller veins, like most of the quartz veins, mark the positions of joints. The larger veins, however, cut across the bedded ores in any direction, but most frequently penetrate them along their bedding planes. The quartz and calcite are usually white. The dolomite is either white or of a dark-pink color.

Dolomite in small brownish-yellow, flat, rhombohedral crystals with rounded faces also forms druses lining cavities and vugs in the ore. This variety and the pink variety are doubtless strongly ferruginous. The former may approach siderite very closely. Often calcite is associated with the dolomite in druses, the former appearing in transparent or translucent scalenohedra or highly modified rhombohedra, and the latter as opaque white simple rhombohedra with curved faces. Sometimes the dolomite crystals are implanted upon those of calcite; at other times the two are intermingled promiscuously. In many cases calcite occurs also alone in druses covering the walls of pores and in crystallized aggregates constituting the cement of ore breccias.

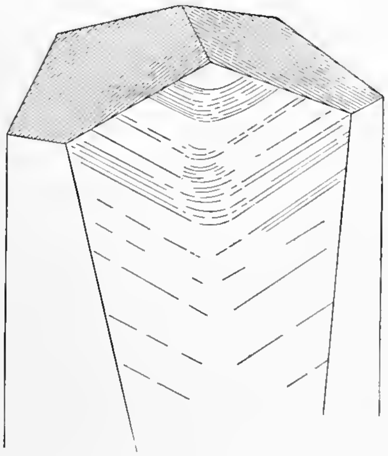

FIG. 28.—Calcite crystal of second type, in ore of West Vulcan mine.

In many instances the calcite crystals are well developed and of large size. In the West Vulcan and a few other mines water channels running through the ore are lined with numerous white calcite crystals, some of which are of great beauty. In the West Vulcan mine the crystals often measure three-fourths of an inch in length and one-fourth inch in diameter. They are of three types. The first type consists of a steep scalenohedron made up of many subindividuals. The second type is a steep rhombohedron, approaching 16 R, terminated by — 1/2 R (fig. 28), and the third type a combination of these two forms with a steep positive scalenohedron that is approximately 4/7 R 5/2 (see fig. 29). The — 1/2 R and planes of the scalenohedron are always striated by lines parallel to the intersections of these planes with a positive rhombohedron which truncates their solid angles and the planes of 16 R by curved lines approximating corresponding directions.

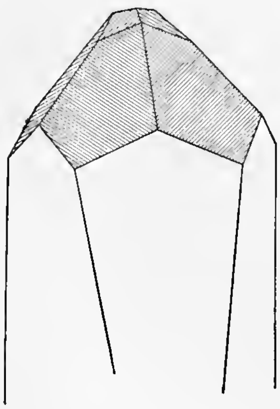

FIG. 29.—Calcite crystal of third type, in ore of West Vulcan mine.

In some places the crystals are implanted directly upon a breccia of ore and jasper fragments. In other places they cover a layer of red ocher which is about one-half inch thick, lying upon the breccia and separating it from the calcite. Again, in still other places the crystals are implanted directly upon banded jaspilite. Sometimes the jaspilite is replaced by pyrite forming a finely granular mass in which the original bedding lines can still be detected, and the calcite crystals are attached to this.

Pyrite and chalcopyrite.—In many instances the calcite occurs alone on the walls of the water course, but frequently there are associated with it a large quantity of pyrite and some chalcopyrite. The pyrite appears on the whole to be older than the calcite, although the two minerals are in most cases so intimately associated that they must have been deposited nearly simultaneously. The chalcopyrite is also older than the calcite, but its age with respect to the pyrite is not known, as the two sulphides have not been seen together.

Both the sulphides also form coatings on the ore, ranging in thickness from a small fraction of an inch to an inch or more. The pyrite, moreover, occurs as isolated crystals implanted on the ore and embedded among the calcite crystals, and occasionally as separate grains disseminated through the jaspilite within a distance of an inch or more from the walls of cavities The coatings are in a few instances mammillary, but in most cases they are crystalline. When broken their inner portions, of course, appear massive, but their outer surfaces are made up of crystals, which in the pyrite are excellent combinations of the cube and octahedron, and in the chalcopyrite are combinations of tetrahedrons. The chalcopyrite crystals are rarely more than a few millimeters in diameter. Their faces are rough and many of them are built up by parallel growths of smaller individuals. The pyrite crystals are larger. Many measure 8 mm. on an edge. All are bright and their planes are well developed.

Other minerals in joint cracks.—The calcite, dolomite, siderite, and pyrite are found in druses so abundantly and in the ores and associated jaspilites at so many different places that they may safely be regarded as universal accompaniments of the ores. In addition to these minerals, there are often found covering the walls of joint cracks in the ores and jaspilites of the Chapin mine, according to Mr. Brewster, druses of feldspar and of rhodochrosite, and, occasionally in the slates associated with the ores, druses of manganite and barite. The joint surfaces of the slates taken from the Pewabic mine are also in rare instances covered with a thin coating of a soft, dark-green mineral that gives the blowpipe tests for chromium and water. It has been found in such small quantities that a satisfactory determination of its nature has not yet been possible. In the only specimen seen by the writer the mineral occurred as a thin, soft, flaky coating devoid of all traces of crystallization. It appeared more like a chromiferous chlorite than anything else.

Serpentine.—Serpentine, as has been stated, occurs almost universally in the ores, but usually in such small quantities as not to be noticeable in the hand specimen. Frequently, however, it can be detected as small gray or white particles scattered so uniformly through the ores as to give them a grayish tinge. It appears to be more plentiful in the lower than in the upper portions of the deposits. This fact, together with the further fact that in the Chapin mine the ore from the upper portions of the lenses is more porous than that from their lower portions, suggests that the mineral has been deposited by downward percolating waters and has accumulated near the impervious basements at the bottoms of the ore deposits. At some places in the Chapin, the West Vulcan, and other mines, the serpentine occurs in large masses within the ore and along water channels, sometimes alone and sometimes associated with calcite crystals. In many cases the walls of cavities are covered with calcite and their interiors filled, or partially filled, with serpentine, forming geodes with serpentine fillings. Rectangular masses of the mineral, almost ideally pure, have been seen by the writer which measure 5 inches along an edge. Undoubtedly much larger masses occur in the mines. The mineral is amorphous. It varies in color from dark pink to snow white, the darker varieties being more prevalent in cracks and fissures in the jaspilites and the white varieties in the geodes and along water courses lined by calcite. In some specimens of the darker varieties distinct and definite bedding lines may be noted.

The analysis by Mr. Brewster of a white, soapy variety from the Chapin ore places the identity of the material beyond question.

Analysis of minerals from the Chapin ore.

	Serpentine.		Talc.	
	Found.	Calculated for $H_4Mg_3Si_2O_9$.	Found.	Calculated for $H_2Mg_3Si_4O_{12}$.
SiO_2	42.99	43.48	61.91	63.49
Al_2O_3	1.18		1.06	
Fe_2O_3	1.40		.39	
Mn_2O_3	.30		.14	
CaO			Tr.	
MgO	39.84	43.48	32.52	31.75
H_2O	14.08	13.04	4.39	4.76
Total	99.79	100.00	100.41	100.00

Talc.—Another white mineral coating slickensided surfaces in the jaspilites and the underlying slates, and filling crevices in the latter, differs from the serpentine in being softer, having a greasy feel, and in having an obscurely flaky structure. Its specific gravity is 2.72. From Mr. Brewster's analysis given above, this mineral is seen to be talc. It appears to be less abundant in the ores than the serpentine, but is very common in the slates underlying them. Flat pieces measuring three-fourths of an inch in thickness and 3 or 4 inches in length and breadth have been picked from the dump heaps of some of the mines, but in no case were any substances attached to the specimens that would help to discover the paragenesis of the mineral. In every case the specimen seemed to have come from a crevice.

Since talc and serpentine are found so frequently along slickensides in the dolomite, and since great deposits of them occur also in the contact between this rock and the overlying Vulcan beds where slipping between the two series has taken place, the inference seems to be warranted that the magnesia of these minerals was derived from the dolomite and that the silicates were deposited by percolating water. The lime of the original rock was carried farther and was deposited in the pores and open spaces of the ores as calcite.

Efflorescence on ores.—Whenever the ores are exposed to the weather in stock piles or the associated ferruginous slates are left exposed in dump heaps for any considerable length of time (six months or more), they become coated with a white efflorescence. In wet weather this washes off, but it accumulates again in dry weather, and on large specimens the thickness of the coating increases with the duration of the dry spell. Mr. Brewster has also analyzed this material with the following result:

Analysis of efflorescence on the ores.

	Found.	Gypsum.	$MgSO_4+H_2O$	Residue.	Residue, exclusive of water.	Calc. for Na_2SO_4.
CaO	0.74	0.74				
MgO	.79		0.79			
K_2O	.24			0.24	0.26	43.7
Na_2O	40.58			40.58	44.02	
SO_3	54.01	1.06	1.58	51.37	55.72	56.3
H_2O	3.05	.48	.36	2.21		
Total	99.41	2.28	2.73	94.40	100.00	100.00

In the course of the analysis the material was washed from the ore and dried. The determination of the water does not, therefore, represent the water content of the original mineral, but simply the quantity of water left in it after solution and desiccation. The principal mineral in the coating is probably mirabilite ($Na_2SO_4+10H_2O$), which is known to become dehydrated upon heating or upon exposure to the air. Its genesis is probably as follows: The pyrite in the ores when exposed to the air and rain becomes oxidized and produces sulphuric acid. This acts on the muscovite or traces of other sodium-bearing minerals (see analysis of the ores, p. 384) always accompanying the ores, yielding Na_2SO_4, which is dissolved in the rain water. This solution is then drawn to the drying surfaces of the individual lumps by capillarity. The water escapes by evaporation, leaving the sulphate as an efflorescence which, on further drying, becomes anhydrous. The dolomite in the ore is also dissolved in the sulphuric acid, yielding calcium and magnesium sulphates, which are likewise drawn to the drying surfaces, where they become intermingled with the sodium sulphates. These sulphates, however, are less soluble than the sodium salt and hence are always present in the efflorescence in smaller quantity.

THE ORE DEPOSITS.

DISTRIBUTION AND SHAPES.

The ore deposits of the Menominee district occur in the two iron-bearing members of the Vulcan formation: (1) The Traders, and (2) the Curry. The ores may occur at any horizon within these members, but other conditions being equal they are more likely to occur at lower and higher horizons than at middle horizons. However, a number of the large ore bodies extend entirely across the members in which they occur.

It has been stated repeatedly in the preceding pages, and the reasons for the statement will be discussed in the following section, that the ores are largely water-deposited material, consisting in part of mechanical sediments and in part of chemical sediments. The enrichment of the ores, which was necessary to make them sufficiently ferruginous to be mined with profit, was almost exclusively a chemical process. Ferriferous solutions penetrated the rocks along every crevice, depositing hematite and, as will be seen later, removing silica. Therefore the richer ores are found in situations where the attitudes of the rocks are such as to furnish converging channels for percolating waters, and the largest deposits are in the main channels toward which the drainage converges. Consequently, the deposits of large size rest upon relatively impervious foundations, which are in such positions as to constitute pitching troughs. A pitching trough may be made (*a*) by the dolomite formation underlying the Traders member of the Vulcan formation, (*b*) by a slate constituting the lower part of the Traders member, and (*c*) by the Brier slate between the Traders and Curry members. The dolomite formation is especially likely to furnish an impervious basement where its upper horizon has been transformed into a talc-schist, as a consequence of folding and shearing between the formations.

While all the largest iron-ore bodies are confined to the pitching troughs with impervious basements of dolomite or slate, smaller ore deposits occur at contacts between the different members and at places within the iron-bearing members where severe brecciation has occurred. The contacts between adjacent formations are favorable places for the concentration of ore, because they are horizons along which important slipping or differential movement has occurred during the folding of the district. Wherever a set of beds is folded there must be differential movement among the layers.

This is well illustrated by the slipping of the leaves of a flexible book over one another when the book is bent. In nature the contact planes between formations of different characters are always planes of weakness, hence at such places the major movements take place. These movements are sure to make the formations porous and thus produce main channels for percolating water, hence the frequent presence of ore bodies at the contact planes. Small ore deposits are found where faulting has occurred or where close plication has brecciated the formations, because the movements that result in these phenomena produce zones or areas where percolating waters are converged into trunk channels and thus favor the concentration of the iron oxide.

The combination of two or all of these conditions is more favorable than any one of them for the deposition of large ore bodies. Where the conditions are such as to combine pitching troughs with impervious basements, contact planes between formations, and faulting or brecciation, ore deposits of the first magnitude may be expected. Such are the conditions at the great mines in the district. However, in the search for an ore deposit, the first of the favorable conditions—a pitching trough with an impervious basement—is the dominant consideration. It can not be too strongly insisted that the essential condition for the development of a large iron-ore body in the Menominee district as well as in the other districts of the Lake Superior region is the production in some way of a pitching trough which is relatively impervious. Where the pitching, impervious troughs are large and continuous, as at the Chapin, Pewabic, and Aragon mines (see figs. 30, 32, 34, 35, 40, 44, 46, and 47), the ore deposits are almost sure to be large. Where the pitching troughs are small, irregular, or broken, the ore deposits are likely to be small.

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 follow along the limbs of the trough to a much higher altitude than in the center of the trough. The ore bodies in cross sections thus frequently constitute a U, which is very thick at the bottom, the center of the U being occupied by the iron formation which has not been transformed to ore (see plats of Aragon mine, figs. 39, 40). 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 limit, where not at the surface, more or less irregular in shape in consequence of the gradual passage of the ore into jaspilite. The Chapin deposits are good illustrations of such lenses. The deposits formed at contacts are usually much more irregular than those formed in troughs. In general, they are broad and thin, or sheet-like masses with irregular boundaries on all sides. Their lower surfaces are the most even and the best defined, but even these are undulatory. For the most part they remain near the contact of the iron-bearing formation with the underlying one, 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. They are not only undulatory to a greater degree, but ore projections extend upward into the overlying jaspilites, and, ramifying through these in an extremely irregular manner, often coalesce and inclose lenses of jaspilite and then continue their separate courses until the contact with the overlying slates is reached, where they again coalesce, spread out, and form a second sheet-like expansion, which, however, is usually much thinner and much less extensive than the deposit at the lower contact. In other words, the shapes of the contact deposits correspond to the shapes of channels that would be occupied by percolating water descending to lower levels mainly along the lower contact plane, but also through any openings that might offer themselves in the course of its downward passage. Where openings across the formation offered easier passages than that along the contact plane, the water, or some of it, naturally utilized these and followed them until they were intersected by other openings offering a channel with a more nearly vertical descent, when it left the former channel and continued its course in the latter one. Since the upper contact of the formation with the overlying slates is apt to offer a channel similar to that at the lower contact, we find that here also the water spread out and deposited sheet-like masses of ore like that at the lower level, but smaller. Deposits of this kind occur principally in the straight portions of the formation, 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 (see figs. 46 and 51).

DEVELOPMENT OF THE DEPOSITS.

From the foregoing statements of facts concerning the distribution, methods of occurrence, and situations of the ore deposits, it must be evident that the ores of the Menominee district, like those of the Gogebic and Marquette districts, were concentrated by waters moving along in definite, if not always circumscribed, channels. Van Hise,[a] in his discussion of the principles controlling the deposition of ores, classified ore deposits produced by underground waters into three main classes: (1) Ores which at the place of precipitation are deposited by ascending waters alone; (2) ores which at the place of precipitation are deposited by descending waters alone; and (3) ores which receive a first concentration by ascending waters and a second concentration by descending waters. The ores of the Menominee district, like those of the other Lake Superior iron-ore districts, belong to the second class. The principal deposits are above an impervious basement, this impervious basement is in a pitching trough, and the ore formation in the pitching trough is often much broken. Smaller deposits occur without pitching troughs at contacts, fault planes, and at sharp folds, where the iron formation is fractured.

These relations of the ore deposits to the troughs (see sections and plans of mines) are such as to show clearly that the iron ores must have been deposited in their present position after the troughs were formed. No igneous or sedimentary rock as originally produced has such forms as those exhibited by most of the ore bodies. These clearly are not altogether original sedimentary rocks, such as the iron-bearing formation as a whole is, but they grade into the other rocks of the Vulcan formation. The ore bodies clearly are not igneous rocks. No igneous rocks ever grade by imperceptible stages into sedimentary rocks, such as the various members of the iron-bearing formation are. If the iron ores were deposited in their present position after the troughs were formed, as the foregoing facts seem to show beyond question, they must have been produced by the work of underground circulating waters. Further, the positions of the principal deposits in pitching troughs bottomed by impervious basements rather than in pitching arches topped by impervious covers are conclusive evidence that the ores were concentrated by

[a] Van Hise, C. R., Some principles controlling the deposition of ores: Trans. Am. Inst. Min. Eng., vol. 30, 1900, pp. 173-174.

descending rather than by ascending water. Descending waters would be converged by pitching troughs with impervious basements, whereas ascending waters would be converged in pitching arches having impervious roofs. In this connection it is also to be noted that the ores are almost exclusively hematite; that is, they belong to the class of oxidized ores. The products therefore accumulated under conditions favorable to oxidation and, if secondary concentrates, they must have been precipitated by water bearing oxygen. Such waters are usually descending, hence the character of the deposits makes it probable that the waters producing the ores were descending rather than ascending. The nature of the minerals associated with the ores is also corroborative evidence that the deposits were made by circulating water, and the fact that these associated minerals are apparently more abundant in the lower portions of the deposits than in the upper portions (p. 389) might be urged as indicating that the waters were descending, or at any rate that the ore deposits lie in the courses of waters descending at the present time. Since there has been no appreciable deformation of the district since the deposits were formed, it is probable that the circulation of earlier times followed the same courses as the present circulation.

That the ores of the Menominee district were concentrated and enriched by descending waters seems to be proved beyond question. From the nature of the ores and the character of their environment it is practically certain that the Menominee deposits were produced in the same manner and by the same processes as those of the Gogebic, the Mesabi, and the Marquette districts. But in the Menominee district the folding has been so close and the protection afforded to the original material which gave rise to the ores has been so scanty[a] that these processes have been carried to completion, so far as the surface and the depths open to our inspection are concerned, and the steps along which they have proceeded have been so thoroughly obliterated that they can not be followed with the same certainty as in the other three districts mentioned. The process of concentration has been so fully discussed by Van Hise[b] in the reports on the Gogebic and

[a] Compare Van Hise, C. R., and Bayley, W. S. (with H. L. Smyth), The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, p. 381.

[b] Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 534. Van Hise, C. R., and Bayley, W. S. (with H. L. Smyth), The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 608. With atlas of 39 plates.

the Marquette districts, and by Leith[a] in the report on the Mesabi district, that little can be added to the explanations there given. These explanations apply as well to the Menominee district as to the other iron-ore districts of the Lake Superior region, and therefore they are drawn upon freely in the following pages.

The greatest apparent difference between the deposits of the Menominee and the other districts is the comparatively large quantity of clastic ore in the former. In addition to this fragmental ore, a large portion of the iron of the ore bodies in the Menominee district was deposited in its present position as an original sediment, containing silica and other impurities, which has since been chemically changed; that is to say, some of it was deposited as iron carbonate or as greenalite, and later transformed to iron oxide in situ. Another part is iron oxide secondarily deposited, by which the originally lean material has been enriched, forming an ore body. The process of enrichment involved concentration of the iron from a source capable of yielding it, convergence of solutions carrying it into trunk channels, and conditions favorable to its chemical precipitation. The source of the iron for the enrichment of the ores is believed to have been partly iron carbonate and partly greenalite. In spite of the fact that the iron-bearing members of the Vulcan formation are largely fragmental and contain no residual iron carbonate or greenalite, it is probable that originally mingled with their material were large quantities of these compounds. The jaspilites, which constitute a considerable portion of the formation, have elsewhere in the Lake Superior region been genetically connected with iron-bearing carbonates and silicates, and there is every reason for believing that they have had a similar origin in the Menominee district. The ferriferous compounds within the Vulcan formation were originally, therefore, probably somewhat abundant. If this is so, the concentration of the ores at the particular places where they now occur may be fully explained. However, we are not restricted to the iron compounds of this formation as a source of the iron for the solutions. The Hanbury slate still contains a considerable amount of iron carbonate, from which there have been developed within the slates small bodies of chert, jasper, and iron ore (see p. 480). While no workable ore deposits have been found in the Hanbury slate in this district the siderite there present may have played an important rôle in the production of the iron-ore deposits in the

[a] Op. cit., p. 316.

Vulcan formation. These iron carbonates are more abundant at low horizons than at high horizons; that is, are more plentiful adjacent to the Vulcan formation. The foregoing facts render it highly probable that percolating waters within the Hanbury formation took up iron carbonate, passed down into the Vulcan formation, and contributed iron-bearing solutions for the enrichment of the ore bodies.

The chemical reactions which resuited in the concentration and enrichment of the ores depend upon the mingling of waters containing oxygen with those containing iron carbonate.[a] The waters following circuitous routes, and especially those passing through the Hanbury slate, had their oxygen abstracted by the iron carbonate in an early stage of their journey. In this way the limonite and hematite of the Hanbury slate developed (see p. 476 et seq.).

In the process of precipitation of these oxides carbon dioxide was liberated and dissolved in the descending waters. Thus carbonated waters freer from oxygen were produced, and these took up in solution more iron carbonate. Large quantities of these solutions were converged upon the sides or at the bottom of the pitching troughs, or in other places where there were trunk channels for water circulation. Water more directly from the surface, and especially that passing only through the Vulcan formation, which contained little iron carbonate, at least in the later stages of the process, retained its oxygen. The waters bearing iron carbonate and oxygen were thus commingled. The result was the precipitation of iron sesquioxide. Furthermore, the great quantity of downward-moving water, converged into the troughs, took silica into solution and transported it elsewhere, and thus abstracted this deleterious element, its place being taken by the deposited iron oxide.

It has been seen that the waters which carried iron carbonate to the ore deposits were carbonated. The precipitation of iron oxide from carbonate liberated more carbon dioxide, so that the waters were very heavily charged with carbonic acid, and consequently were particularly efficient solvents for the iron carbonate.

The iron oxide of an ore body thus consists in part of iron compounds originally deposited in situ and in part of iron brought in by underground waters. Which of the two constituents of the iron ore, the original material or that added by underground water, is on the average more

[a] Cf. Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 260–265.

abundant it is impossible to say. It is almost certain that in some cases the original detrital iron oxide is the more abundant, and in other cases that the material added by underground water is more abundant; but in all cases it may be said that were it not for the secondary enrichment by underground waters through the addition of iron oxide and the abstraction of silica the material would not be iron ore. The evidence of this lies in the fact that the ore bodies are universally confined to the places where underground waters have been converged into trunk channels. In order that this process should have produced the large ore bodies, it is necessary that it should have continued for a long period during progressive denudation. Many of the large ore bodies known in the district somewhere reach the surface. The secondary material now found near the surface must have been derived largely from the upper portions of the Vulcan formation and from the Hanbury formation, i. e., from material which was once at higher levels, but which since has been removed by erosion.

During the process of denudation the ore deposits must have begun to be formed shortly after the iron-bearing formation was cut through. For a time they increased in size, but it is probable that later the increase in size practically ceased, for when the oxidizing waters reached the limit of their working depth denudation must have removed the ores at the top as rapidly as they were formed beneath. However, with lowering of the upper surface there was a corresponding lowering of the inferior limit at which the waters worked, and a consequent continuous migration of the deposit downward pari passu with denudation. On account of the pitch of the basements in which the deposits were formed, lateral migration must have accompanied downward migration. We therefore must conceive of the iron-ore deposits as slowly migrating downward through thousands of feet, their lower surfaces at any given time being just in advance of the plane of erosion. As denudation proceeded a part of the ores must have been carried away mechanically and thus lost. Another, but probably a relatively small part, was doubtless taken into solution and carried downward, to be precipitated again at lower levels. However, as erosion extended downward and swept away the ore at the surface, the process of concentration also continued downward, so that the amount of ore existing at any one period through much of the pre-Glacial time was roughly constant, although there was doubtless considerable variation in its quantity depending upon topographic and climatic conditions during the different periods.

For that portion of an ore deposit which now reaches the surface or is overlain by completely altered cherts, it is probable that there is little addition in iron oxide at the present time; for it has already been explained that the iron oxide for an ore deposit is mainly derived from that part of the iron-bearing formation which has been removed by erosion. However, it does not follow that the enrichment of an ore deposit by the abstraction of silica has not effectively continued after practically all of the iron was added. Indeed, there is every reason to believe that the solution of silica has continued to the present time, and, moreover, this process has probably been more effective in those parts of an ore deposit near the surface; for there the waters have been longest at work in abstracting the silica. It is a well-known fact that in many mines there is a tendency for the silica to run somewhat lower in the upper than in the lower levels of the deposits, and this is readily explained by the greater depletion of silica in the upper than in the lower parts of deposits. Also many of the ore deposits have a broken and porous character, and appear to have sagged, as if some compound or compounds had been abstracted. The material abstracted was doubtless mainly silica. Moreover, as has been indicated in a preceding page (p. 389), silicates appear in some cases to have been leached from the upper portions of the deposits, if not also deposited in lower portions. It is probable that some of the porosity referred to above is due to the abstraction of serpentine and talc, although the cavities which these substances occupied may have been formed originally by the removal of silica The tendency of the abstraction of these two minerals would be to diminish the contents of magnesia, silica, and water in the ore, and, as a consequence of this diminution, to increase the percentage of iron.

Furthermore, the ore deposits seem to have been made more valuable by the abstraction of phosphorus and sulphur compounds by descending waters in a way similar to the abstraction of silica and silicates. The most notable published cases illustrating this process are those of the Ludington mines, described by Browne (see p. 89), and of the Pewabic and Aragon mines, described by Brown[a] and Larsson,[b] where the deposits near the surface are low phosphorus and those deeper down are high phosphorus ores. In general the phosphorus seems to be low where the iron is high and the ore

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[a] Brown, E. F., Distribution of phosphorus and system of sampling at the Pewabic mine: Proc. Lake Superior Min. Inst., vol. 3, 1895, p, 49.

[b] Larsson, Per, ibid., p. 55.

porous, and therefore where the water circulation was very effective. The same is true of sulphur, but to a much less noticeable extent, because of the very slight quantity of this element in the ores of the district. The formation of sodium sulphate as an efflorescence on the ores exposed in stock piles indicates that the sulphur is oxidized under the influence of meteoric waters and forms a soluble salt, which naturally must be carried off by moving water. The oxidizing waters that gain access to the ore deposits should produce similar effects, and, as a consequence, the ore should be rendered more valuable thereby. It is a well-substantiated fact that iron ores which have been exposed to the atmospheric agencies for a considerable lapse of time lose both phosphorus and sulphur.

In conclusion we may therefore say that the chemical processes have tended to make the ore deposits more valuable at the present time, although the additions of iron may have long since ceased.

TOPOGRAPHIC RELATIONS OF THE DEPOSITS.

In order to produce great masses of ore, such as some of those characterizing the Menominee district, the water circulation must have been long continued. The volume of water which circulated through the ore deposits must have been many thousand times, probably hundreds of thousands of times, as great as the volume of ore. It is certain that as depth increases the rocks in the earth's crust become more and more compact, until finally the zone of rock flowage is reached, into which the water can not be assumed to pass. We therefore must conclude that water converged into trunk channels must again reach the surface. Hence we find that the majority of the ore deposits where they approach the surface are on the slopes of the elevations, the crests being usually occupied by the Randville dolomite or the Cambrian sandstone. This is true for all of the important mines of the district with the exception of the Chapin, the Aragon, and the Loretto. However, each of these deposits is so connected with troughs which rise toward the higher grounds as to make it almost certain that they had elevated feeding areas. Moreover, while the Chapin deposit was discovered in low-lying ground, a little way to the west is the broad valley of the Menominee River, which is still lower. Probably, therefore, there were lower areas where the water issued. However, it is possible that in the subordinate cross valley at the Chapin mine descending oxidizing waters met ascending carbonate-bearing waters, and thus precipitated a part of this deposit.

The crests of the elevations above the Ludington, Millie, Walpole, and Pewabic mines rise to 1,500 or 1,600 feet above sea level. The broad valley of the Menominee to the west has an elevation of about 1,060 feet, and this valley is probably filled to the depth of 100 feet or more. Between Prospect Hill and Hughitt Bluff is a subordinate cross valley. In this valley is the Chapin mine, the surface of which has an elevation of only about 1,150 feet, or not more than 90 feet above the valley of the Menominee River; but if the valley of the river is filled to a depth of 100 feet by sand and gravel the elevation of the present surface at the Chapin mine is 190 feet above the rock floor under the river channel.

With respect to the other mines of the district the relation between the topography and the ore deposits is in strict accord with the theory that the ores are the result of the action of descending waters; although in this district this relation does not corroborate the theory as effectually as it does in some of the other districts. While it is true that nearly all the ore deposits of the Menominee district thus far discovered are on hillsides, nevertheless it is also true that the iron formation is nowhere at low levels except in the vicinity of the Chapin, Aragon, and Loretto mines, as before mentioned. The great dolomite constitutes the dominant factor in determining the positions of the elevations. The iron formation lies immediately upon this, and consequently must of necessity be on the slopes of hills, and, since the ore deposits are in this formation, these, too, must be on hill slopes. The principal value of the discussion of the relation between the topography of the Menominee district and its ore deposits is to show that this district offers no important exceptions to the generalization that the iron-ore deposits of the Lake Superior region are usually situated below slopes or crests.

East of Iron Mountain it is notable that adjacent to each of the localities where important mines are found there are valleys across the south limestone range and the Vulcan formation, although these valleys are now partly filled with thick deposits of drift. East of the Quinnesec mine is the low-lying area now partly occupied by the road running north. Northeast of Norway is another transverse depression. The Norway mine is located on the hill to the northwest. The West Vulcan mine is located on Brier Hill, to the northeast. The Aragon mine is in the depression. East of the East Vulcan and Verona mines is the valley of the Sturgeon River.

The Breen mine is on a slope with a cross valley immediately to the west. The Loretto mine pitches directly below the valley of the Sturgeon River. Adjacent to the central range of dolomite the most important deposit is the Traders. This mine is on the westward slope of a hill which rises to an elevation of 1,500 feet. The ore deposit pitches toward the valley of the Menominee only a short distance to the west.

Thus it appears that nearly all of the large ore deposits in the Menominee district are either related to the topography in the same manner as are the deposits in the other Lake Superior iron-ore producing districts, or that their relations are such as can be explained on the supposition that before the district was denuded by erosion agencies they were surrounded by elevations greater than those at which the surfaces of the deposits then lay.

TIME AND DEPTH OF CONCENTRATION.

The beginning of the final concentration of the Menominee ores must have been after the folding which produced the troughs and after the removal of the Hanbury formation covering the Vulcan formation—that is, in the interval between the Upper Huronian and the Upper Cambrian. In this district it is certain that the process of concentration was carried far toward completion before the end of Cambrian time, for considerable areas of the Huronian rocks and certain of the ore bodies themselves, as, for instance, parts of those of the Traders, Cuff, Chapin, Pewabic, Walpole, Quinnesec, Norway, Cyclops, Breen, Emmett, and other mines, are capped by the Upper Cambrian sandstone, at the base of which are detrital ores derived from the ore deposits below during the Cambrian transgression over the area. It is therefore highly probable that the main concentration of the iron ore of the deposits of the Menominee district took place before the end of the Cambrian period, although since that time there probably has been additional enrichment, mainly by the solution of silica, magnesia, phosphorus, and sulphur, and the deposition of some iron oxide.[a]

[a] A large portion of the above discussion of the development of the ores and their relations to the topography, as well as the statement as to the time and depth of concentration, is taken almost verbatim from Van Hise's paper on the iron-ore deposits of Lake Superior, "The iron-ore deposits of the Lake Superior region:" Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 323–332, 396–400.

ILLUSTRATIONS OF DEPOSITS, INCLUDING GEOLOGY OF THE IMPORTANT MINES.

The ore deposits now being exploited and those that have been worked in the past are confined to three belts:

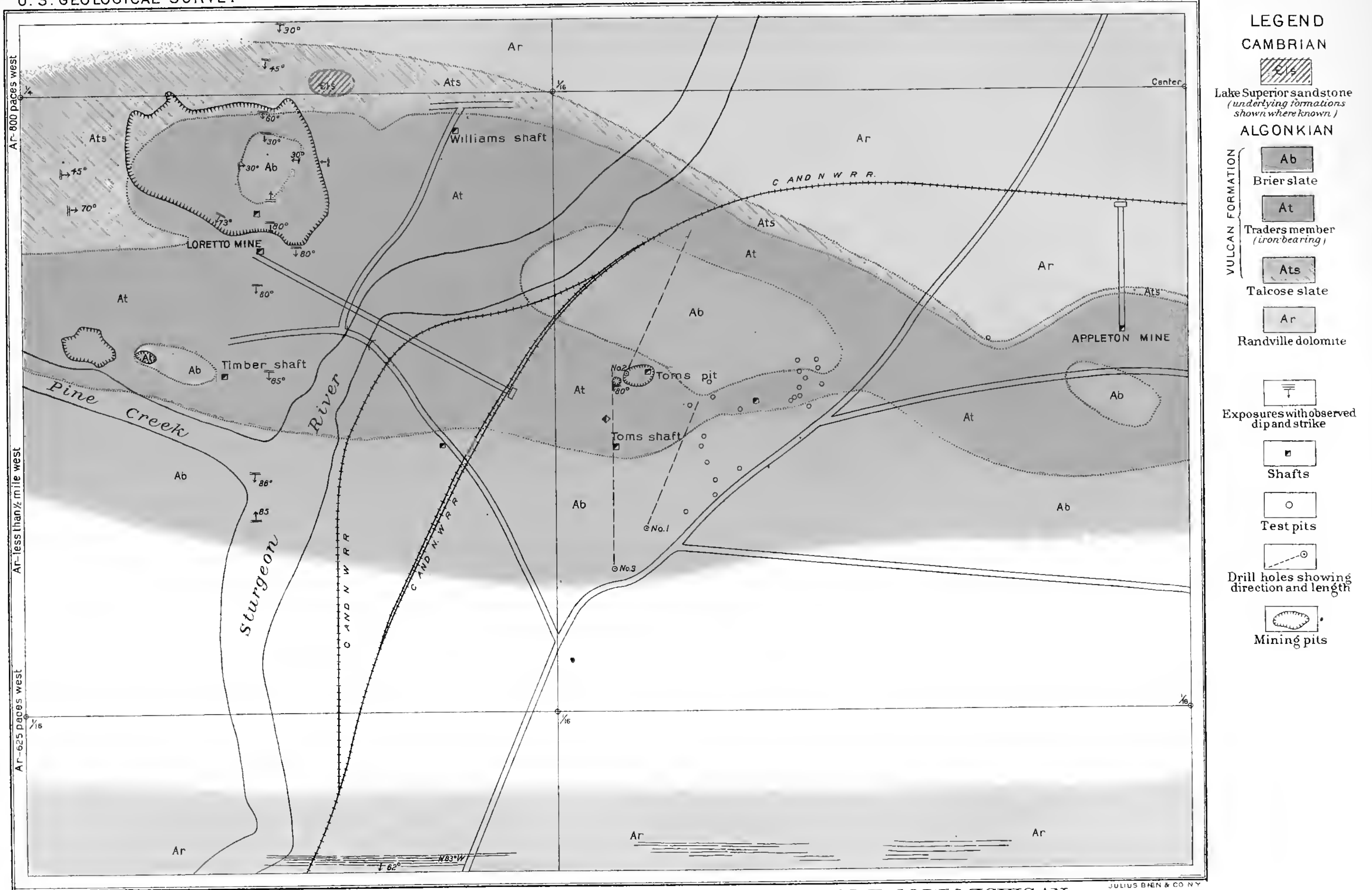
(1) The Loretto-Appleton belt, east of the locality where the northern and southern belts of dolomite unite, or, at least, where they approach very near to one another.

(2) The Traders, Cuff, Cornell, Indiana, and Forest belt, mainly south and west of the central dolomite belt, and possibly also in one case north of it.

(3) The belt extending from the Menominee River on the west to Waucedah on the east, lying on the south flank of the southern belt of dolomite. On this belt are situated the Ludington, Chapin, Walpole, Pewabic, Keel Ridge, Vivian, Quinnesec, Cundy, Norway, Perkins, Cyclops, Aragon, Brier Hill, Curry, West Vulcan, Central Vulcan, East Vulcan, Verona, Breen, and Emmett mines, besides many as yet unnamed explorations to the west of Iron Mountain.

LORETTO-APPLETON DEPOSIT.

The Loretto-Appleton deposit, more particularly that portion being exploited by the Loretto mine, furnishes one of the most typically developed trough deposits to be found in the district. West of the Loretto mine the northern and central belts of dolomite probably join (see maps, Pls. IX and XXIII), giving continuous dolomite from the Sturgeon quartzite on the north to the southern iron-bearing belt on the south, or, at any rate, if not at the surface, the dolomite bridges this interval a short distance beneath the surface, the surface rocks in this case being a thin layer of the lowermost beds of the Traders member of the Vulcan formation. East of this bridge of dolomite, between the northern and southern belts of dolomite, is the iron-bearing Vulcan formation. To the west of the bridge are possibly the iron-bearing Vulcan formation and certainly the Hanbury slates. It is therefore clear that a cross anticline here exists which brings to or near the surface the dolomite that to the east and west is buried beneath the younger rocks. Hence it follows that the major structure adjacent to the Loretto mine is that of an eastward-plunging syncline, the dolomite being to the north, to the south, and to the west. From an inspection of the surface map of the mines it will be seen that this syncline is widest to the west and is here



HYPOTHETIC GEOLOGIC MAP OF PORTION OF SE. ¼ SEC. 7, T. 39 N., R. 28 W., MICHIGAN

LORETTO AND APPLETON MINES

PREPARED FROM RECORDS OF PITS, MINE WORKINGS, AND DRILL HOLES

BY W S BAYLEY

1903

Scale

100 50 0 100 200 300 400 600 feet

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composed of a northern subordinate syncline, separated from a southern monocline (see cross section, fig. 30) by a narrow, compressed anticline. These folds pass to the east into what appears to be a simple syncline, which continues at least as far as the Appleton mine. The rocks involved in the folds are the Randville dolomite, the Traders quartzites and jaspilites, and

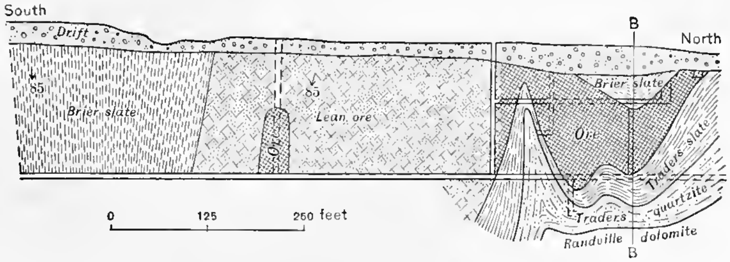


Fig. 30.—Vertical north-south cross section of the Loretto mine. (Section A–A in fig. 31.)

the Brier slates. The dolomite nowhere reaches the surface, but it is found in drill holes under the jaspilites at several points. The Brier slates occur in three small areas, capping the jaspilites along the axis of the syncline. Thus in longitudinal section there are three synclines and two anticlines from the west side of the Loretto mine to the east side of the Appleton property.

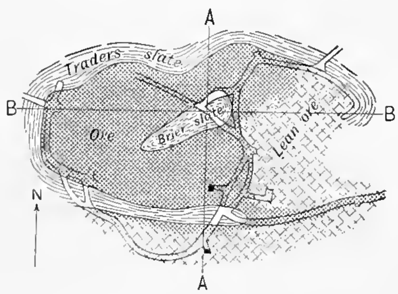


Fig. 31.—Horizontal section of the Loretto mine at the first level. Scale: 1 inch=250 feet.

The principal surface rocks within the boundaries of the syncline are the Traders jaspilites. These are bounded on the north by the Traders quartzites, and the same rocks may occur at the surface at the crest of the first anticline west of the Loretto mine. No exposures of the quartzite are to be found here, but the eastern workings of the Loretto mine show that it approaches very close to the surface, and that a short distance farther east it may actually reach the surface. The structure of the area, if the inferences above outlined are correct, is that of an east-west fairly compressed syncline to the north, passing into an anticline to the south, and followed farther south by another syncline, the south portion of which has not been seen. These folds are moreover affected by three cross (north-south) synclines, separated by two anticlines, all of which are open.

The character of the fold in which the main Loretto deposit occurs is beautifully shown by the horizontal outline of the ore body (see fig. 31). The outer limit of the ore makes a broad U which opens to the east; the bottom of the U being to the west. The cross section of the main ore deposit also makes a wide U, the southern limb of which passes into a sharp subordinate anticline (fig. 30). In the center of the syncline slate caps the ore. Moreover, the longitudinal section of the mine is also a syncline (fig. 32) likewise capped by the slate. East of the slate capping is lean ore-bearing material, which passes into ore under the slate and under the drift west of the slate. The failure of the rock to change to ore east of the slate is apparently due to the cross anticline, which has prevented the convergence of downward-moving currents of water, and therefore the transformation of the rock into ore. No better illustration of an ore body in a trough on an impervious basement could be desired than that furnished by this deposit.

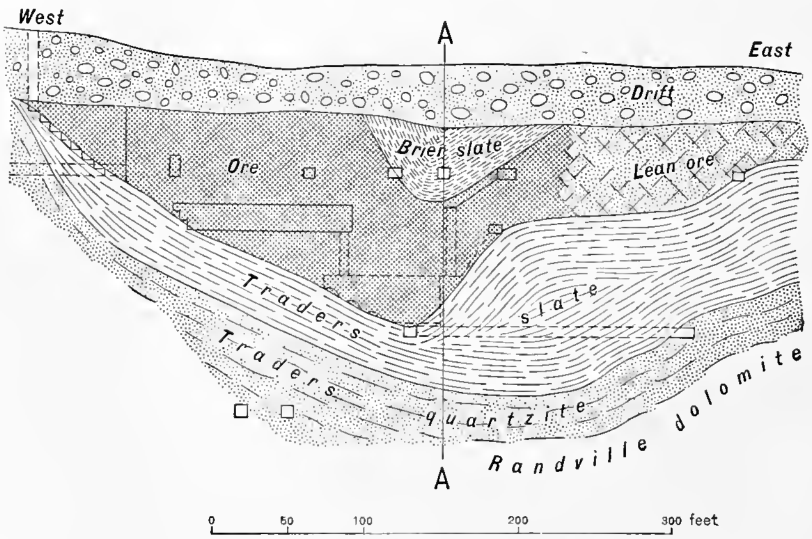
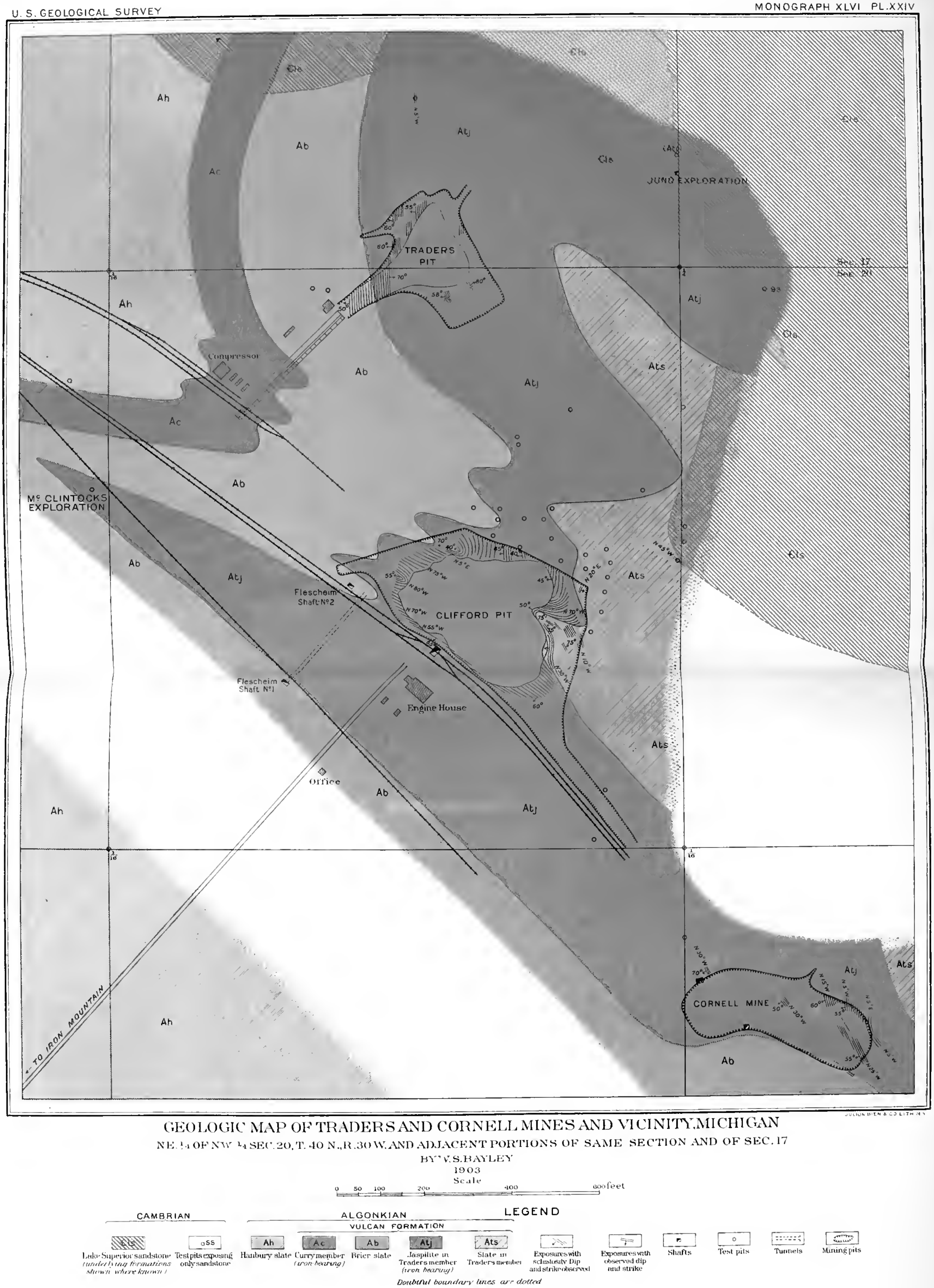


Fig. 32.—Vertical east-west longitudinal section of the Loretto mine. (Section B-B in fig. 31.)

The southernmost deposit of the Loretto mine and the deposit in the Appleton mine had not been sufficiently developed to warrant statements as to their relations to folds. If the slate south of the south deposit of the Loretto mine is Brier, as is supposed, this deposit may be a contact deposit at a little greater depth than has yet been reached. The slate dips slightly to the north at its contact with the iron-bearing beds, producing a steep slope dipping toward the ore body, which slope must have served to some extent at least to direct descending water in this direction. At the Appleton mine the greater portion of the ore that has been taken out (12,102 tons between 1892 and 1895) was obtained from north of the shaft on or near the contact of the jaspilites with the underlying Traders slates.



GEOLOGIC MAP OF TRADERS AND CORNELL MINES AND VICINITY, MICHIGAN

NE. ¼ OF NW. ¼ SEC. 20, T. 40 N., R. 30 W. AND ADJACENT PORTIONS OF SAME SECTION AND OF SEC. 17

BY W. S. BAYLEY

1903

Scale

0 50 100 200 400 600 feet

JULIUS BIEN & CO. LITH. N.Y.

TRADERS-FOREST BELT.

The second belt of the Vulcan formation, that adjacent to the central belt of dolomite, is now being worked only at the Traders and the Forest mines at the two extremities of the belt. Formerly the Cornell, the Cuff, and the Indiana mines were also in operation. The Cornell mine ceased shipment in 1887, having mined 49,302 tons of ore, and the Indiana ceased work in 1886, having raised 17,871 tons. The Cuff shipped 20,210 tons in 1899. At the Forest mine exploration has not proceeded far enough to warrant a definite statement as to the character of the deposit.

TRADERS MINE.

The Traders mine is at the west end of the Traders-Forest ore-bearing belt, which in this vicinity constitutes a westward-plunging anticlinorium On the mine property are two pits—a northern one, known as the Traders pit, and a southern one, known as the Clifford pit (see map, Pl. XXIV). Southeast of the Clifford pit and distant about 800 feet is the abandoned pit of the old Cornell mine. The formation exposed in both of the Traders pits is the same in character. It consists of a sheared jasper and ore breccia overlain by a red slate and underlain at the Clifford pit by a ferruginous slate. At the Traders pit the ore formation strikes nearly north and dips at 55° to 60° to the west. The rock is jointed and schistose. On the west side of the pit schistosity and bedding are approximately parallel, but on the east side the strike of the schistosity varies from N. 10° W. to N. 25° W., and its dip from 50° W. to 80° NE. The jointing is inclined to the schistosity and also to the bedding. At the northwest corner of the pit the joints strike N. 30° W. and dip 75° W. At the southeast corner their strike is N. 45° W. and their dip 25° NE. Where the schistosity and jointing are inclined to the bedding the latter feature is exceedingly obscure. The variation in the directions of the schistosity and of the joints is evidence that folds of some kind exist here, though they have not been detected, and these may be connected in some way with the occurrence of the ore. No shipments are now being made from this pit, nor is any development work being done. The ore deposit is therefore not thought to be promising under the present conditions of the ore market. The contact of ore beds with the overlying Brier slates is plainly seen on the walls of the pit at the southwest corner. Beyond this to the west are two pits in red slates, and about 200 feet farther west is a third pit in jaspilites that may belong in the Curry member. Northwest of the pit is an old shaft, on the dump of which are fragments of red sandstone and of gray sheared quartzite. It is probable that this is a quartzose bed in the Hanbury formation; but since quartzites are found also in the Traders formation, not much confidence can be placed in this identification. If the rock is a component of the Hanbury formation, the Traders beds must swing to the east.

Northeast of the Traders pit, at what is known as the Juno exploration, are two shafts that offer another problem. Here the rocks on the dumps are sandstone and an abundance of an evenly banded jaspilite quite unlike the brecciated rock of the Traders and Clifford pits. Some of the jasper is of the flinty or waxy kind, characteristic of the typical jaspers. In other specimens, however, the siliceous component is a gray quartzite or chert that resembles very closely some of the cherty phases of the Curry jasper. Two suggestions offer themselves in explanation of this occurrence—(1) the jaspilites may belong in the Curry member on the east side of an anticline and across its crest from the Traders pit, or (2) they may be Traders beds which have escaped the severe brecciation to which the beds in the Traders and Clifford pits have been subjected. The second suggestion seems to be the more plausible one because of the short distance intervening between these pits and the east end of the Traders pit. Even in this case the beds must be separated from those in the Traders pit by an anticline.

The only deposit at present being worked in this area is that of the Clifford pit. Here the iron-bearing rocks are the same as at the Traders pit (Pl. XXIV), with dark-gray and black Traders slates to the east and red weathered Brier slates to the west. The contact between the iron-bearing beds and the underlying slates is beautifully exposed on the east side of the pit, where it can easily be followed for 250 feet or more. The upper contact of the iron-bearing member with the Brier slates can also be traced on the stripped surface west of the pit. The mapping of these contacts shows conclusively that the rocks are plicated into several minor synclines and anticlines, and a study of the relations between the ore deposits and the folds show that the richest ore is in the synclines. The best ore at present being mined is taken from the northeast corner of the pit, where the syncline in the underlying slate is largest and most typically developed (see map, Pl. XXIV). The entire area occupied by the pit is ore producing, but the ore is everywhere richer along its eastern—i. e., lower—side than toward its western—i. e., upper—side. The pitch of the folds is approximately 50° NW. The greater richness of the Clifford ore as compared with that from the Traders pit is evidently due to the repeated folding of the ore-bearing beds in the former pit and the consequent production of several pitching synclines bottomed by the black slates.

In addition to being folded, the iron-bearing beds are deformed by jointing and schistosity, the latter structure being very closely related to the former. The schistosity strikes uniformly N. 75° to 80° W., and is therefore in some places parallel to the bedding and at other places transverse to it. Although all the joints strike approximately at right angles to the schistosity, there seem to be two sets with respect to dip. In one set the dip is about 50° to the northwest, and in the other 20° to the southeast. It has already been explained that the brecciated character of the ore beds in this pit is due to the causes that produced marked schistosity transverse to the bedding (see p. 302). It should be mentioned in addition to what has already been stated in this connection that the most conglomeratic-looking jaspilite layers are found on the north side of the pit, where schistosity and bedding are approximately perpendicular to one another.

The nature of the folding south of the Clifford pit and between this and the Cornell pit is not known, as there are no outcrops in this area and practically no explorations. A drift running about northeast from the bottom of the Fleischman shaft No. 1 (see map, Pl. XXIV) to a point under the railroad track alongside of the Traders pit was driven through ore-bearing beds throughout nearly its entire distance. At the shaft, however, a gray quartzite was encountered with the peculiarities of the quartzite at the base of the Traders member. No explanation of its occurrence at this place is hazarded. The rock may be a locally developed member of the Traders series. The wide expanse of the ore-bearing member revealed by the drift suggests its repetition by folding, and the occurrence of ore like the Clifford ore at the McClintock exploration, about 600 feet northwest of the shaft, suggests that at least one of the folds extends on the surface to this point. About 250 feet north of the McClintock exploration is a pit in graphitic slates identical with those at the bottom of the Hanbury slate south of the southern ore belt.

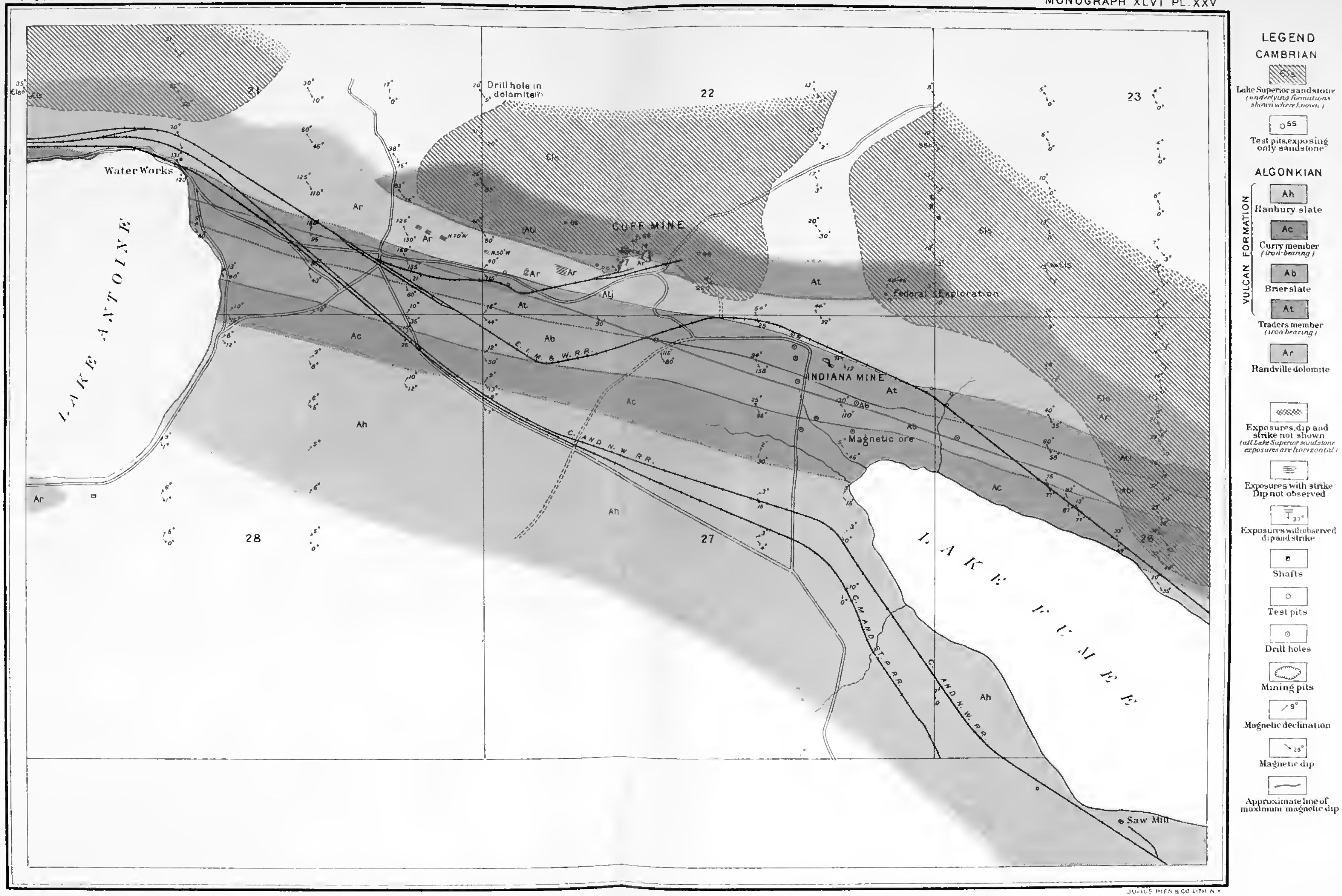
Nothing is known of the rocks in the intervening distance. The interval is scarcely wide enough for the occurrence in it of both the Brier slates and the Curry member with their normal thickness. Their thickness, however, might be much diminished on the sides of a close fold, such as must exist here if the southern pit is in Traders rocks, and both members may occur in the interval between the two pits. An alternative theory to explain the structure at this point suggests that the McClintock pit is really in Curry beds and that the similarity which exists between the rocks in this pit and those of the Clifford pit is due to the fact that in both instances they were subjected to the same kind of close folding and shearing.

CORNELL MINE.

The Cornell pit at present affords but little information as to the structure of the iron formation in its neighborhood. It has not been worked for more than ten years and its walls have in many places become covered with a talus of loose material. Enough can be seen of the rocks, however, to show that the ore-bearing beds are practically identical with those in the pits of the Traders mine, though they are not as completely brecciated as these. It is reported that a "conglomerate ore" exists to the north of the western shaft along a drift running north, and that red slates occur about 200 feet south of the bottom of this shaft in a drift running about south. In the northeast portion of the pit there are indications of the existence of folds in the ore-bearing beds (see Pl. XXIV). Near its northeast corner the strike of the jaspilites is in some places nearly north. Farther west the strike is N. 30° W. Somewhere between these points there must be a syncline pitching to the south, and in this the best ore would be expected to occur. As a matter of fact, the few thousand tons shipped from this mine are reported to have come from the northern part of the pit. There are also a few gentle corrugations visible in the jaspilites in this portion of the pit. They are significant only as indicating that the beds are involved in larger folds that are not visible. The minor corrugations are too open to have afforded distinct channels for percolating waters and so have not been efficient in determining the positions of ore deposits. The absence of more distinct folds in this place may account for the absence of a larger ore deposit.

CUFF MINE.

At the Cuff mine the exposures are not sufficiently abundant to disclose the presence of sharp folds if they exist in its vicinity (Pl. XXV). The ore-bearing rocks are very similar to those of the Traders and Cornell mines, but



GEOLOGIC MAP OF THE COUNTRY ADJACENT TO THE CUFF AND INDIANA MINES, MICHIGAN
SECS. 21, 22, 23, 26, 27, AND 28, T. 40 N., R. 30 W.
BY W. S. BAYLEY
1903
Scale
1000 500 0 1000 2000 3000 4000 feet

they are apparently less brecciated than these. In the open pit west of the shaft the strike of the jaspilites is N. 10° to 15° W., and their dip 40° N. (fig. 17). In the large pit east of the shaft the strike is the same except at the southeast corner, where it is N. 45° E. The dip in this pit is 25° N. East of this again is a small pit in red slates, believed to be at the base of the Traders formation, and east of this about 100 paces is a trench uncovering banded ore and cherts to the north and a brecciated ore, like that at the Clifford pit, to the south. Southwest of the shaft a number of openings have been made disclosing jaspilites and red slates with a wavy contact line between them that suggests the presence of minor folds.

At the surface just east of the shaft, at the southwest corner of the pit already referred to, is a white or light-gray dolomitic sandstone, covering a pinkish-gray, even-banded dolomite dipping 45° N. Within the mine there is also to the east of the shaft, according to the testimony of the former superintendent, Mr. Shephard, a "horse of white soapstone" which upon investigation proves to be a dolomite. This is on the first level. It does not reach the surface, the surface rocks above it being contorted jaspilites. The great northern displacement indicated by this occurrence of dolomite in the mine very strongly suggests the existence of a fold in this rock and also, of necessity, in the overlying jaspilites. The fold is not sharp and well defined, and consequently the ore is lean, containing from 36 to 40 per cent metallic iron.

In the pit to the east of the shaft the relation of the ore to the folding and crushing of the jaspilites is well exhibited on a small scale. The jaspilites exposed in this pit are generally flat lying, their dip being about 25° N. Toward the north side of the pit, however, the rocks are bent into a small monocline. Here they are crushed into breccias and here also the richest ore is developed. All the jaspilites in this pit are characterized by the green alteration product noted in connection with the brecciated ores of the Norway and other mines on the south belt (see pp. 375 and 386).

The pit lying about 650 feet west of the shaft encountered an evenly laminated ferruginous slate, or lean ore, devoid of jasper bands. It is placed in the Brier belt on purely petrographical grounds.

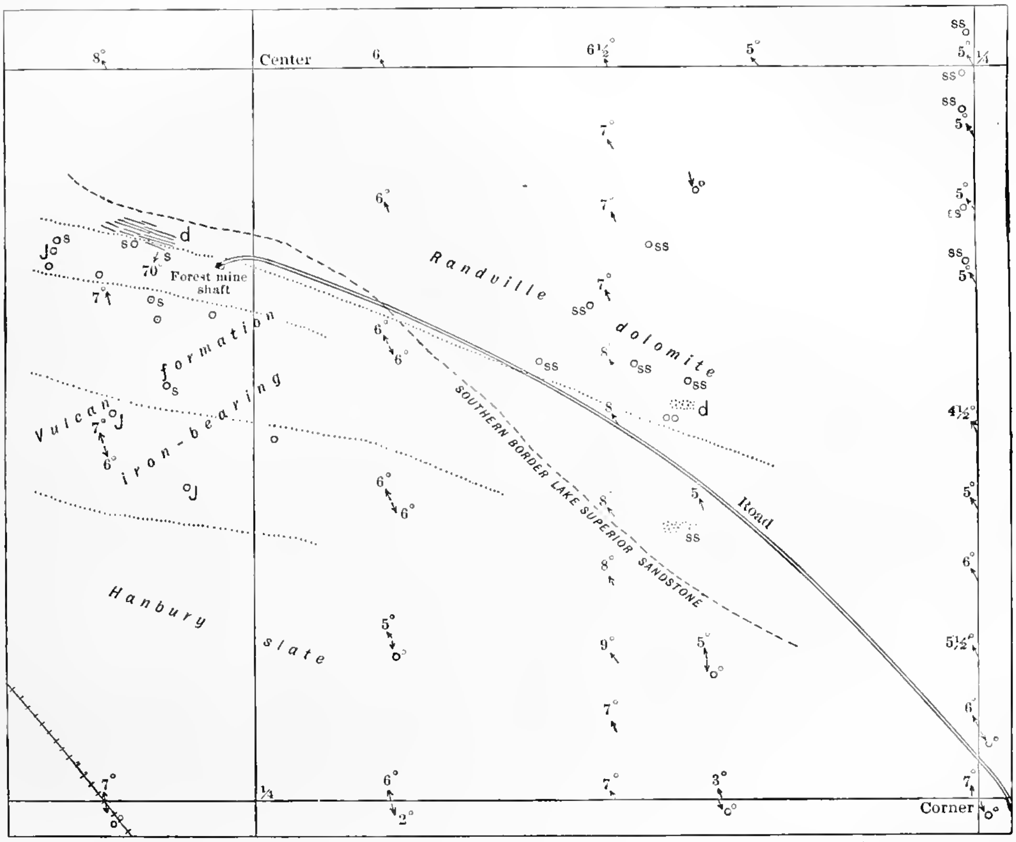
INDIANA MINE.

The geology of the environs of the Indiana mine is indicated on the map (Pl. XXV). The plats of the underground workings have not been seen. The results of drilling, however, give no indication of the presence of folds in the vicinity of the shaft, the output of which, as stated above, was only about 18,000 tons. The rocks on the dump are argillaceous Traders slates, even-banded jaspilites, brecciated jaspilites, and even-banded ferruginous slates that are probably Brier. In the little pit opened to the west of the shaft the argillaceous slates form a northern wall dipping south. Even-banded jaspilites are south of these, on the northwest and southeast sides of the pit. The dips vary slightly in different places, but no distinct folds were made out. The brecciated ores found in the dump are reported to occur between the banded jaspilites and the slates. Northwest of this pit and at a distance of only 350 or 400 feet is a ledge of dolomite with a strike that would carry the rock along the north edge of the excavation. Moreover, drill holes put down south of the mine and directed northward encountered dolomite after passing through Traders slates, jaspilites, and Brier slates in the inverse order from that mentioned. At the contact between the Traders slates and the dolomites the first-named rocks were everywhere brecciated. From these slight data it is thought probable that the Indiana deposit is a contact deposit, like that of some of the mines on the southern belt, but that it is one of small dimensions, because, as the drill holes indicate, the dip of the dolomite flattens out with increasing depth.

FOREST MINE.

In the neighborhood of the Forest mine the exposures of pre-Cambrian beds are likewise very few (fig. 33). The shaft is at the base of a hill which partially encircles it on the north and east. This hill is capped by the Lake Superior sandstone which, of course, completely hides the underlying rocks. At the base of this sandstone is a conglomerate varying in character at different places in such a way as to show that the dolomite and the jaspilites continue under it toward the east. In some places the basal layer contains numerous large fragments of the chert that often occurs at the top of the dolomite formation. At other places the principal fragments and the largest ones consist of ore or of jasper. While, therefore, it is almost certain that the two formations continue for some distance to the east of the mine, there is, nevertheless, no evidence to indicate how far they extend. A few hundred feet northwest from the mine shaft is a ledge of dolomite forming a little cliff to the south, faced by a veneering of sandstone conglomerate.

At the base of the cliff is a slate band dipping 70° S. This is exposed through a thickness of 7 or 8 feet, and is followed to the south by jaspilites. The sequence, so far as it has been worked out, is identical with that at the Indiana mine. The mine has not been opened up sufficiently to yield



o Test pits. ↖ Magnetic variation. ↘ Magnetic dip. ⊙ Drill holes. SS, Sandstone. S, Slate. J, Jaspilite. d, Randville dolomite.

Fig. 33.—Sketch map of exposures in south half of sec. 25, T. 40 N., R. 30 W.

important geological details. There is no evidence at present of the presence of a fold in the jaspilites to account for the ore deposit, but this is in the normal position of a contact deposit.

THE SOUTHERN BELT.

The third belt of ore deposits occurs along the south side of the southern dolomite belt, and extends from the Menominee River on the west to Waucedah on the east. It includes the most important mines in the district and all of the older ones that are still being worked. All the mines that are at present productive lie between Iron Mountain and the Sturgeon River.

It has already been explained that the southern belt of dolomite is an anticlinorium. Further, it has been pointed out that superimposed upon this major fold are folds of higher orders (see pp. 237–246). The occurrences of the ore deposits in the Vulcan formation south of this belt of dolomite are closely related to these subordinate folds. The folds of the second order superimposed upon the major fold are a series of very close plications, which, for the western part of the district, plunge steeply to the west. The result of these plications is to produce a number of westward-pitching synclinal troughs directly underlain by some phase of the dolomite formation or by the slates of the Traders member. As the result of this folding, the surface outcrop of the southern boundary of the dolomite has a notched-like distribution, producing bays in the dolomite. The iron-bearing formation occupies the bays which open out to the west into the main belt of the Vulcan formation, each bay being surrounded on the north, south, and east by the dolomite.

CHAPIN-PEWABIC DEPOSITS.

Beginning at the west, the first and most important set of folds of the second order are those adjacent to Iron Mountain. Here are two important folds, superimposed upon which are folds of the third order (Pl. XXVIII). The western one produces the troughs in which the Chapin, Millie, and Walpole mines are located (see Pl XXVI, *A* and *B*) and the eastern one the trough in which the Pewabic mine occurs. The western trough is especially complicated, it being really composed of two minor troughs or folds of the third order, with an intervening anticline, and even these folds have folds of a higher order superimposed upon them. If one were to follow a geographical order, beginning at the west, the Chapin mine should be first mentioned, but the interpretation of the occurrence of the ore at the Chapin mine depends upon the facts furnished by the Walpole and the Pewabic mines. They are therefore first considered.

WALPOLE MINE.

The Walpole mine has a north and a south ore deposit (fig. 34). These ore bodies occur in subordinate synclines, separated by an intermediate anticline. The synclines and the anticline together constitute the east end of the western important fold of the second order. The northern

PLATE XXVI.

PLATE XXVI.

VIEWS OF THE CHAPIN MINE.

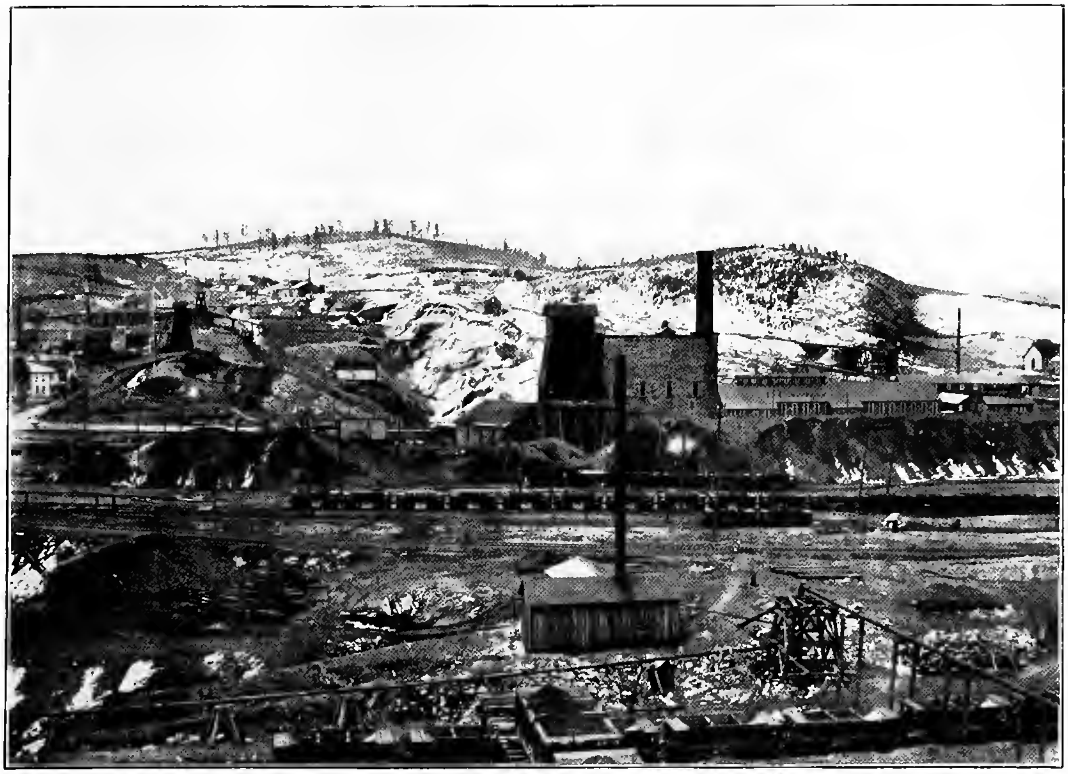
FIG. *A*.—View east from D shaft, Chapin mine, showing shafts on Walpole-Chapin fold. Photograph by J. J. Eskil.

The shafts to the left of the sink hole are the C and the B shafts, the one in the distance at the end of the sunken ground is the abandoned A shaft, and that in the foreground is the D shaft of the Chapin mine. The top of No. 2 shaft can be seen projecting above the roof of the engine house connected with the D shaft. The mine in the notch on the top of the hill, nearly in the center of the view, is the Millie mine, and that in the far distance to the left is the Walpole mine. The Pewabic mine is over the hill to the right of the Millie mine. The hill behind the A shaft is composed of Randville dolomite, topped by horizontal layers of sandstone. The knob to the right is Hughitt Bluff. It consists of evenly banded Traders jaspilites. The gully to the south of the C and B shafts was caused by settling of the ground in consequence of removal of the ore.

FIG. *B*.—View west from A shaft, Chapin mine, showing distribution of shafts on Chapin property. Photograph by J. J. Eskil.

B and C shafts are to the right, No. 2 shaft to the left, and D shaft at the end of the large sink hole. In the distance, to the left of the second sink hole, is the Ludington shaft. The shaft to the right of the B shaft is the Hamilton shaft. The sink holes are produced by the settling of the ground, due to the removal of the ore from beneath.

The hill in the distance is Prospect Bluff.



A. VIEW EAST FROM D SHAFT, CHAPIN MINE, SHOWING SHAFTS ON WALPOLE-CHAPIN FOLD.

B. VIEW WEST FROM A SHAFT, CHAPIN MINE, SHOWING DISTRIBUTION OF SHAFTS ON CHAPIN PROPERTY.

deposit is an excellent illustration of a steep pitching trough which is bottomed by slate and dolomite, and is bounded on all sides but one by the same rocks. The fold is here so close that the iron-bearing member on the south limb has all but been pinched out. The southern ore body is just as clearly in a westward-pitching syncline. Shaft No. 2 of the Walpole mine is on its southern side at the contact of the iron-bearing rocks with the underlying dolomite, and the Millie mine is near the center of its southern limb farther west. The workings of the Walpole mine beautifully illustrate

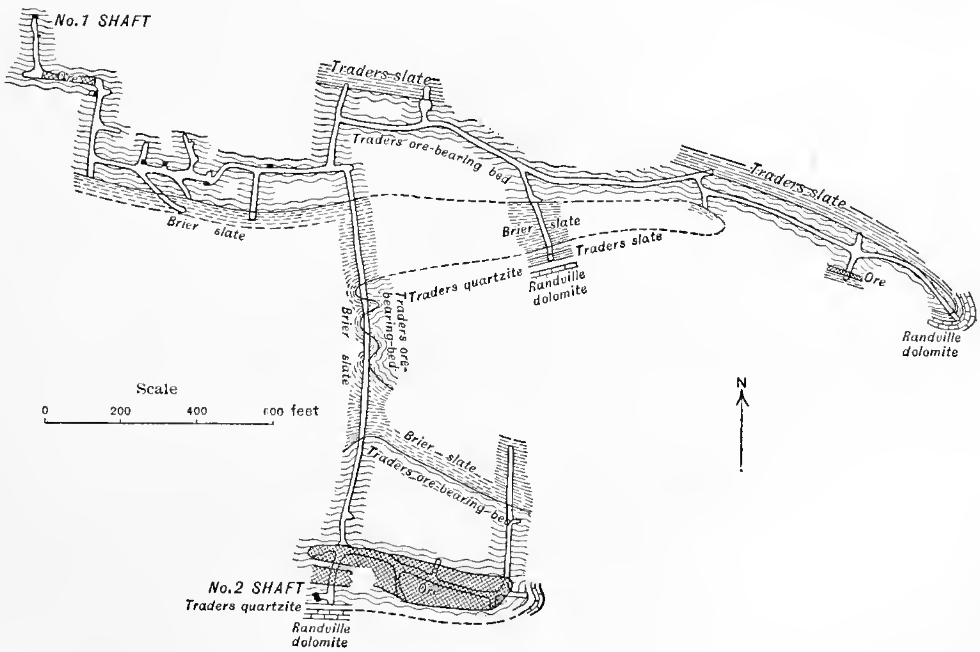


FIG. 34.—Horizontal section of the Walpole mine at the third level.

the relation and succession of the formations which occur between the limestone and the Brier slate in places where the folding is of a very complicated character.

The ores of the Walpole mine and the Millie mine are often brecciated to a remarkable extent. The fragments of the rock are cemented together either by subsequently deposited ore or by drusy masses of a yellowish dolomite. This is especially true of the ores in the eastern ends of the folds where they are closely compressed. The brecciated ores are beautifully exposed on the walls of the long crosscut that connects the workings of the two shafts.

PEWABIC MINE.

The Pewabic mine is on a single, closely compressed fold (fig. 35). The slate and dolomite are here again found on the north, east, south, and at the bottom of the ore body. Here, however, on the south limb of the fold the ore-bearing member does not appear between the dolomite and the Brier slate. It has therefore been squeezed out by the very great pressure, or else slight faulting has taken place. A crosscut north on the first level from the ore-bearing Traders bed to the limestone shows several repetitions of the foot-wall slates, the quartzite, and the iron-bearing members, these being found in narrow belts (fig. 36). The reduplications are regarded as due to very close subordinate folding. The thickness of the Brier slate as developed on the surface by test pitting in the vicinity of the Walpole shaft

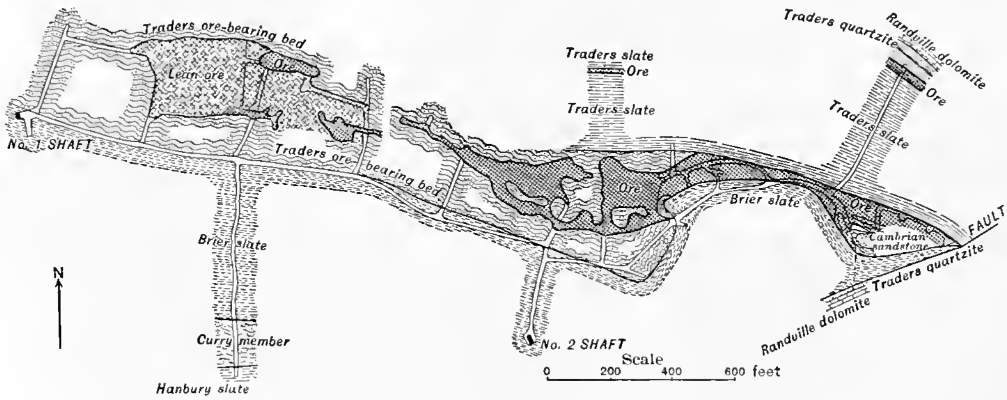


FIG. 35.—Horizontal section of the Pewabic mine at the third level.

No. 3 (see map, Pl. XXVIII), seems to confirm this view. The succession of beds, so far as they could be seen at the time the section was examined, is indicated in the figure. The talcose slates are typical light-colored serpentinous, or talcose Traders slates. The quartzites are like those near the base of the Traders formation elsewhere, and some beds are conglomeratic. Toward the south side of the section there is a series of banded jaspilites, which for 118 feet south of their contact with the Brier slate appear to be continuous. To the south of this point, however, they are cut by seams of the Lake Superior sandstone, and contain irregular pockets of the same sand rock. Gradually the jaspilites diminish in quantity, the sandstone increasing at the same time, until finally the jaspilites appear as distinct bowlders and fragments in the sandstone, and the rock becomes a typical ore conglomerate at the base of the Cambrian. The transition from the bedded jaspilites to the ore conglomerate is so gradual that it is not possible to recognize a distinct line of demarcation between them. The conglomerate was evidently deposited immediately upon the rock which yielded its bowlders. The surface upon which it was laid down was made up of the ends of vertical layers of the jaspilites, which were fractured and shattered, and in which joints had been opened by weathering. Into the latter sand had filtered and formed the veins, seams, or dikes noted as cutting the jaspilites in the drift. The shattered parts were cemented by small quantities of sand that sifted down between the loose fragments. Near the surface of the unshattered rock the fragments had not been much disturbed in their position, and the sand consequently appears as pockets in a solid rock. Farther away from the solid surface the fragments were more separated. A greater quantity of sand sifted down between them, and made a well-defined conglomerate. At the extreme southern end of the drift the conglomerate passes into a pure sandstone.

A second drift passing north from the main ore-bearing belt on the third level toward the dolomite near the east end of the fold (see fig. 35) shows a similar alternation of talcose or serpentinous slates, quartzites, and an ore bed. A drill hole, put through the Brier slates south of the ore-bearing beds and starting at a point nearly opposite the mouth of the crosscut, passed through a small thickness of the slates and immediately thereafter entered a bed of Traders quartzite. The ore-bearing bed encountered on the south side of the Brier slates farther west (see fig. 35) is not met with at the east end of the fold, nor is its manner of disappearance known. It is believed, however, to have disappeared by faulting along

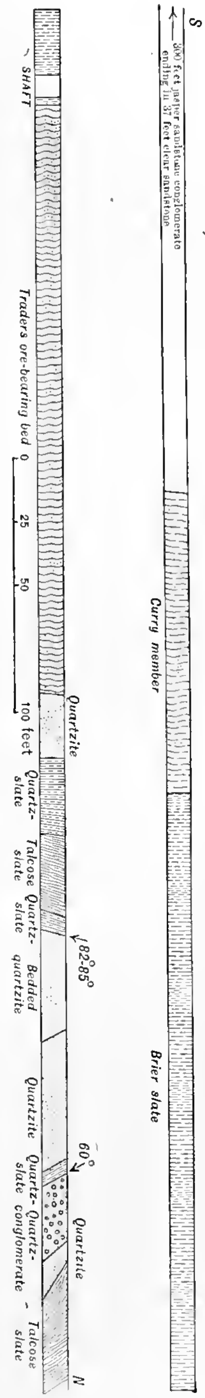


FIG. 36.—Vertical section through No. 1 shaft along north-south crosscut, first level, Pewabic mine.

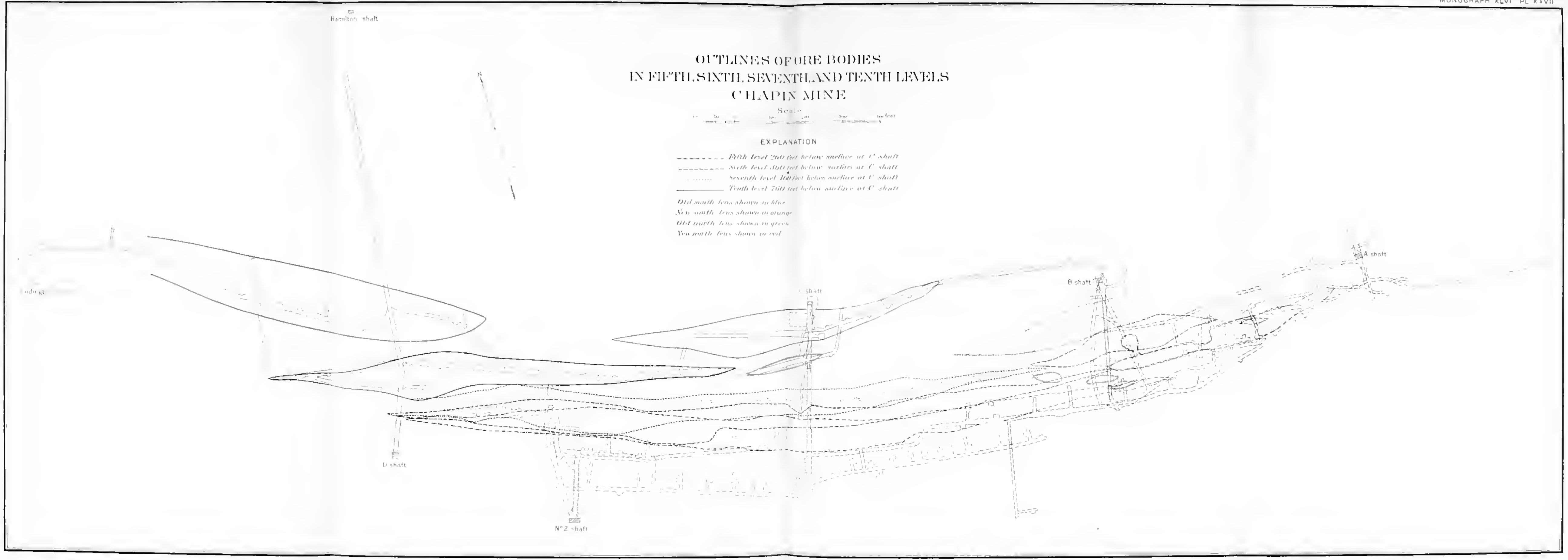
the contact plane between the Randville dolomite and the Upper Menominee series. There is a well-defined fault on the fourth and lower levels of the mine between the Brier slate and the ore formation, but whether this is a continuation of the fault on the contact line at the east end of the mine or not has not been determined.

It is thus plainly seen that the ore of this mine is in a sharply compressed synclinal fold that pitches to the west. The syncline becomes flatter with depth, but it continues to pitch westward as far as mining has progressed. In a publication to which reference has already been made, Mr. E. F. Brown reports the higher phosphorus-bearing ore to be toward the bottom of the fold.

CHAPIN MINE.

At the present time the workings of the Chapin mine have not extended sufficiently far to disclose beyond question the relations of the ore bodies. As yet these have not been connected underground with the ore deposits of the Walpole in such a manner as to show the continuity of the Chapin folds with those of the Walpole mine. However, two main belts of ore have been developed at the Chapin mine, and it is believed that the northern belt of ore will be found to correspond with the northern fold of the Walpole mine and the southern belt with a subordinate fold in this.

North of the northern ore body is a succession of slates and quartzites similar to that north of the Walpole and the Pewabic shafts. A slate with the characteristics of the Brier slate occurs between the two belts of ore bodies and a similar slate bounds the southern ore lens on the south. South of this slate is a wide iron-bearing formation which is apparently continuous with the Millie and South Walpole belt, and south of this again are slates and quartzites that are believed to be the westward continuation of the Brier slate belt of the Pewabic mine (see fig. 37). The south ore lens at the cross section given in the figure is bounded by slate above as well as below. The explanation of this anomaly is probably that the compression was so severe that the lower portion of the ore-bearing bed was actually pinched out, the slate on each side of the ore coming together. The same is true of the top of the new south lens of ore, the upper part of which is inclosed by slates.


OUTLINES OF ORE BODIES
IN FIFTH, SIXTH, SEVENTH, AND TENTH LEVELS
CHAPIN MINE
Scale
EXPLANATION
Fifth level 200 feet below surface at C shaft
Sixth level 360 feet below surface at C shaft
Tenth level 760 feet below surface at C shaft
Old south lens shown in blue
New south lens shown in orange
Old north lens shown in green
New north lens shown in red
Hamilton shaft
C shaft
B shaft
A shaft
D shaft
N°2 shaft

It is impossible at present to be absolutely sure as to the horizon at which the great lenses of ore of the Chapin belong, although they are apparently all of the same age. Since, however, the relations of the ore bodies to the surrounding rocks at the Chapin are parallel in many particulars to the occurrences at the Walpole mine, and since the northern ore belt is continued

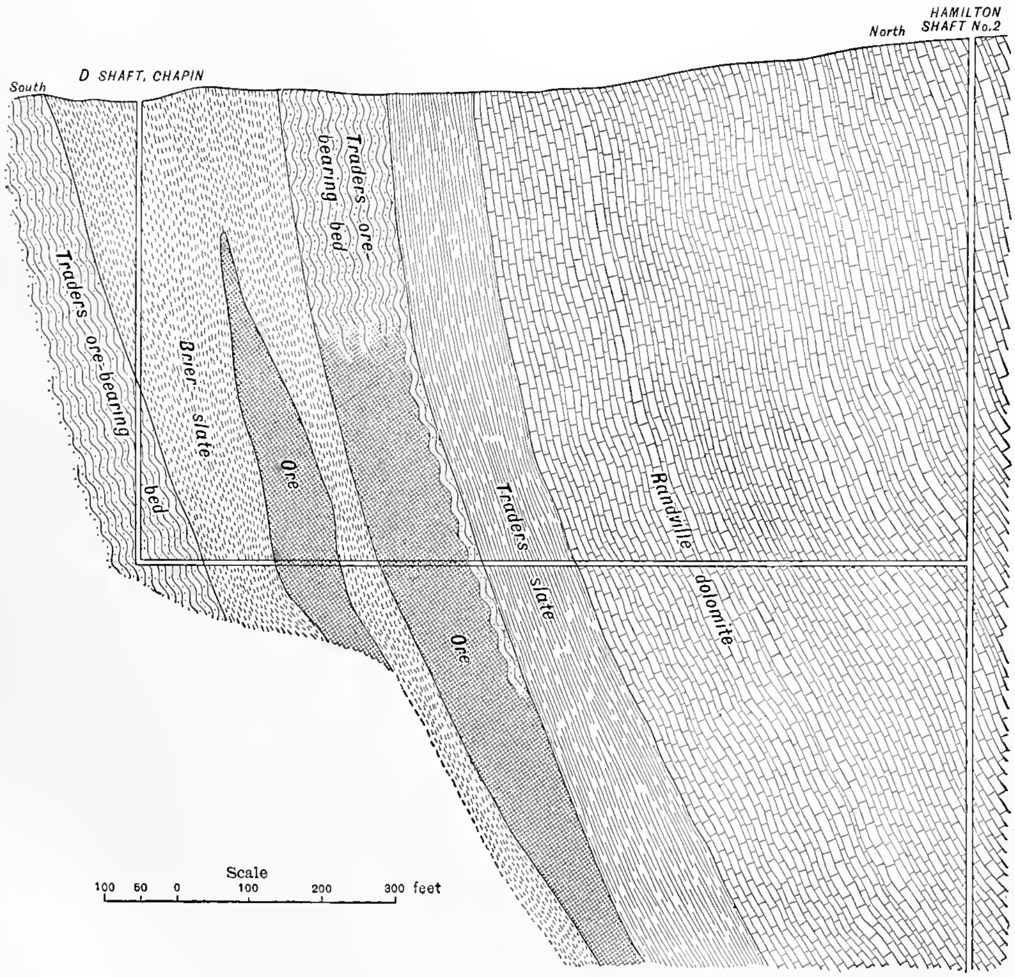


FIG. 37.—Vertical north-south cross section through D shaft, Chapin mine.

eastward by jaspilites beyond the east end of the old north lens toward the Walpole deposit, it is thought that the two ore belts belong to the Traders member of the iron-bearing formation, that member being repeated by close folding. According to this explanation, each of the two northern ore lenses would constitute the north limb of a synclinal fold, separated from the southern belt of lenses, which must be anticlinal, by a syncline of slates corresponding to the syncline of the same rock in the northern part of the Walpole area. The belt of slate south of the southern ore lenses would also be synclinal, corresponding to the syncline in the southern portion of the Walpole area. This structure would fix the position of the next southern iron-bearing belt, in which no large ore bodies have been found, as an anticline of Traders beds. The slates and quartzites south of this would be Brier, and the southern belt of iron-bearing formation would be a monocline of the Curry formation. Because of its monoclinal character, ore bodies

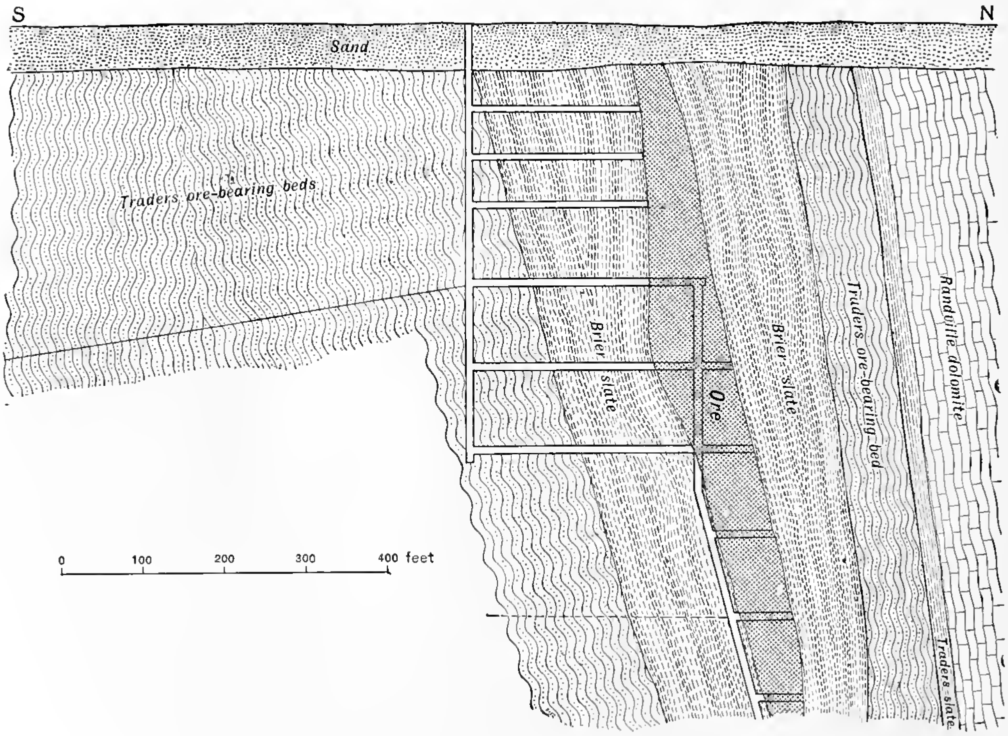


FIG. 38.—Vertical north-south cross section through No. 2 and C' shafts, Chapin mine.

are wanting in this. Following the southern jaspilite series to the south are the Hanbury slates.

The isoclinal folds at the Chapin mine are overturned; the axial planes dip to the north and pitch to the west (Pl. XXVII). The dolomite, which belongs, structurally, below the Vulcan formation, really rests upon it with a steep northern dip, about 80° at the surface, but bending so as to be as low as 70° deep in the mine. For a long time it was a question with the miners which of the two formations was geologically the higher. How-

GEOLOGIC MAP OF THE CHAPIN-PEWABIC FOLDS, MICHIGAN

PARTS OF SECS. 29, 30, 31, AND 32, T. 40 N., R. 30 W.

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 1500 2000 feet

ever, the occurrence of undoubted dolomite bowlders in the Traders member and the continuity of the dolomite from the vicinity of Iron Mountain to the east end of the district have shown beyond question that the dolomite is the lower formation. With the possible exception of the Quinnesec, the Chapin mine shows the most intense folding known in the district, the structure being, in short, a set of isoclinal overturned folds.

If the above be the correct explanation of the structure, the Chapin and Millie mines (see map and section, Pl. XXVIII) present a case of isoclinal folding, the strata of which are reduplicated three times, not to mention the minor duplications north of the northern lens of ore. While it is freely admitted that as yet this interpretation has not been proved to be the true one, it is the one which on the whole appears to correspond most closely with the facts.

This explanation of the structure is different[a] from that proposed in the preliminary report on the district, which regarded the lenses of ore in the Chapin mine as structural synclines and the slates between them as anticlines. More mature consideration of the facts known at the time the previous report was written and a better knowledge of some facts not fully appreciated at that time seem to render the former theory of the structure untenable.

The lenticular shape of the ore bodies in the Chapin mine is explained as due to pinching out of the formation by the intense folding. Lens-shaped masses of the iron-bearing formation became entirely or nearly entirely surrounded by slates and thus were practically in basins with impervious bottoms.

If the structure as outlined above is correct, there should be a tongue of the southern belt of the iron-bearing Traders beds projecting eastward into the Brier slates opposite the southern ore lens at shaft D. This portion of the area has, however, not been thoroughly explored, and any statement as to the existence of such a tongue at that place would be unwarranted at the present time.

OLD KEEL RIDGE MINE.

The old Keel Ridge mine, situated in the northeast quarter of the southwest quarter of sec. 32, T. 40 N., R. 30 W., was abandoned prior to 1885. During its active life it shipped about 60,000 tons of ore. There are a number of open pits and tunnels surrounding the main shafts, but their

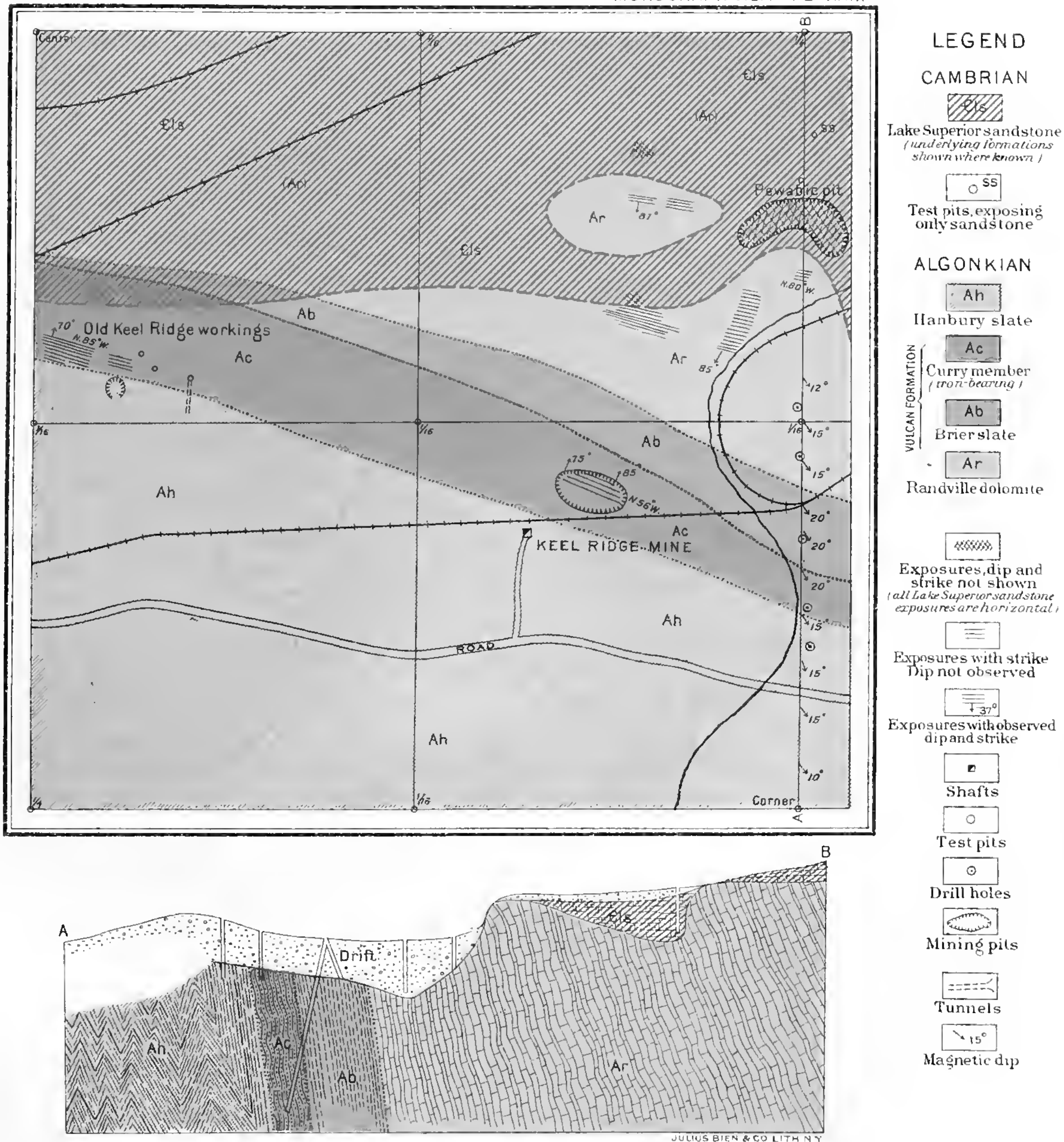
[a]Geologic Atlas U. S., folio 62, U. S. Geol. Survey, 1900, pp. 7–8.

condition is not such as to afford favorable opportunities for study (Pls. XXVIII and XXIX). The rocks exposed in these openings are jaspilites, with red fissile slates to the south. The slates in many instances look very much like the Brier slates, but in other instances they are like the typical sericite-slates of the Hanbury formation. The jaspilites resemble more closely the Curry jaspilites than those of the Traders member. They are frequently evenly banded and cherty, and in a few cases their siliceous bands are gray cherts containing streaks and shots of ore. The general dip of the beds appears to be to the north at about 70°, but departures from this are common. The ore is on the foot-wall side of the iron-bearing member at its contact with the slates. These are stratigraphically above the ore-bearing beds, but the overturn of the series to the north places them underneath the ore Moreover, the iron-bearing beds are strongly contorted (see fig. 24, p. 357), furnishing many little synclines in which the ore may have been concentrated. These pitch westward at low angles, a few of those measured varying in pitch between 17° and 20°. It is probable that the deposition of ore at this place in larger quantity than at any other place in the practically straight course of the Vulcan formation between the Pewabic and Quinnesec mines was due to the contortion of the beds, which was doubtless connected with the sharp turn of the formation around the anticline of dolomite between the Keel Ridge and the Pewabic mines.

Between the Keel Ridge area and the Pewabic mine to the north there should be an anticline of the Vulcan beds over the Randville dolomite which separates the Pewabic from the Keel Ridge deposits. Absolutely nothing is known of this area, in which the Huronian rocks are buried beneath thick deposits of the Cambrian sandstone; consequently on the map (Pl. XXVIII) it is left uncolored.

KEEL RIDGE MINE.

The present Keel Ridge mine is in the southeast quarter of the southeast quarter of sec. 32, T. 40 N., R. 30 W., about three-fourths of a mile east and a little south of the old Keel Ridge workings (Pl. XXIX). Prior to 1900 the shipments from this mine amounted to 33,636 tons. The ore is highly siliceous (see analysis, p. 382). The ore-bearing series consists of even- and thin-bedded cherty jaspers and ore bands striking about N. 56° W., and dipping 75° to 85° N. Following this to the south are



GEOLOGIC MAP AND SECTION

SE. ¼ SECTION 32, AND A PORTION OF ADJACENT SECTION 33, T. 40 N., R. 30 W., MICHIGAN

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 feet

Note: *The data for the section were furnished by the management of the Pewabic mine. The topographic features are unduly exaggerated*

mottled and gray slates of the Hanbury formation. To the north there are no exposures of any kind until the cliff of cherty dolomite overlain by sandstone is reached (see p. 262). Between this point and the open mine pit there is abundant room for the presence of a slate formation, and in a drill hole on the section line nearly east of the open pit a slate was obtained. In the cross section this slate is indicated as being Brier, and the dolomite is made to extend about 350 feet south of its southern exposure on the surface. The data are woefully deficient for determining the structure of the area, but they are perhaps sufficiently full to show that folding is lacking. There is no noticeable brecciation of the ore-bearing beds in the mine, and so far as can be determined no definitely marked ore deposit has yet been encountered. All the ore that can be seen from the surface consists merely of particularly rich portions of the jaspilite.

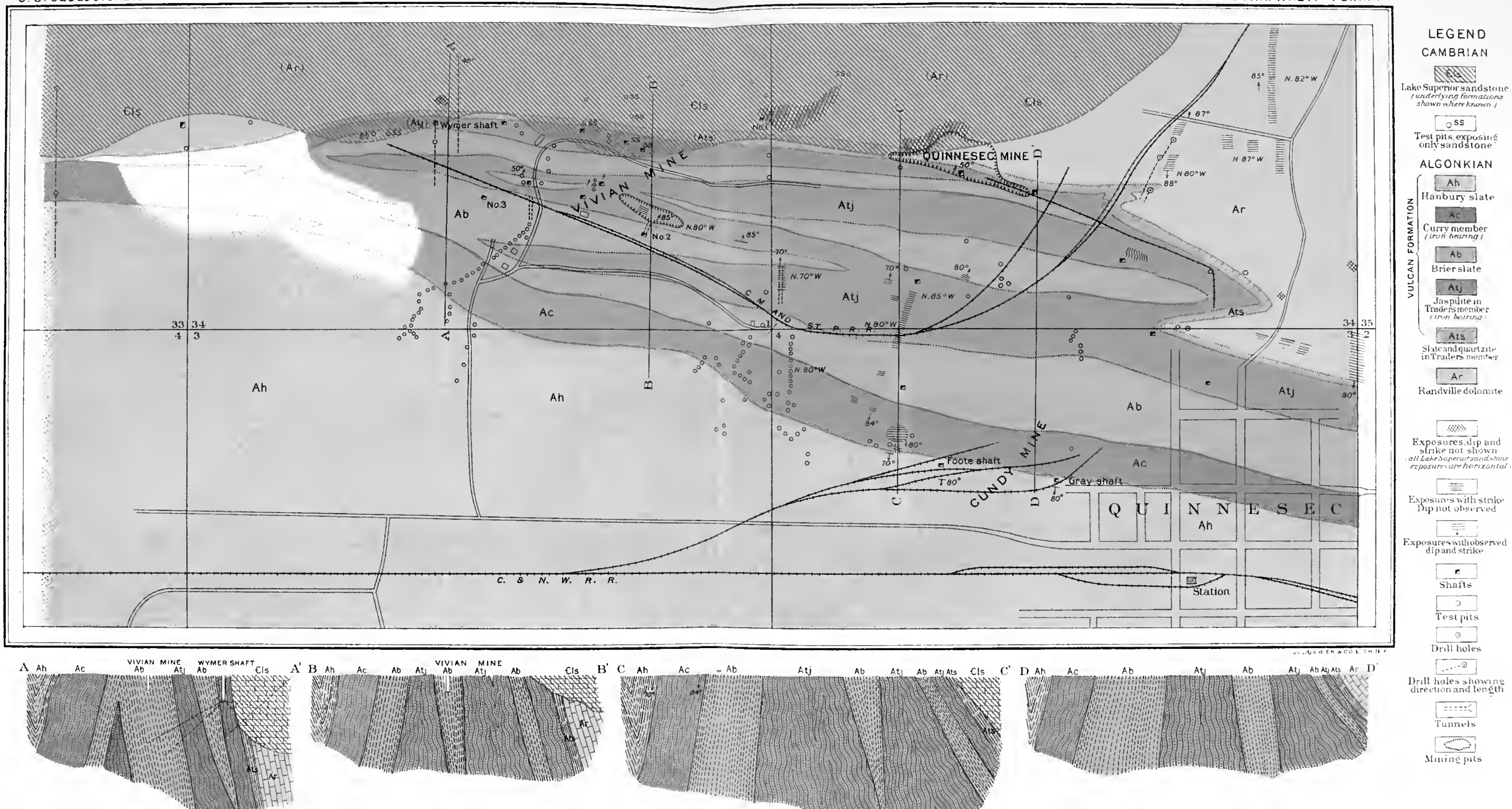
QUINNESEC, CUNDY, AND VIVIAN MINES.

The next important point to the east of the Pewabic mine where ore is produced is at Quinnesec. Here there are three mines, the Quinnesec mine, north of the village of Quinnesec; the Cundy mine, on its western outskirts; and the recently opened Vivian mine, northwest of the village and about one-fourth mile west of the Quinnesec mine. Between the Quinnesec and the Cundy mines are three belts of jaspilites and three belts of slate with the physical characters of the Brier slate. These belts can be traced westward by test pits and trenches for a distance of over one-half mile, but toward their ends explorations are scarce and the exact manner of the termination of all the belts is not known (see map, Pl. XXX). Drill holes a few hundred feet west of the west line of sec. 34 seem to show that beyond this line the three belts of jaspilite are reduced to one. About one-half mile east of the east line of the section the entire Vulcan formation is absent. The disappearance of the whole or a large part of the formation both to the east and the west of sec. 34 is explained by the overlap of the Hanbury slates.

The scarcity of exposures and explorations east of the line joining the Gray shaft of the Cundy mine and the east shaft of the Quinnesec mine, and in the western portion of the area, for a distance of 600 feet on both sides of the section line between secs. 34 and 33, renders the interpretation of the geology at this place very doubtful. It is known, however, that the boundary of the Randville dolomite southeast of the Quinnesec mine is indented by a reentrant extending eastward. This is interpreted as indicating a synclinal fold pitching to the west (see p. 239). With this as a starting hypothesis a reasonable explanation of the geology of the district would appear to be as follows: The ore of the Quinnesec mine and the quartzites and slates between it and the dolomite to the north belong in the Traders member, which at this place is the north limb of a syncline overturned to the south (see sections D–D and C–C). South of this is a narrow syncline of the Brier slates, and to the south of this an anticline of Traders beds. Following this belt in succession toward the south are a syncline of Brier slates, another anticline of the Traders member, and a succession of Brier slates, the Curry member, and the Hanbury slates in a southward-dipping monocline. This structure would place the Cundy deposit in the Curry member. At about the west line of the section the northern belt of the Traders member disappears by overlap and the second and third belts by the westward pitch of the anticlines. The third belt bifurcates near the north-south line of sec. 34. Its northern limb unites with the western end of the second belt and disappears, as explained, by an anticline plunging beneath the overlying slates. The narrow syncline of slate immediately south of the Quinnesec ore deposit, according to this view of the structure, is canoe shaped and is terminated at both ends by inclosing synclines of the underlying Traders beds. The identification of this slate as Brier rests on purely lithological evidence.

The second belt of slates is also a canoe-shaped syncline which terminates both to the east and to the west by anticlines. West of the west end of this belt is another small area of slates separated from the main belt by an anticline of the underlying jaspilites. The third belt of slates stretches west, wraps around the end of the southern portion of the southern belt of Traders jaspilite, makes a salient between the bifurcating legs of the southern jaspilite belt, and surrounds the western end of the northern jaspilite anticline at this place. Thus, at the quarter line of the section there are four jaspilite belts and four slate belts, and a little farther west there are but three of each.

Beyond the point at which the jaspilite belts disappear there are no exposures for some distance, but one-fourth mile beyond, several drill holes reveal the presence of a jaspilite belt between talcose slates to the north and a thick series of slates on the south that are supposed to belong in the Hanbury formation. This belt of jaspilite is correlated with the



GEOLOGIC MAP AND SECTIONS OF QUINNESEC AREA, MICHIGAN

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 1500 2000 feet

Curry belt farther east, in which the Cundy mine is opened up. There is no evidence as to the manner of disappearance of the northern jaspilite belt or of the wide slate belt formed by the merging of the three slate belts noted in the eastern portion of the area. The disappearance is, however, supposed to be due to overlap and the boundary lines between the belts are drawn accordingly.

The structure of the Quinnesec area, as indicated by the explorations, is represented on the map (Pl. XXX) and the four cross sections. It will be noticed that while the area as a whole is a westward-pitching synclinorium with three closely compressed and overturned east-west folds, it is also affected by two broad north-south folds, the synclines of which are indicated by the broader portions of the slate belts and the anticlines by the entire disappearance of these and the appearance of the wider portions of the jaspilite belts.

The Quinnesec ore body, according to this view, is a narrow deposit at the contact of a thin series of jaspilites with a bed of slates that underlie them in position, though overlying them stratigraphically. The dolomite and the talcose-schists at this locality apparently overlie the ore, the dip being about 70° N. The ore is bounded by the talc-schists on the north and by slates on the south. South of these slates is an iron-bearing formation. The ore in longitudinal section passes into jaspilites both to the east and to the west. To the east is the sharp embayment in the underlying dolomite which suggests a corresponding westward-pitching fold in the adjacent iron formation. The Quinnesec deposit is, therefore, on the north side of a pitching trough. Southeast of the easternmost shaft of the mine, on the south side of the tramroad from the mouth of the pit, is a large exposure of jaspilites showing very complicated contortions that are in many instances extremely sharp. These indicate close and complicated folding of the iron-bearing member, but throw little light on the exact character of the folding.

The Cundy deposit is in the southernmost ore-bearing belt. This is a monocline dipping south at from 70° to 80°. The ore is hard and lean and contains considerable magnetite. No distinct jaspilites have been met with in the mine. The ore contains a great deal of fragmental material, the major portion of which is quartz. There is some crystalline quartz between the fragmental grains and a large quantity of some carbonate, a considerable proportion of which is in little rhombohedra. This carbonate is fresh and there is no evidence that it is changing into ore. It is probably an infiltration. The Cundy ore thus appears to be a fragmental rock that has been greatly enriched by iron oxides. West of the Foote shaft of the mine the ore-bearing beds are exposed in an open pit. Here they are even-bedded quartzites or fragmental-looking jaspers and ores dipping about 70° S. The quartzite or jasper is in places richly ferruginous. The ore is in thin layers which get thicker toward the north. Joint cracks intersect the rocks at right angles to their bedding, and many of them are occupied by quartz veins. At the present time developments in the mine have not progressed far enough to show the relations of the ore body to the adjacent rocks.

The Vivian mine has but recently been opened up. Its three shafts occupy the southeast quarter of the southwest quarter of sec. 34. One of them apparently obtains ore from the basal layers of the Lake Superior sandstone, and the others from synclinal portions of the Traders jaspilite near the contact of this member with the overlying Brier slates.

NORWAY AND CYCLOPS MINES.

Another exceedingly important ore-producing center is Norway, about 4 miles east of Quinnesec, where the Norway, Cyclops, and Aragon mines are situated (Pl. XXXI). In this neighborhood there is undoubted evidence of the presence of two westward-pitching synclines in the dolomite, within the northern of which the Norway mine is located and within the southern one the Aragon mine. The northern syncline is the broader, but it is shallower than the southern one (see pp. 240–245); hence it is in the latter that the best developed ore deposit occurs. The geological structure of this area is difficult to determine because of close folding, brecciation of the slates and jaspilites involved in the folds, and the lack of exposures at critical localities. Moreover, sandstone covers the hill to the west and northwest of the mines and prevents the tracing of the folds in that direction. The structure of the area occupied by the Aragon mine, the northeast quarter of the northeast quarter of sec. 8, and northwest quarter of the northwest quarter of sec. 9, T. 39 N., R. 30 W., is fairly well known from the underground workings of this mine. All three members of the Vulcan formation exist with their average thickness. They occur in a rather sharply compressed syncline, pitching a little north of west at an angle of about 45° and dipping a little east of south at an angle approximating 60°. On this are superimposed several smaller folds, dipping and pitching in approxi-

GEOLOGIC MAP OF NORWAY AND ARAGON FOLDS AND VICINITY, MICHIGAN

PARTS OF SECS. 4, 5, 8, AND 9, T. 39 N., R. 29 W.

BY W. S. BAYLEY

1903

FOR SECTIONS SEE PLATE XXXII

Scale

500 0 500 1000 1500 Feet

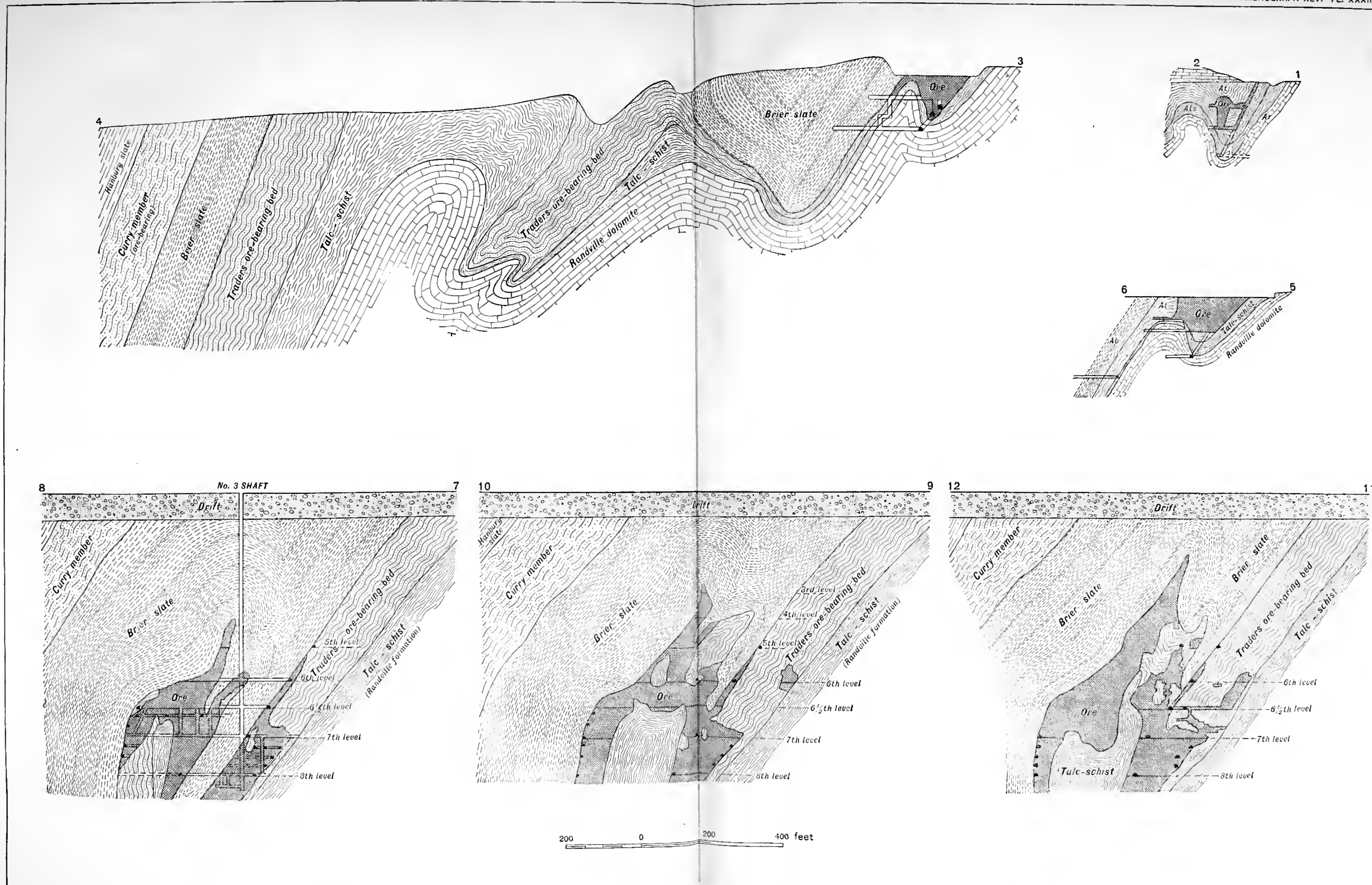
mately the same directions. These folds are overturned to the north, so that the north sides of the intervening anticlines are either vertical or dip high to the south.

The structure within the Norway fold is so very obscure, for the reasons above mentioned, that it is only with the greatest hesitation that any explanation of it is hazarded. The three members of the Vulcan formation have been traced northwest from the Aragon mine about one-half mile by the aid of drill holes, pits, and exploring shafts, and the two lower members have been followed over one-fourth mile by the lower workings of the Aragon mine. Near the quarter post between secs. 5 and 8 the Traders member appears to turn suddenly to the northeast and to extend in this direction at least as far as a point south of the main shaft of the Norway mine, which is nearly due north of the principal workings of the Aragon mine. They are traceable through this distance by the shafts and open pits of the Cyclops mine. Beyond the Norway shaft the iron-bearing beds have not been seen, but it is supposed that they join the northernmost belt of the Traders member somewhere within the Perkins pit. From this pit the belt runs a little north of west through this and the Norway pit until it is lost under a thick covering of sandstone near the center of the section. From the point where the belt makes the sharp turn to the northeast there is a prolongation of the iron-bearing beds to the northwest for a distance of about 1,250 feet. Here they are apparently terminated by Brier slates, though the evidence of this is very scanty. In this prolongation the belt is about double its normal width and incloses an axis of slates. Thus the iron-bearing beds that have been described as Traders form a Z-shaped belt with a slight prolongation from the lower left-hand angle of the Z parallel to the upper and lower lines. Beyond the points mentioned as the western termini of the belts on the surface nothing practically is known about their further extension. The country to the west is covered with a layer of sandstone which only a few test pits have penetrated. On the west line of the section there is a shaft in iron formation material, but there is nothing between this shaft and the Norway pit to indicate whether this is an extension of the Norway belt or of the more southerly Cyclops-Aragon belt.

Another source of difficulty in the interpretation of the structure is the brecciated character of the rocks involved in the folding and the obscure character of their contacts. In nearly all the pits of the Cyclops and the

Norway mines the slates and jaspilites are severely shattered and brecciated. Into the crushed slates ferruginous material has penetrated to such an extent that in some instances they have been wrought as ore. At the Norway and the Cyclops pits faulting has unquestionably accompanied the brecciation, so that the ore-bearing beds in some places appear to be above a slate, whereas the same beds apparently underlie the same slate in other places. On the east side of Barbara's pit (see map, Pl. XXXI), for instance, the iron-bearing beds are apparently under the slates in an anticline pitching east, while at the west end of the same pit they are apparently over the slates with reibungsbreccia between them. To the south the jaspilites may be traced almost without break into Green's pit, where they are much brecciated, and on the south side of this pit they dip south at a high angle (about 80°) beneath even-bedded, red slates. Traced west they again appear in pit No. 1, where they constitute a sharp syncline underlain by a slate which on the north side is severely brecciated, and still farther west on the west face of pit No. 2 they are in a distinct, nearly symmetrical syncline underlain by slates that are not brecciated or which are brecciated only to a very slight extent.

There is little opportunity for comparing the normal characters of the different slates with each other, principally because of the severe brecciation and the attendant alteration to which the rocks have been subjected. Cross sections of the Norway pit, however, seem to show that the slates south of the ore deposits at this place are in the stratigraphical position of the Brier slates, while the drill holes on the Aragon property and the underground workings of this mine appear to prove that the slates between the Aragon and the Cyclops ore beds are beneath the ore formation. On the supposition, therefore, that the slates between the Norway and the Cyclops are Brier and those between the Cyclops and Aragon are Traders, or talcose slates belonging on top of the Randville dolomite, the map and cross sections shown on Pls. XXXI and XXXII and fig. 18 have been constructed. These seem to explain the facts now known as to the distribution of the ore-bearing beds in the three belts and the relations of these beds to the adjacent slates. It is fully realized, however, that there may have been a mistake made in the identification of the northern slates as Brier. The Norway ore beds may be in a compressed syncline with the slates to the south in an anticline, in which case the structure as indicated on the maps would have to be modified to this extent. There appears at present to be no way of deciding this point.



VERTICAL NORTH-SOUTH CROSS SECTIONS THROUGH THE NORWAY-ARAGON AREA, ILLUSTRATING GEOLOGICAL STRUCTURE.

For positions of sections, see map, Pl. XXXI.

The explanation of the structure as above outlined is to the effect that the Norway belt is the north side of a syncline dipping under the slates to the south and rising on the north side of the Cyclops belt in an anticline. This anticline is confined to the northern part of the Cyclops belt, its southern portion consisting of a syncline which is overturned to the north in Green's pit. In pit No. 3 this syncline is upright and normal and is separated from the anticline to the north by a narrow belt of talcose slates. The entire belt is supposed to terminate to the west by pitching beneath the overlying Brier slates.

South of the Cyclops belt the ore-bearing beds span an anticline of Traders slates and Randville dolomite, its south limb reappearing again as a southward-dipping monocline at the Aragon mine.

The Curry member has been excluded from consideration in the above discussion, because no inkling of the course of the belt has been obtained beyond the pits 1,000 feet west of the quarter post between sections 5 and 8. According to the view outlined above, this member must turn to the northeast around the west end of the Cyclops belt of the Traders beds, make a reentrant to the east, and then turn sharply to the west and extend into section 6.

The distribution of the ore deposits in this area confirms beautifully the generalizations of a former paragraph in which the manner of occurrence of the ore is discussed. At the Norway mine a pitching, shallow trough is being mined for ore. It is bounded on both the north and the south by dolomite. The fold is so important as to bring the dolomite very near the surface (see sections on Pl. XXXII and figs. 18, 19). Between the dolomite and the ore is a certain amount of ferruginous and siliceous slate, which, until the demands for low-grade, nonphosphoric ores arose, could not be mined. During the summer of 1900, however, a large amount of this lean material was shipped.

In the Cyclops belt are several large pits, from which, in all, some 286,000 tons of ore had been raised prior to 1892. Since this date only an inconsiderable quantity has been mined. Practically all of this ore came from the southern half of the belt, in which the structure is synclinal. At the southwest end of the Cyclops belt, where it turns southeastward toward the Aragon mine, no ore has been discovered, though the jaspilites are crushed into very distinct breccias. The structure at this place is, of course, anticlinal.

ARAGON MINE.

The Aragon mine gives, perhaps, the clearest illustration furnished by the district of the principle of the formation of ore in pitching troughs on impervious basements. Just east of the Aragon mine is a sharp embayment in the dolomite, which may be beautifully seen above ground, an amphitheater of limestone entirely surrounding the low land occupied by the iron-bearing formation. A short distance to the west of this embay-

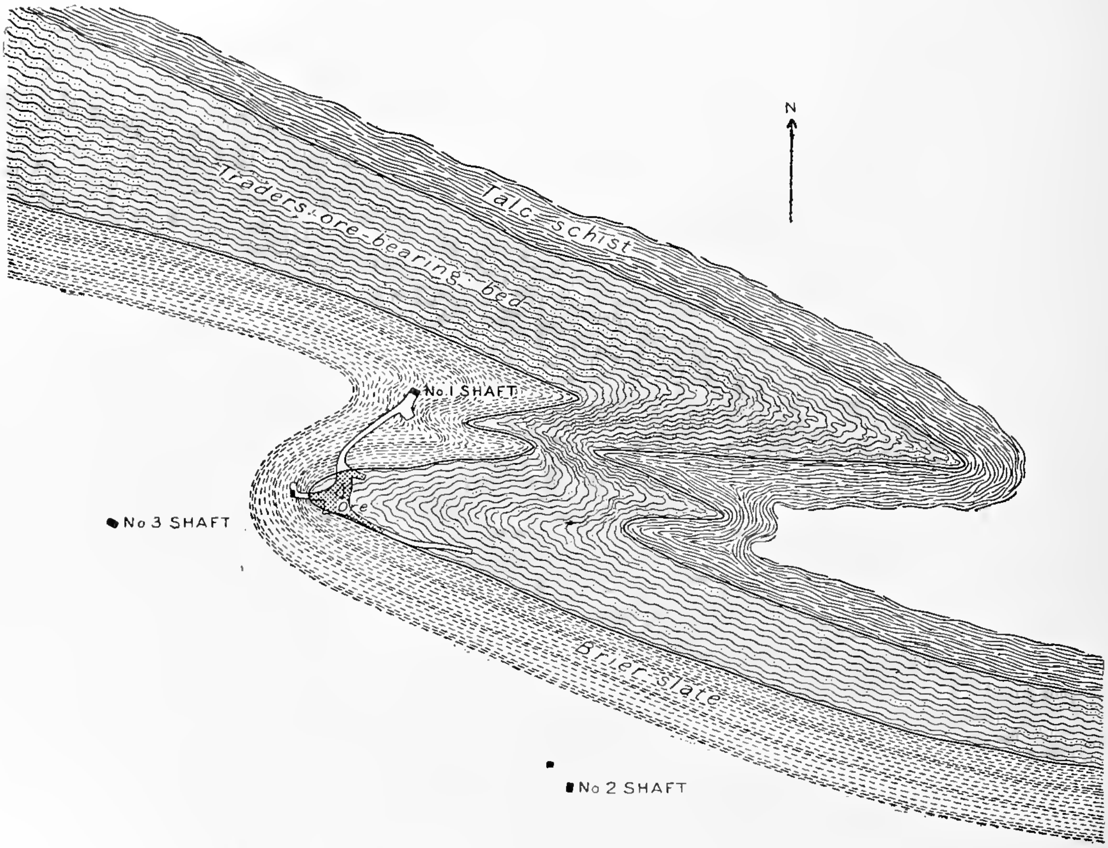


FIG. 39.—Horizontal section of the Aragon mine at the first level. One inch=250 feet.

ment the Aragon body was discovered. Where first found it was at the top of the Traders member of the ore formation, just below the bottom of the Brier slate (see fig. 39). At this time no one could have predicted that this ore body is really related to the impervious talc-schists of the dolomite below. However, as mining continued, the ore deposit gradually and irregularly widened, and at the fifth level assumed definite relations to the dolomite. From the fifth level downward (figs. 20, 21, and 40) this relation has continued, the main mass of the ore body being found at the apex of the trough, and long arms of ore extending up along both limbs of the fold, but especially along the main dolomite wall to the north (see fig. 40). This occurrence is especially interesting since the ore deposit was found steadily to increase in size as it assumed definite relations to the

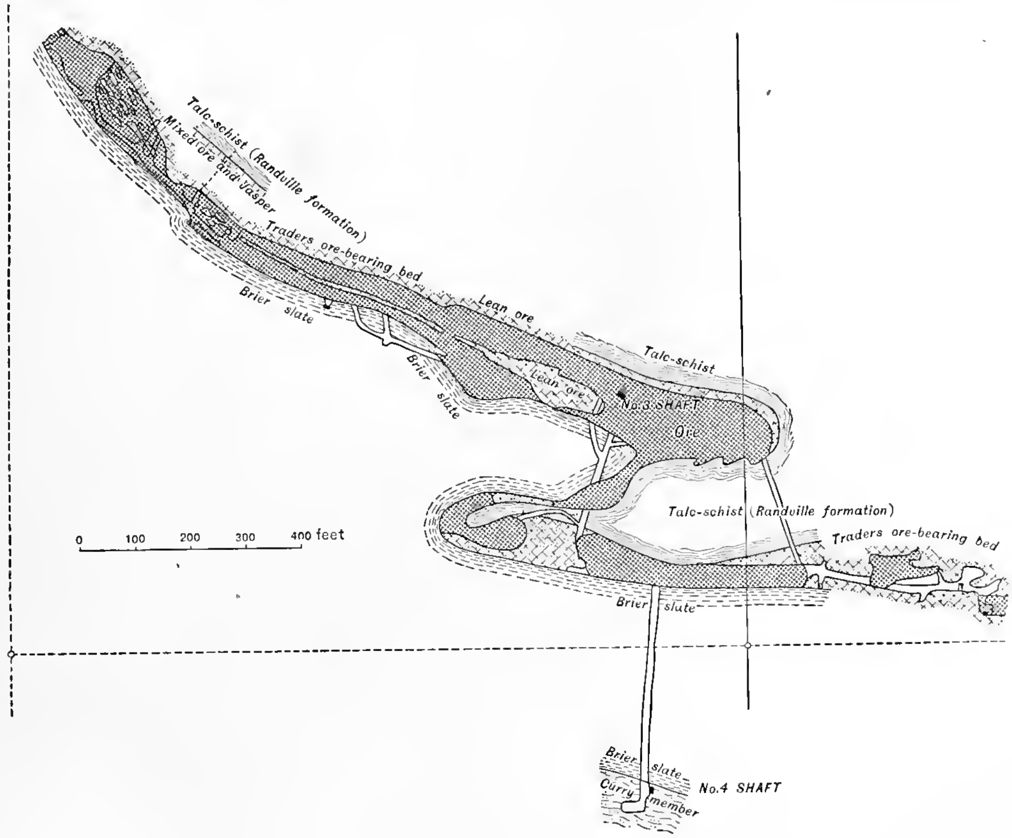


FIG. 40.—Horizontal section of the Aragon mine at the eighth level.

underlying pitching trough (fig 41). At the high levels, where it did not have an impervious basement furnished by the dolomite formation, it was comparatively small. As soon as it had assumed, at lower levels, definite relations to the dolomite trough it became a large ore body, and has continued to increase in size to the present depth now reached at the eighth and ninth levels, where the relations of the ore to the pitching trough are perfectly illustrated.

MINES EAST OF ARAGON MINE.

East of the Aragon mine there are found in rapid succession the mines of the Penn Iron Mining Company, viz, the Curry and the various shafts of the West Vulcan, Central Vulcan, and East Vulcan mines. East of these again is the Verona mine. Beyond this there are no mines that are active at present, although at the extreme east end of the district are the abandoned pits of the oldest of all the Menominee mines—the Breen and the Emmett. Except at the last two mentioned mines, at the West Vulcan and at the western shafts of the East Vulcan mine, the geological relations of the different members of the Vulcan formation with one another appear to be simple, and the ore deposits are apparently contact deposits.

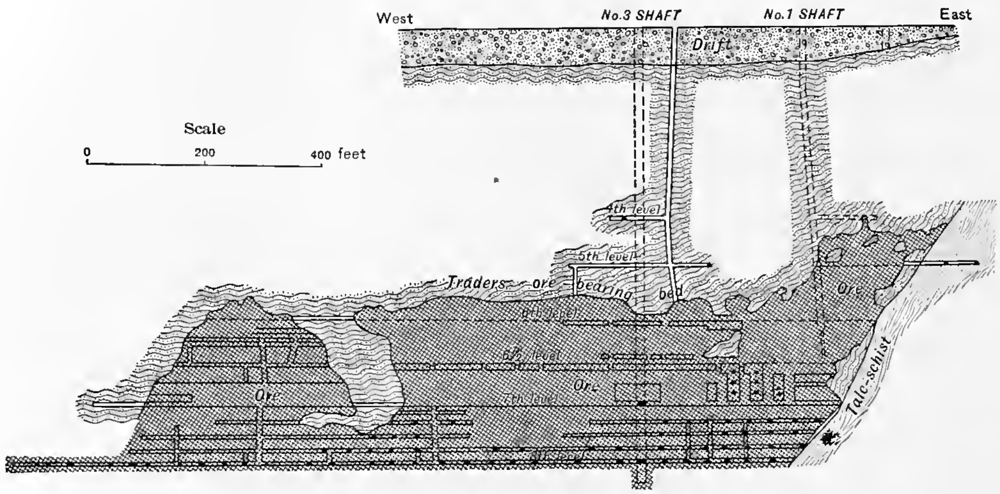
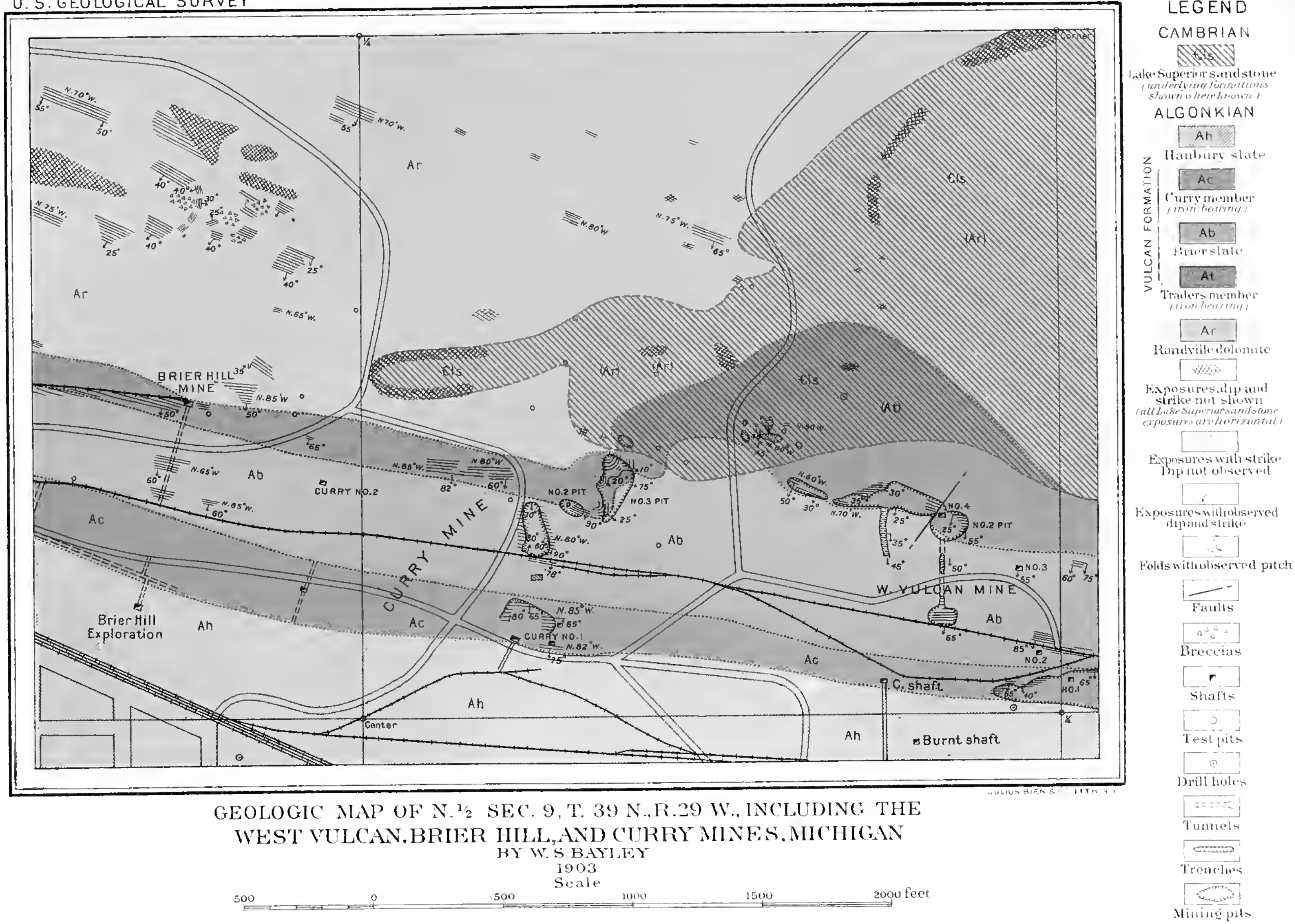


FIG. 41.—Vertical east-west longitudinal section of the Aragon mine, north fold.

At the West Vulcan and the eastern shafts of the East Vulcan mine folds exist in the Curry member at least, and these have determined to some measure the deposits in this member. From these shafts and that of the Curry mine ore is raised from the Curry member as well as from the Traders beds, and at the East Vulcan shaft No. 3 the ore has come exclusively from the Curry beds.

BRIER HILL AND CURRY MINES.

The Brier Hill explorations occupy the southeast quarter of the northwest quarter of sec. 9, T. 39 N., R. 29 W., which is immediately east of the Aragon location. East of this, in the southwest quarter of the north-



GEOLOGIC MAP OF N. ½ SEC. 9, T. 39 N., R. 29 W., INCLUDING THE WEST VULCAN, BRIER HILL, AND CURRY MINES, MICHIGAN

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 1500 2000 feet

east quarter of the same section, is the Curry mine (Pl. XXXIII). The Brier Hill mine was abandoned after yielding 14,981 tons of ore. The Curry mine is still an important producer.

To the east of the Aragon mine the three members of the Traders formation can be traced almost continuously by surface exposures, test pits, and mine workings to the east side of the Curry location. For most of this distance they follow a uniform direction of about 15° south of east without notable variations in thickness. To the north are splendid exposures of the Randville dolomite (see p. 267), and to the south is the Hanbury slate, which has been developed at a number of places by the drifts and crosscuts from exploring shafts. Between the Brier Hill and the Aragon mines there is an excellent section exhibited on the surface from the bottom of the Traders member to the top of the Brier slate, and near by a crosscut from the Brier Hill exploring shaft extends the entire width of the Curry member. The approximate widths of the several belts on the surface are: Traders member, 150 feet; Brier slate, 350 feet; Curry member, 225 feet; or a total of 725 feet. The dip of the beds in the north—i. e., at the base of the formation—is only 20° S. This increases gradually to the south, the dip of the beds at the top of the Brier slate being as high as 80° S. The thickness of the members calculated from their widths and dips is: Traders, 60 feet; Brier, 338 feet; Curry, 220 feet; making a total thickness of 618 feet. A section across these beds is shown in fig. 42. To the north, at the base of the little cliff overlooking the swamp that stretches to the dolomite cliffs about 300 feet still farther north, are a few layers of a light-colored slate, with which are interleaved a few thin beds of quartzite. Above these and forming the main portion of the face of the little cliff is a 3-foot bed of quartzite conglomerate, and above this a series of beds consisting of layers of conglomerate, slates like those at the base of the cliff, and thin beds of specular mottled ore. The conglomerates are fairly coarse-grained quartzites, inclosing fragments of jasper, ore, and quartz. These constitute the principal portion of the series, the slates and ores being in thin beds

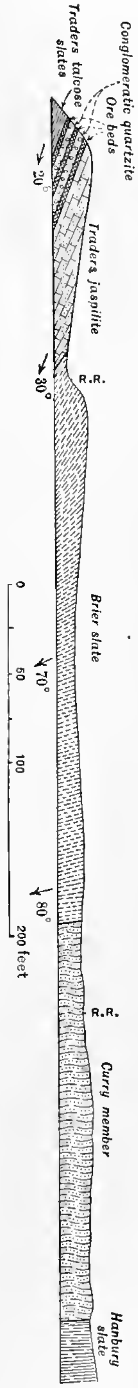


FIG. 42.—Section across Vulcan formation about 600 feet west of Brier Hill mine. For position of section see map, Pl. XXXIII.

and in greatly subordinate quantity. Following these to the south is a series of bedded jaspilites about 75 feet wide, and south of these is a wide band of Brier slates showing beautiful bedding bands in their weathered surfaces. To the north, at the base of the series, they are very jaspery and quartzose, but higher up the proportion of siliceous matter diminishes and the slates become typically developed. The Curry ore-bearing beds are not exposed on the surface at this place, but farther east, at the open pit of the Curry mine, they are well shown. Here the slates grade into the jaspilites by interlaminations of slaty and siliceous materials (see p. 351). Just east of the little ridge composed of the quartzite-conglomerates is a pit, on the dump of which are dark-gray slates with all the microscopical characteristics of the Hanbury slate, and a few paces south of this is a small ledge of a dark, serpentinous-looking rock that apparently contains small fragments of ore and jasper. It is cut by irregular veinlets of calcite. Under the microscope serpentine is seen to constitute a large portion of the rock. It is arranged in such a way as to suggest the flowage structure in lavas. The rock is probably a breccia on the contact of the dolomite and the Traders beds like that so well developed in the Norway pit and in the open pits of the Curry mine. The slate is more difficult to explain. The pit from which it was taken is north of the breccia ledge. Of course the relations of the slate to the serpentinous breccia and to the Traders slates are not known, since the rock has been seen only on the dump pile of the pit. Two explanations suggest themselves to account for the presence of the slate in this place. Either one is plausible. The first is that the slate is one of the lower beds of the Traders member, in which case the boundary of the Vulcan formation on the map should be placed a little farther north, with the breccia an inlier of the Randville formation, surrounded by Traders beds. The second explanation accounts for the presence of the slate at this place on the supposition that it is a small remnant of Hanbury slate, overlapped beyond the Traders beds and preserved from erosion by its position in the lowlands of the swamp.

East of the Brier Hill mine the dolomite and the Traders beds are very close together, the Traders layer nearest the dolomite being a coarse-grained quartzite conglomerate. This has already been described on a preceding page (p. 271).

The position of the ore deposit in the Brier Hill mine is not known, but judging from the structural relationships of the various rocks in its vicinity the deposit must be on or near the contact of the Traders member with the underlying dolomite, which on the surface, near the shaft, dips about 50° S.

The Curry location is immediately west of the Brier Hill mine. The iron-bearing formation continues from the Brier Hill mine eastward in a uniform direction to the open pits of the Curry mine, where the Traders member departs sharply from this direction, its northern boundary making a deflection to the north, forming an embayment in the Randville dolomite. The extent of this deflection is not accurately known because the Huronian rocks are covered with a fairly thick deposit of the Lake Superior sandstone. This, however, has been penetrated at a number of places, uncovering the underlying Traders beds dipping south at 45°. West of the northward turn the jaspilites of this member are exposed in a little hillock with all the features of typical phases of these rocks (see pp. 273–277). Indeed, the jaspers interbanded with the ore layers are so similar to the typical jaspers of the Negaunee formation in the Marquette district that for some time the beds were supposed to be of Negaunee age. These rocks strike N. 80° to 85° W. and dip 60° to 82° S. East of this exposure the Traders beds make their northward turn, and at this point there are several large open pits which well display both the jaspilites and the Brier slates. These pits mark the southern boundary of the Traders belt, which is continued eastward through the West Vulcan property by another series of equally large pits. In the western pits, those on the Curry location, the jaspilites are folded into a number of small synclines and anticlines pitching southeast at low angles. Near the contacts with the overlying Brier slate slipping has taken place. The jaspilites are profoundly brecciated, the cement between the fragments of the breccia oftentimes being an ore which is now schistose and specular. It was from this brecciated zone that the ore was removed in earlier days. Pit No. 3 (see map, Pl. XXXIII) exhibits the relations of the rocks in a very beautiful manner. A sketch of its plan is shown in fig. 43. At the northwest corner of the pit is a little syncline in interbanded flinty jaspers and specular layers pitching about 20° SE. Superposed on this are several minor rolls. Above this is a conglomerate or breccia, composed of fragments of ore and jasper cemented together by a sandy matrix which is not unlike the material of the Brier slates on the east side of the pit. The conglomerate is not more than 3 or 4 feet thick. It is overlain by banded slates and fragmental-looking jasper and ore layers. A little farther east, on the north side of the pit, the jaspilites are well bedded. Large lenses of jasper occur in them and in many places the series appears to be brecciated. Above the jaspilites are the Brier slates at the northeast corner of the pit. The former rocks are brecciated and between them and the overlying slates is a deposit of ore. That portion of the series here exposed measures not more than 45 feet in thickness. The most distinct breccia is at the top of the Traders member near its contact with the slate. It is this breccia that furnished the ore that was formerly mined at this place. Several other synclines and anticlines are indicated in the sketch. Pl. XXII, *A* is a reproduction of a photograph of the upper surface of the southernmost anticline. This shows a breccia which has been sheared until it simulates a conglomerate. It is now composed of large lenses of jasper in a matrix of beautifully schistose ore. The jasper lenses are coated with ore, so that they do not stand out clearly in the reproduction. Their positions, however, can be recognized by the differences in the reflections from the glistening surface. A little to the northwest of pit No. 3 a small excavation in sandstone has uncovered the underlying jaspilites, which at this place are very flat lying. Thus the larger fold in the iron formation in the north portion of the Curry and West Vulcan locations is accompanied by minor folding in pit No. 3, which may be regarded as being situated on a flat anticline pitching at a low angle to the southeast. The gentle character of the major folding is likewise indicated by the gentle minor folds exhibited in the pit. Along the contact of the iron formation with the overlying slates movement took place, and this was accompanied by brecciation,

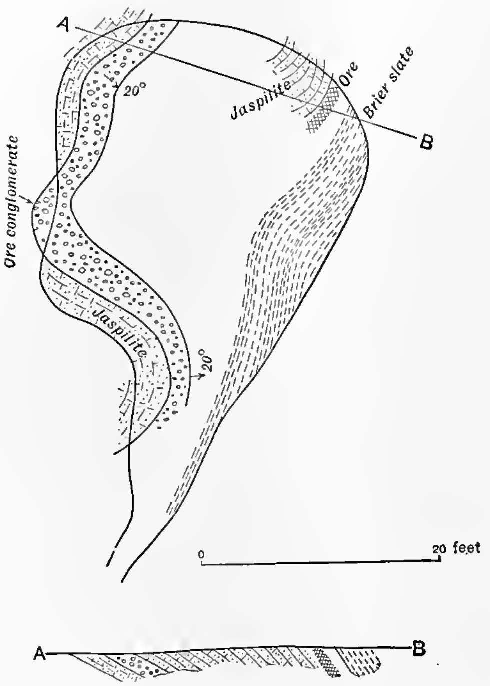
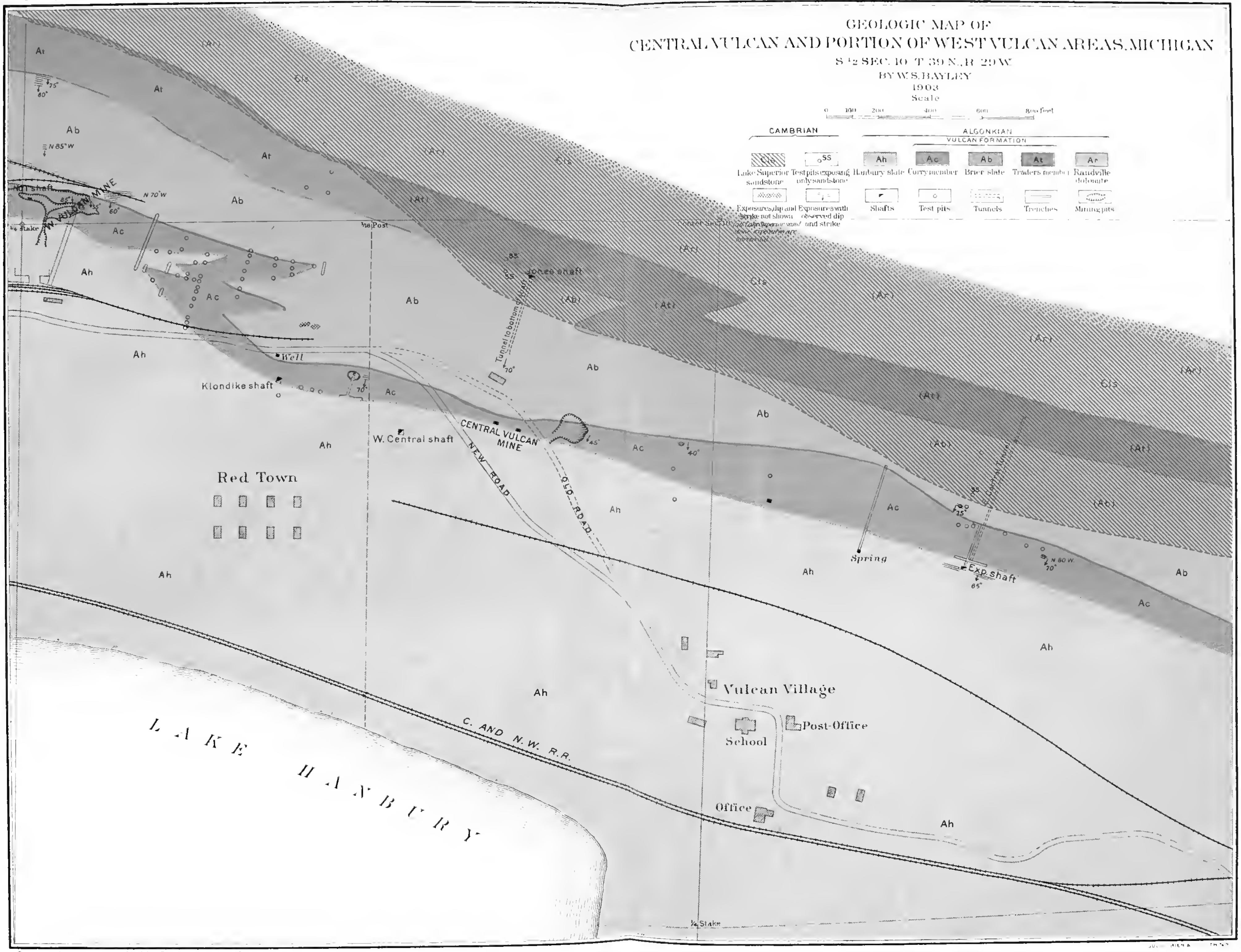


FIG. 43.—Plan of No. 3 pit, Curry mine, and section along its north end.



Base of this map furnished by Penn Iron Mining Company

which affected not only the jaspilites, but also to some extent the overlying slates. The latter, where not brecciated as a whole, contain bands of brecciated material. Where brecciation occurred the slates are traversed by quartz veins and the jaspilites are ferruginized.

South of the Traders beds the Brier slates and the Curry member are exposed in pits and tunnels which furnish an almost uninterrupted section from the bottom of the former to the top of the latter. The gradation between the two members as exhibited at this place has already been described in preceding pages (pp. 350–351), and the fact that both the slates and the ores are characterized by the presence of an abundance of dolomite, which not only saturates the rocks and constitutes a matrix in which the other components lie, but also cuts the Curry beds in veins, has been likewise sufficiently emphasized (pp. 339 and 347).

The ore of the Curry mine comes largely from the Curry beds. The exact method of occurrence of the ore deposit in this case is not known. There appears to be no fold here, but the ores are so shattered that it is possible that there was movement along the contacts of the Curry with the Brier member and that the ores are the result of the ensuing brecciation, just as they are in the case of the pits to the north. In any event the ore deposit is apparently along the contact with the underlying slate, which at this place dips about 75° S.

WEST VULCAN MINE.

The West Vulcan location occupies the southeast quarter of the northeast quar' r of sec. 9, and the southwest quarter of the northwest quarter and the northwest quarter of the southwest quarter of sec. 10, T. 39 N., R. 29 W. The principal shafts now working are C shaft and No. 2 in sec. 9 and the Klondike shaft in sec. 10. (See Pls. XXXIII and XXXIV.)

The three members of the Vulcan formation can be followed uninterruptedly across the West Vulcan locations by means of exposures, test pits, and shafts. Exposures are not as common in the eastern half of the area as they are in its western half, and test pitting is not as uniformly distributed. There is abundant evidence, however, to show that the Traders member resumes its normal thickness and direction at the line between secs. 9 and 10 and continues in a straight course across the western portion of the last-named section. The greatest width of the member in sec. 9 is about 650 feet. This is due to the fold referred to in the descriptions of the geology of the Curry mine. The southern boundary of the belt is marked by the large open pits already mentioned and a group of small pits that penetrate the sandstone. Its northern boundary is not definitely known. A drill hole situated near the northern limit of the southeast quarter of the northeast quarter of sec. 9, put down at an angle of 35° N., after passing through 300 feet of sandstone, penetrated 56 feet of "ore and jasper" into dolomite. A little group of pits to the southwest of this drill hole have uncovered jaspilites with an average dip of 45° S. At the base of the sandstone is a layer of conglomerate composed in large part of bowlders of ore and jasper.

In the large pits on the southern side of the belt the relations of the rocks are, in the main, much the same as those in the pits to the west. Distinct folds are, however, absent, though slight corrugations are noted in the jaspilites. This is to be expected, since the large fold is not as sharp at this place as it is to the west, and therefore disturbances in the bedding are less marked. Just west of pit No. 2 the strain was relieved by a slight fault between the jaspilites and the Brier slates. The jaspilites in these pits are low dipping, 35° to 55° S., and they are fractured into fragments forming distinct breccias. As was the case in the pits to the west, these breccias furnished a large quantity of ore that was mined from the surface. The south sides of the pits mark the contact between the Traders member and the Brier slate. A few hundred feet west the slate can be seen to make a slight embayment north into the Traders beds, indicating the presence of a small fold conforming to the larger one in the jaspilites. South of the open pits, however, it resumes its normal direction, but with a little greater width than normal because of the diminution in the angle of dip, which here is only 50° to 65° S. Farther south the dip increases, until at the south border of the slate belt it reaches 85° S. Tunnels and pits afford a nearly complete section across the slate member, which is not essentially different from the section at the Curry mine. The dips of the slate vary from place to place, as indicated on a former page (see fig. 26, p. 358). In the large, open pit of shaft No. 1 the Curry member is well exposed.

In that portion of the West Vulcan location east of the section line between secs. 9 and 10, as has been stated, there are few exposures. In the open pit at shaft No. 1 the Curry beds can be seen dipping south at high angles. North of the jaspilites are the Brier slates bordering the north side of the pit and forming an exposure along the railroad track, on its north side, in which the strike and dip of the slates are well shown. The rocks are of the normal type, somewhat weathered and stained brown by limonite. They strike N. 70° W. and dip 65° S. at the east end of the exposure and 85° S. at the west end. South of the jaspilites, in some places forming the south side of the pit, gray slates are exposed. These, in many places, are graphitic, and on the contact with the jaspilites are much sheared. Small crumplings are noted at many places, especially where the shearing is marked. On the east side of the pit a narrow band of a greenish decomposed rock lies between the slates and the jaspilites. Sections of this rock under the microscope show slight evidences of being

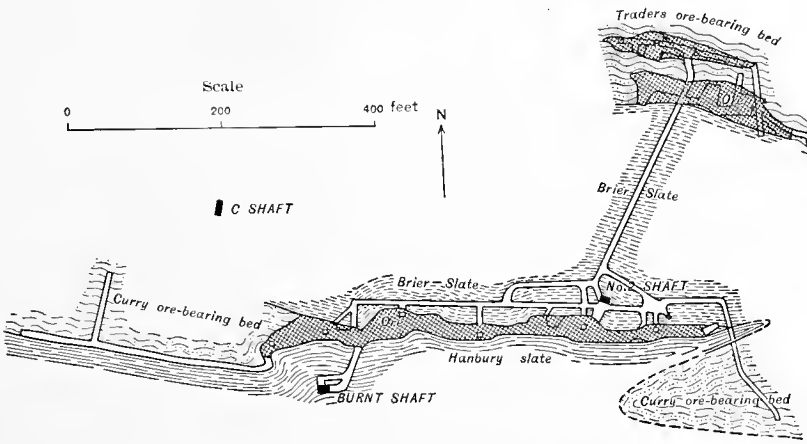


FIG. 44.—Horizontal section of the West Vulcan mine at the eighth level.

igneous in the presence of masses of secondary products that may have been derived from feldspars. The rock is probably a basic dike that cuts between the jaspilites and slates. It is the best example of a dike in the iron-bearing series within the district. Igneous intrusions within the Hanbury slate area are quite common, but intrusions into the Vulcan series are extremely rare.

All the other pits in this sixteenth of a section are small. Individually they exhibit no features that throw light on the relations of the rocks to one another. Their distribution, however, is such as to develop beyond question the existence of a fold in the Brier slates, the Curry beds, and the overlying Hanbury slates, as indicated on the map. The fold is sharp and somewhat compressed. Along its north limb the Curry member is only 50 feet wide, whereas farther west, where the dip is approximately the same, its width is about 175 feet. If this fold is the same as that discovered on the eighth level of shaft No. 2 (see p. 444, and fig. 44), its pitch must be about 40° W. North of the north side of the fold there are no explorations within less than 280 feet. At this distance there are two pits, and a third is situated 100 feet farther north. These are all in jaspilites, which must

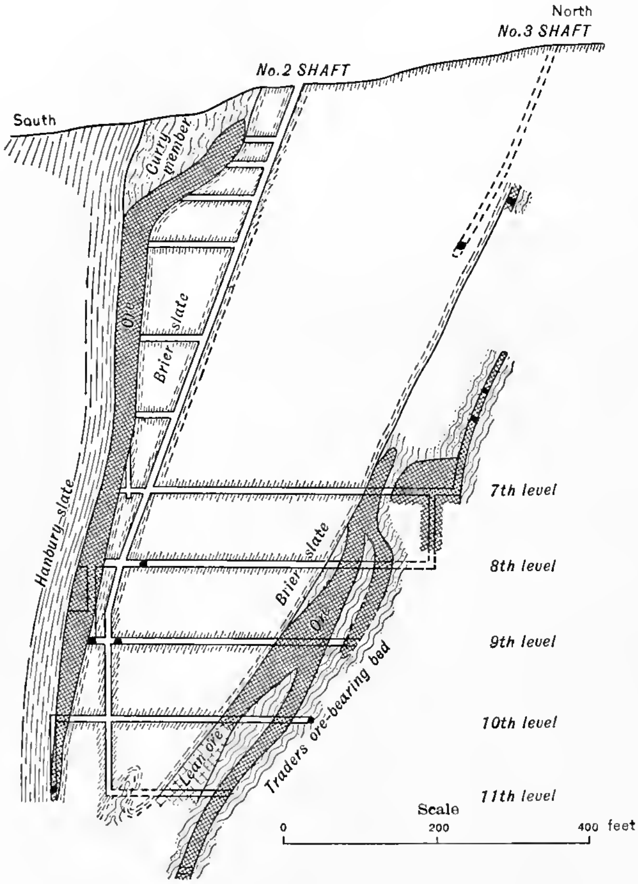


FIG. 45.—Vertical north-south cross section through No. 2 shaft, West Vulcan mine.

belong in the Traders member, the intervening space between them and the fold being occupied by the Brier slate, which would have about its normal thickness. North of the northernmost of the pits just mentioned, and distant from it about 100 feet, is an isolated excavation in talcose slates, such as usually occur between the Randville dolomite and the lowermost Vulcan beds. The dolomite must be only a few feet to the north.

The country, however, is covered by the Cambrian sandstone, which constitutes an effectual obstacle to any attempts to map the areal distribution of the Huronian formations in the absence of test pits.

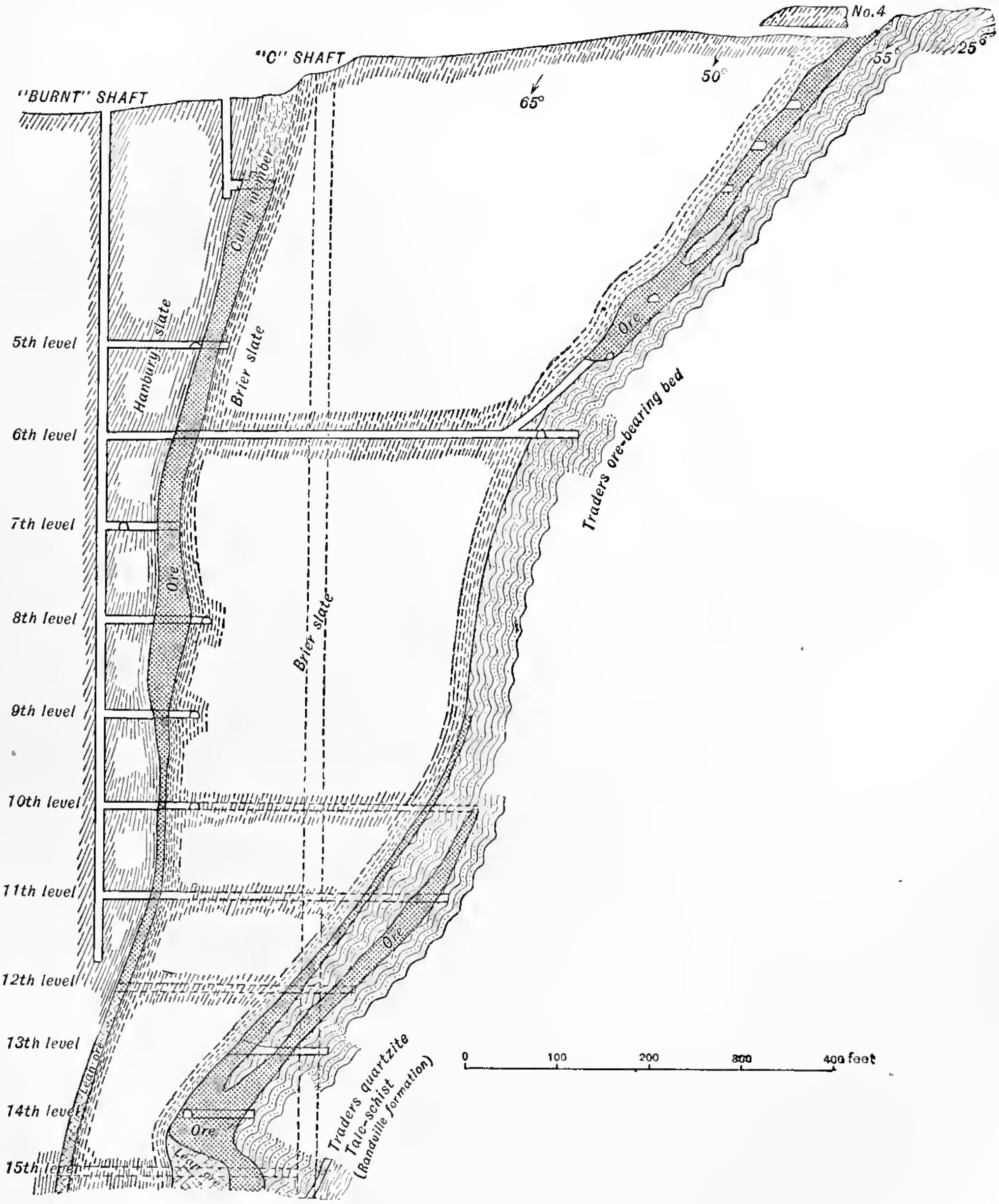


Fig. 46.—Vertical north-south cross section through Burnt shaft, West Vulcan mine.

The ore of the principal West Vulcan shafts is obtained from both the Traders and the Curry horizons, as shown in figs. 45 and 46. The ore of the lower horizon now being exploited occurs immediately below the Brier slates, at the top of the Traders member. The ore of the higher horizon occurs in the Curry member between the Brier slates and the Hanbury slate, extending from one to the other (see figs. 45 and 46). The three contacts of the two iron-bearing horizons with the Brier and Hanbury slates are planes along which movement and brecciation have occurred, and therefore where percolating waters have been active. These ore bodies have a considerable longitudinal extent, but as yet have not shown great width. The southern

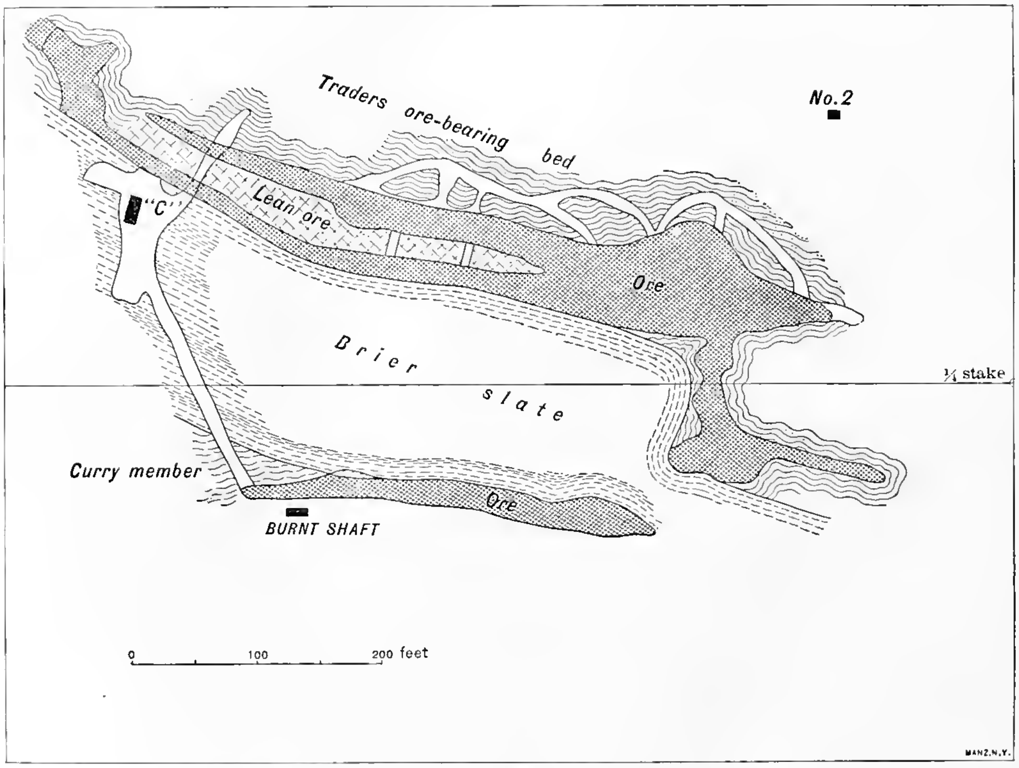


FIG. 47.—Horizontal section of the West Vulcan mine at twelfth level.

deposit of the West Vulcan mine at shaft No. 2 shows very well the relation between sharp folding, and therefore brecciation, and differential movement between the iron-bearing member and Brier and Hanbury slates. Here, at the west end of the mine, is a very sharp fold in the slate and iron-bearing member (see fig. 44). This fold appears on the surface to the east of the section line, where it is exploited in part by the Klondike shaft. From the relative positions of the apex of the syncline in the Hanbury slate at the surface and on the eighth level of shaft No. 2, it is seen that the fold pitches almost due west at about 40°. It is probable that the existence of this fold in the Curry member has a great deal to do with the productiveness of the formation at this place, for when folding is not present the Curry member is usually very lean.

The plan and cross sections of the levels leading from the "C" shaft show the same disposition of ore with respect to the surrounding rocks (see figs. 46 and 47) as at shaft No. 2. The irregular shapes of the ore bodies are beautifully shown on the plan of the twelfth level (fig. 47) and in the cross sec-

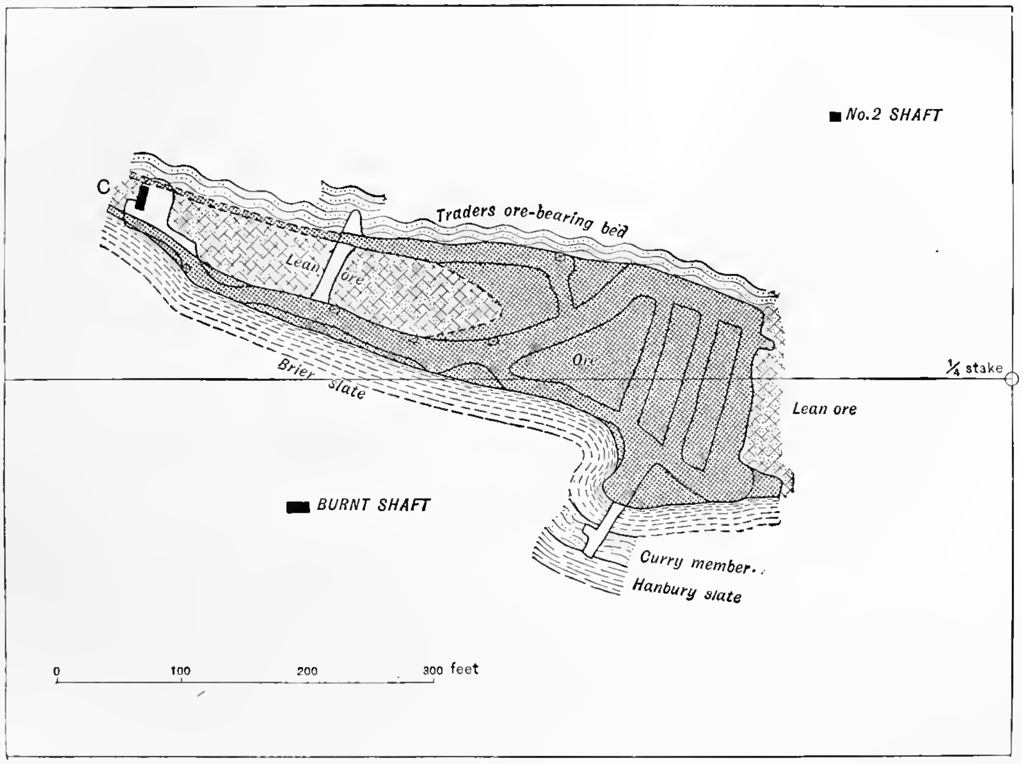


FIG. 48.—Horizontal section of West Vulcan mine at the thirteenth level.

tion (figs. 46 and 49). The southern ore body appears at present to be a western pitching lens, but additional work to the east of the cross section may show that the Curry beds at that place have been pinched out and that they reappear again farther east. It will be noted that the Brier slates have nearly disappeared, the thickness of 200 feet, which separated the two ore deposits in the ninth level, having diminished to about 30 feet on the thirteenth level. The plan of the thirteenth level (fig. 48) seems to show that the east end of the ore deposit which terminates on the twelfth level, 250 feet east of the Burnt shaft, does not extend to the depth of the thirteenth level, its place being taken by a narrow belt of jaspilite. If upon further exploration it is found that the Curry beds actually end at this place, as the ore deposit appears to do, or if it is found that they end a little farther east, their termination will undoubtedly be discovered to be due to the little fold already referred to as exhibited on the surfaces east of shaft No. 1 and on the eighth level of shaft No. 2. If this fold continued to pitch west at the same angle below the eighth level as it does between this level and the

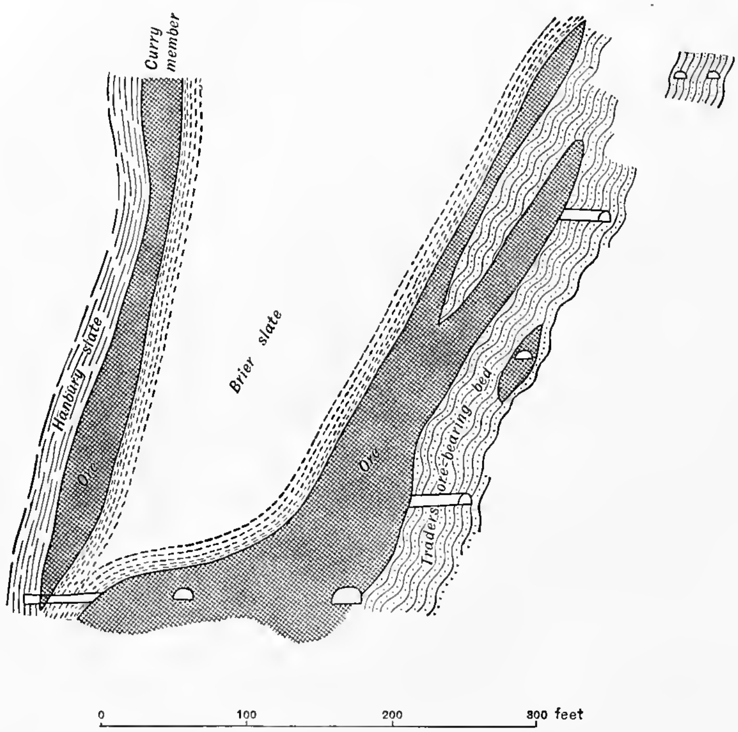


FIG. 49.—Vertical north-south cross section through West Vulcan mine, 250 feet east of the Burnt shaft. The dip is to the south.

surface its apex should occur somewhere near the position of the end of the cross cut on the thirteenth level of "C" shaft (compare also fig. 49).

Fig. 50 is a plan of the fifteenth level of the "C" shaft. This is a cross-cut traversing the entire Vulcan formation from the talc-schists underlying the Traders member to the Hanbury slates overlying the Curry member. The width of the formation is here 300 feet, of which 160 feet is occupied by the Traders member, 125 feet by the Brier slates, and 15 feet by the Curry beds. The narrowness of the Curry member may again be due to the presence of the fold alluded to above.

At the contact of the Curry jaspilites with the Hanbury slates at the south end of this crosscut and at the south end of the little crosscut extending south from the east end of the thirteenth level is the peculiar cherty-looking rock which has already been referred to as differing somewhat from anything else seen in the district, with the exception of an apparently similar rock found at the end of a drift from the Klondike shaft and interbedded in thin layers with the jaspilites on the dump heap

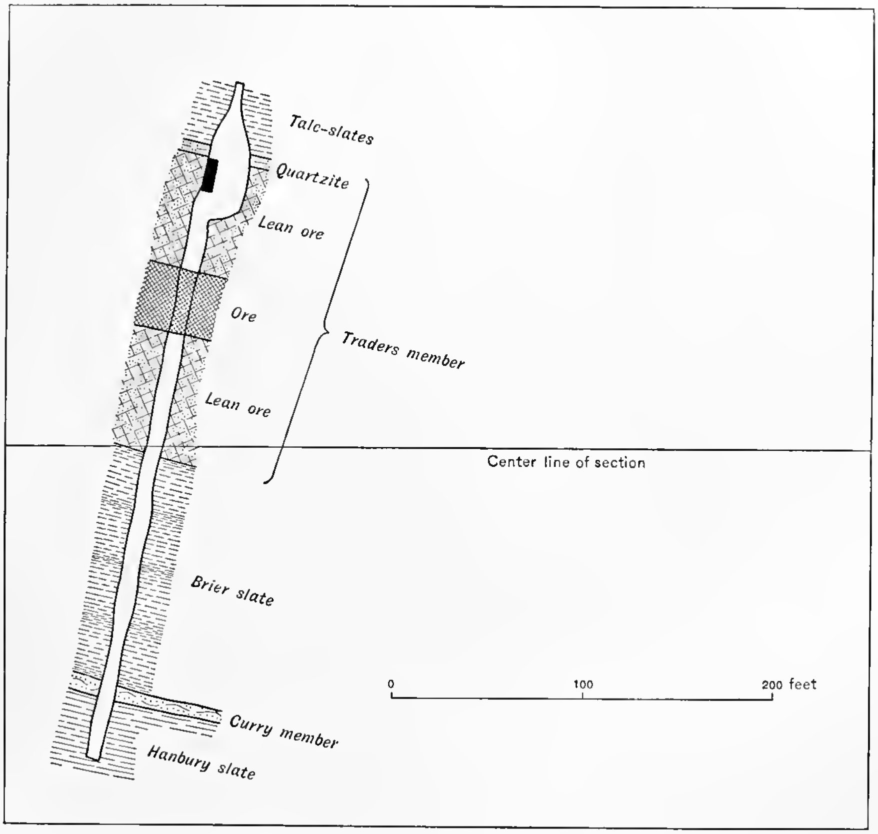


FIG. 50.—Horizontal section of West Vulcan mine at the fifteenth level.

of this shaft. The West Vulcan rock is evenly but thinly laminated, hard, dense, and gray, and is traversed by very narrow veins of dark-green chlorite along joint cracks and cut by wider veins of calcite or dolomite and of pyrite, or by veins composed of a mixture of the last-named mineral and quartz. Pyrite is also disseminated through the mass of the rock, in some places as minute granules so small as to be almost imperceptible to the unaided eye; in other places in larger particles so thickly crowded together as to make the rock almost a massive aggregate of pyrite granules. In the latter case the pyrite also occurs in veins the main trunks of which run parallel to the bedding, and send off minor branches that anastomose through the rock in all directions. In the specimen collected from the dump of the Klondike shaft the cherty rock appears as a layer between thin, dense ore layers. It contains very little pyrite, but in place of this mineral there are tiny veins of limonite and of hematite. In some places the chert passes into normal jasper. In this particular case the light-colored band appears to be a true chert belonging to the Curry member. From the depths at which the West Vulcan specimens were found, viz, 1,000 feet and 1,200 feet beneath the surface, it was at first thought that they might represent remnants of the original rock that gave rise to the jaspilites. Upon examination in thin section, however, the rock is found to be made up mainly of fragmental and cherty quartz and sericite, with the addition here and there of small fragments of plagioclase, rutile, and possibly minute particles of zircon. In some sections these are the only constituents, but in many others dolomite is also rather abundant in the form of small veins and nests disseminated irregularly through the mass. No crystals of this dolomite were observed in the specimens studied, nor was any trace of a nodular structure discernible. The rocks are plainly not original carbonates, nor are they representatives of original pyritiferous beds that may have served as the sources of the iron in the Vulcan formation. They are presumably dolomitic phases of the Hanbury slates that were silicified near the contact with the Curry beds by the same process that silicified these, the pyrite and much of the carbonate being subsequent infiltrations. The rock in the drift at the Klondike shaft was obtained from a depth of only 175 feet. It differs from the specimens from the West Vulcan levels in containing so much carbonate and so little secondary quartz that it may be rightfully called a cherty dolomite. In this particular instance the rock is minutely brecciated and is cut by both calcite and chert veins, so that it is difficult to determine exactly the proportions of chert and carbonate in the original rock. It is certain, however, that the rock does not represent original sideritic beds from which the iron of the ore deposits was obtained.

CENTRAL VULCAN AREA.

This area includes the east half of the southwest quarter of sec. 10 and the entire southeast quarter of the same section. It lies immediately east of the West Vulcan area and occupies the whole stretch of the iron-bearing belt between the West Vulcan and the East Vulcan mines. There are no mines at present operating in this district, nor are there any natural exposures of the iron-bearing rocks. A number of exploring pits and a few exploring shafts, besides the old open pit of the Central Vulcan mine, serve to trace the Curry belt about three-fourths of the way across the area. The Traders belt has been opened up at only two points—by a shaft indicated on the map (Pl. XXXIV) as Jones's shaft and by a crosscut from a shaft in about the center of the northeast quarter of the section. From Jones's shaft a drift extends south into the Brier slates. The width of the slate belt here is about 540 feet, as against about 270 feet north of the West Vulcan or Klondike fold, and 340 feet in the East Central tunnel, running north from the exploring shaft in the eastern portion of the area. The excessive width of the belt at Jones's shaft is ascribed to repetition of the beds by the fold discovered to the west. This folding necessitates the existence of a corresponding fold in the Traders beds east of Jones's shaft and a corresponding embayment in the margin of the dolomite a little farther east. These can not be observed because of the covering of sandstone. Their position is approximately indicated on the map by dotting the borders of the several belts. The thickness of the Traders beds across this area and the position of the southern boundary of the dolomite are, of course, unknown. The former is arbitrarily represented as having the same width as it has north of the Klondike fold.

The absence of known noteworthy ore deposits in this area is probably accounted for by the general absence of folding or brecciation. Where the Curry member is narrowest, and where, presumably, more or less brecciation exists, is the deposit of the Central Vulcan shafts. On the Traders belt the only promising exploration is Jones's shaft, and it is significant that this is near the fold in the Traders beds corresponding to the Klondike fold in the Curry beds.

EAST VULCAN MINE.

This area extends through the southwestern portion of sec. 11, T. 39 N., R. 29 W., just east of the Central Vulcan area (Pl. XXXV). In it are the Nos. 1, 3, and 4 shafts of the East Vulcan mine and east of it the one shaft of the Verona mine. The Vulcan beds occur on the side of the same ridge that extends all the way from the Curry mine, and which is bordered everywhere by the iron-bearing formation. The top of this ridge is covered with the sandstone that presents in so many areas an unconquerable obstacle to the investigation of the Huronian rocks. Fortunately, this sandstone covering overlaps the iron-bearing beds to only a slight extent, its southern boundary being nearly coincident with that of the

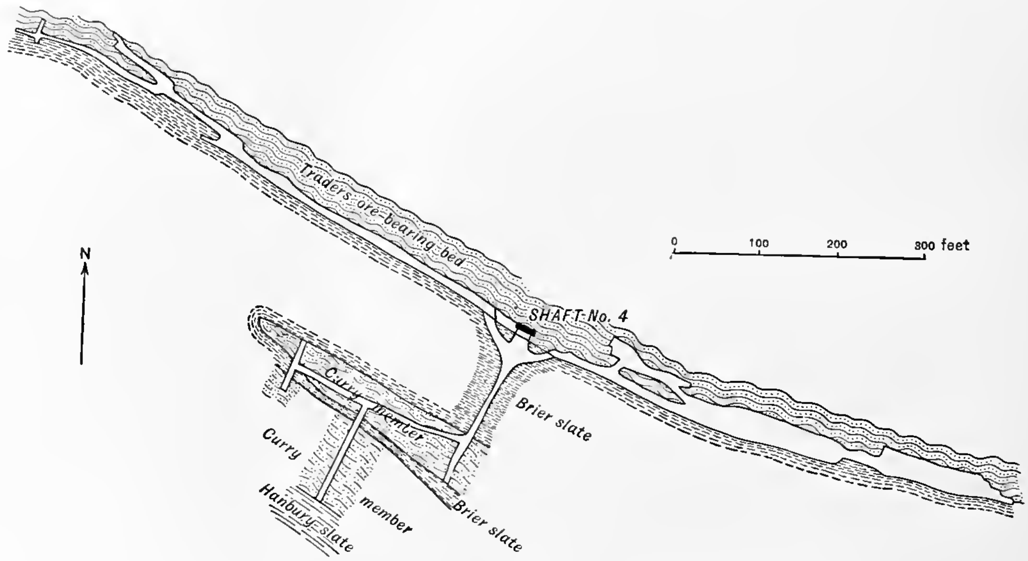
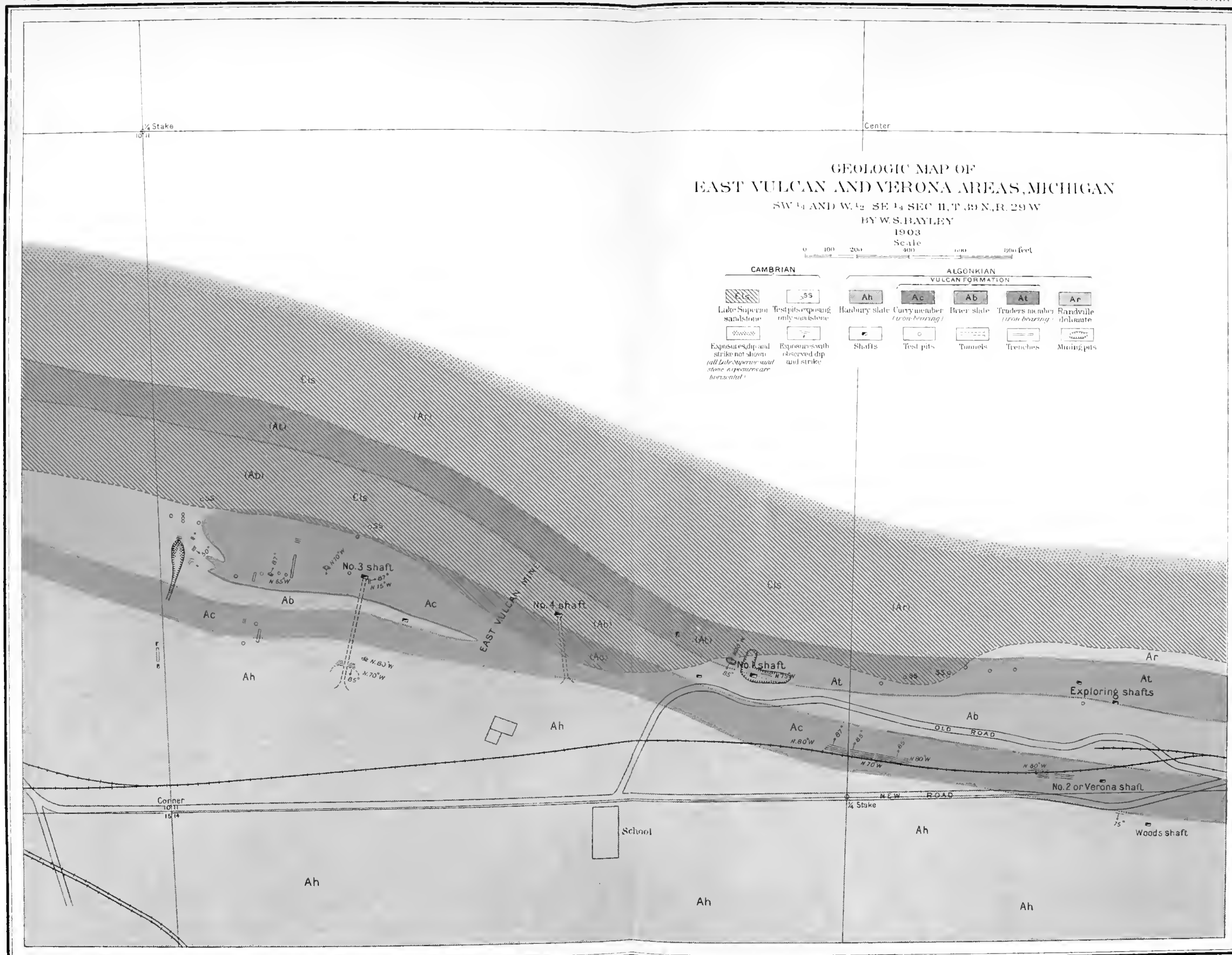


FIG. 51.—Horizontal section of East Vulcan mine at eighth level, No. 4 shaft.

Randville dolomite. It is usually, however, a little south of the southern limit of the dolomite; hence the exact position of this can only be indicated approximately. Just west of the west line of sec. 11 the Brier slate widens and passes into the section as a belt 500 to 600 feet in width. About a hundred yards farther east this belt divides into two belts, separated from one another by a belt of iron-bearing beds, which is interposed between the Traders belt to the north and the belt of Curry beds to the south Between this place and the meridian of shaft No. 4 there are therefore in a section across the Vulcan formation three belts of iron-bearing beds and two of Brier slate. Farther east the middle and southern iron-bearing belts appear



Base of this map furnished by Penn Iron Mining Company

to coalesce in consequence of the disappearance of the southern belt of Brier slate. Beyond to the east, as far as the Sturgeon River, only two iron-bearing belts and one slate belt are known. A study of the distribution of the slates as exposed by ledges and test pits near the west line of the section shows clearly that the slates wrap around the western end of the middle ore-bearing belt and that at the turn their beds are broken and contorted into many little folds pitching east. The southern belt of Brier

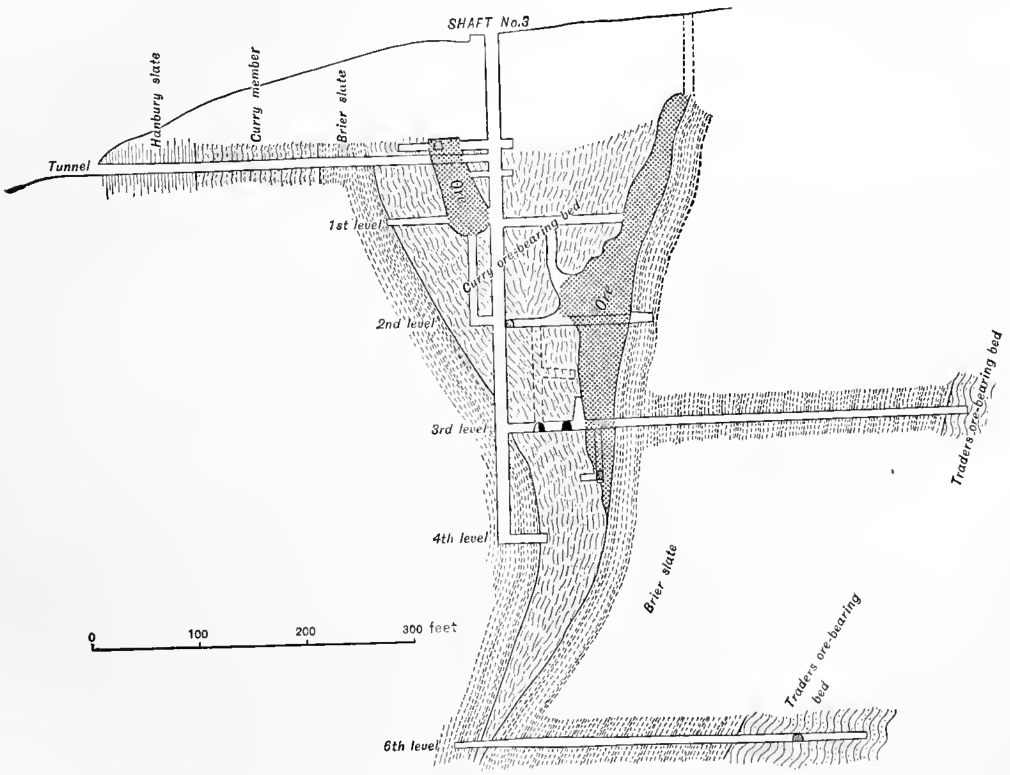


Fig. 52.—Vertical north-south cross section through shaft No. 3, East Vulcan mine. The general dip of the beds is to the south.

slates becomes thinner to the east and on the eighth level of shaft No. 4 it is only 10 or 15 feet thick (fig. 51). Thus the middle belt of the iron-bearing beds is a syncline of the Curry member, pitching east, and the southern belt of Brier slates a closely compressed fold, also pitching in the same direction. The cross section through shaft No 3 (fig. 52) shows the synclinal character of the intermediate (northern Curry) jaspilite belt very beautifully. If we assume that the end of this belt is only a short distance below the sixth level of the mine, the pitch of the fold is about 35°.

On the plan of the eighth level of shaft No. 4 (fig. 53) the fold in the Curry beds again appears.

The principal ore deposits thus far exploited in shaft No. 3 are along the sides of the syncline in the Curry beds. That being worked from shaft No. 4 is in the Traders beds, partly on the contact of these with the overlying Brier slate (see fig. 53). The dip of the contacts is about 60° S. The only indication of the presence of the dolomite in this area is the existence of talcose slates north of the Traders jaspilites on the eighth level, shaft No. 4. The contact between the two formations projected to the surface would make the surface contact occur under the sandstone covering about 300 feet north of shaft No. 4. On the map (Pl. XXXV) the Traders belt is represented as of uniform width across the area, making the southern boundary of the dolomite parallel with the southern boundary of the Traders beds. That this contact is sinuous can hardly be doubted. It is probable that it is deeply indented.

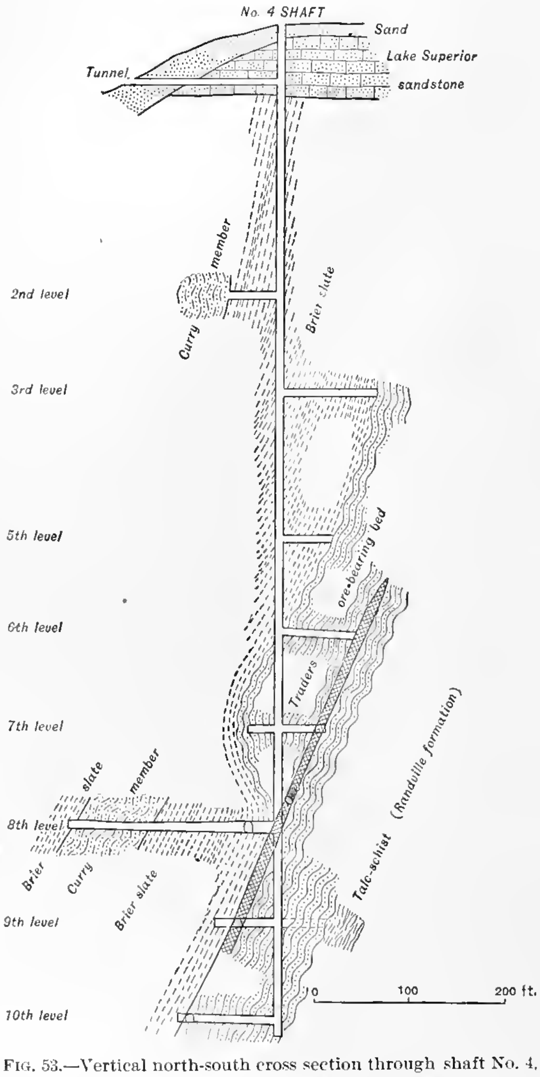
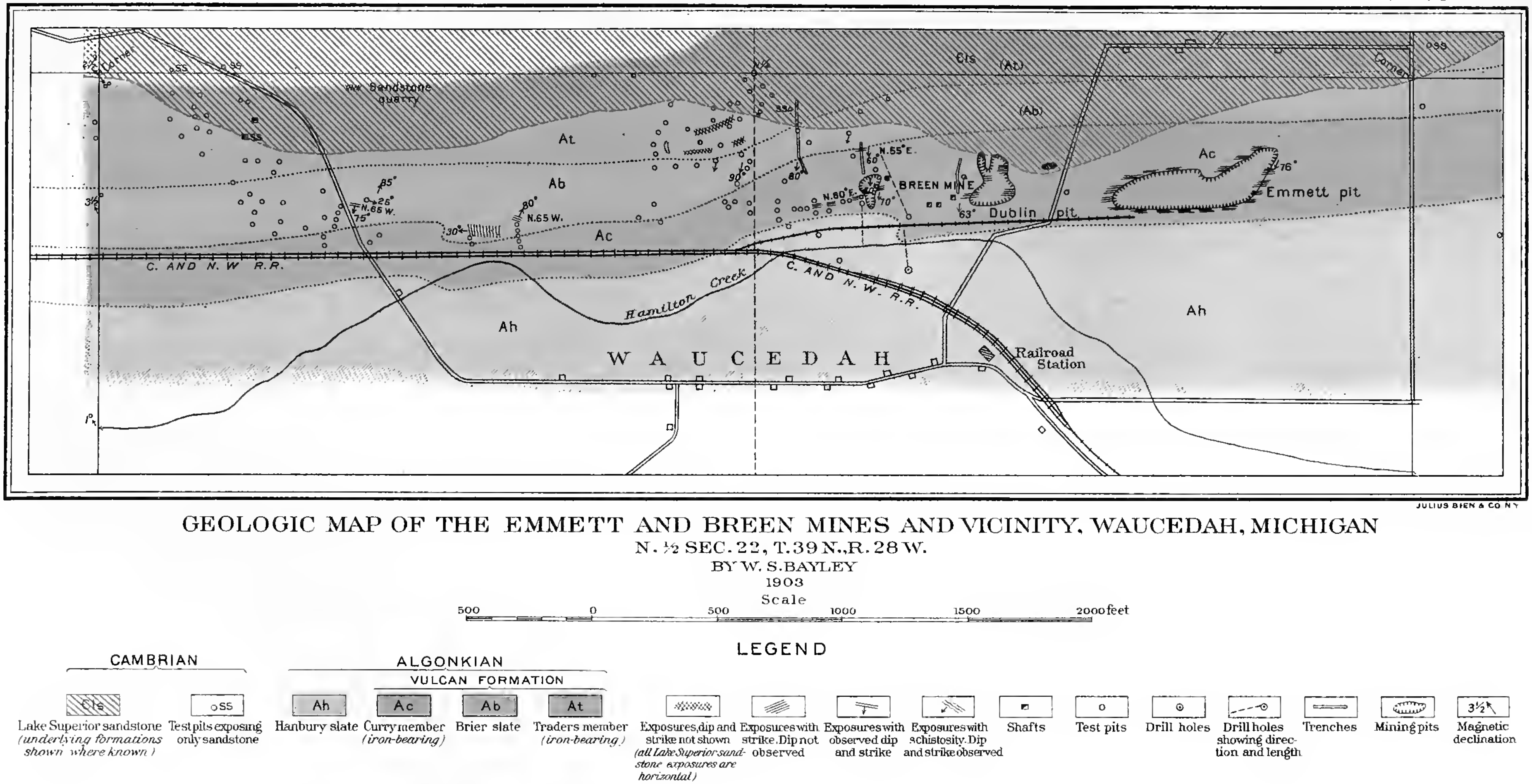


FIG. 53.—Vertical north-south cross section through shaft No. 4, East Vulcan mine. The dip of the beds is to the south.

West of shaft No. 3 the exposures are abundant. The strikes and dips observed confirm the inferences outlined above with respect to the existence of a large fold in the Curry beds at this place. The Brier slate is very much contorted beyond the observed termination of the northern belt of the Curry beds, and the exposures of the latter indicate that these, too, are folded. A little exposure just east of shaft No. 3, for



GEOLOGIC MAP OF THE EMMETT AND BREEN MINES AND VICINITY, WAUCEDAH, MICHIGAN

N. ½ SEC. 22, T. 39 N., R. 28 W.

BY W. S. BAYLEY

1903

instance, shows a strike of N. 15° W., i. e., nearly transverse to the direction of the belt, and a dip 87° E.

East of shaft No. 3 the exposures and test pits are comparatively few. The several belts appear to continue with approximately uniform width to the center of the section (north-south quarter line).

VERONA MINE.

The Verona area is east of the East Vulcan location. It occupies the southern half of the southeast quarter of sec. 11 and the northern portion of the adjoining sec. 14. The mine shaft, which was formerly known as Southeast Vulcan, is situated near the south line of the southwest quarter of the southeast quarter of sec. 11.

Information concerning the geology of the area is scanty, since rock exposures are few and the ground has not been explored to any great extent. In the cuts alongside the railroad track west of the Verona mine the Curry jaspilites are exposed in long ledges striking N. 70° to 80° W. and dipping about vertically or very high to the north. In the Woods shaft, southeast of the Verona shaft, the contact of the Hanbury slate with the Curry beds dips 75° to 80° S. The normal dip over most of the area seems to be to the south at high angles, as it is for some distance to the west, but here and there for short distances the beds are overturned to the north.

The Traders member has been traced by test pits and an exploring shaft nearly to the east edge of the section, but very little has been learned of its structural features.

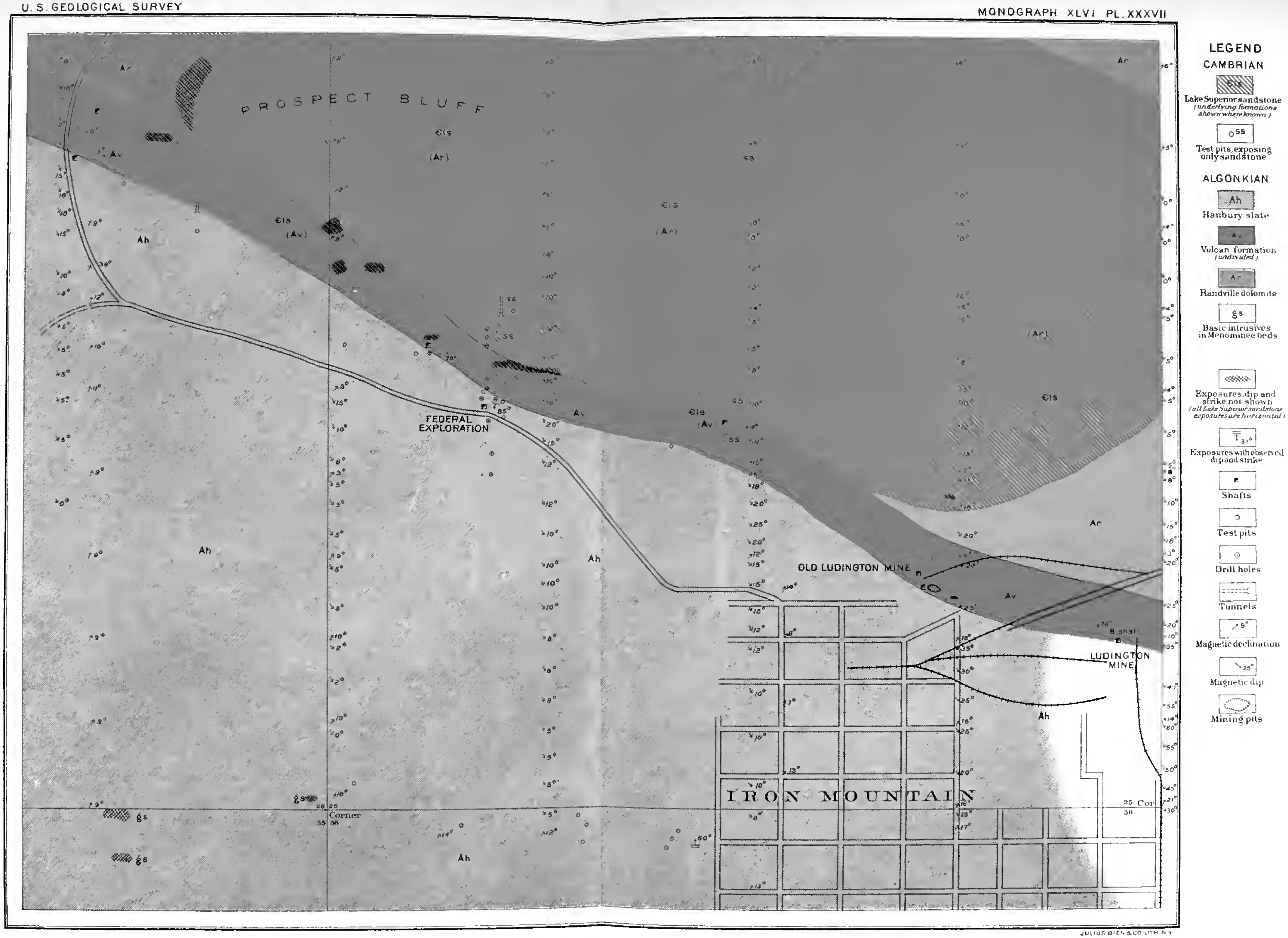
The ore deposit in the Vérona mine has been only partially explored. So far as now known, it comprises an ore body in the Curry member. Drill holes put in to the south of the seventh level, near its east end, penetrated a belt of Brier slate that apparently lies between two belts of jasper, which farther west unite and form a single belt. This may indicate the presence of a fold in the iron-bearing series, but its exact nature has not yet been ascertained.

EMMETT AND BREEN MINES.

These minés are situated at the village of Waucedah, in sec. 22, T. 39 N., R. 28 W. (Pl. XXXVI). They were the first mines opened on the Menominee range, and consequently have been more fully described than any others in the district. From the descriptions, however, very little can be gleaned with reference to the occurrence of the ores. At present the difficulties met with in attempting to decipher their geology are almost insurmountable. The great open pits are full of water. Sandstone covers the ore-bearing beds in many places, resting upon a very irregular pre-Cambrian surface, and therefore in some instances reaching considerable distances beneath the present surface. Moreover, the basal layers of this sandstone are often highly ferruginous, sometimes consisting mainly of hematite intermingled with a small portion of siliceous and other impurities. These ferruginous beds resemble very closely some of the Traders slates elsewhere, consequently it is exceedingly difficult to identify them as Cambrian. Further, the ore-bearing beds exposed in the mining pits and in their immediate vicinity contain much more fragmental material than has been encountered elsewhere. The thin sections show great numbers of round and sharp-edged quartz grains, much muscovite and other light-colored micaceous minerals, light-green earthy substances resembling serpentine, and occasional clastic grains of feldspars. The ore is in little bands between these components and in well-defined narrow layers interbedded with layers composed principally of the siliceous minerals.

To the west of the mine pits much more typical cherts and jaspilites are found, not only in the dumps of the numerous test pits scattered over the area, but also in natural ledges. By the aid of these pits the three separate belts of the Vulcan formation can be traced entirely across sec. 22, and their limits with reference to one another can be delimited with a fair degree of accuracy. On the other hand, the exact boundary of the formation with respect to the dolomite on the north and the Hanbury slate on the south can be indicated only approximately, the former because of the sandstone covering and the latter because of lack of exposures of the slates.

The Traders belt enters the section from the west at the northwest corner, continues east to the north-south quarter line, and then trends east of north and leaves the area between the north quarter post and the northeast corner of the section, its southern boundary passing through the corner or a few feet north of it. The belt is traced almost exclusively by test pits and shafts, but near the quarter post there is a large craggy ledge of cherts and jaspilites that suggests more strongly the Curry beds than the Traders. At the southwest corner of the ledge there is an excellent



GEOLOGIC MAP OF PORTIONS OF SECS. 25, 26, 35, AND 36, T. 40 N., R. 31 W., MICHIGAN

BY W. S. BAYLEY

1903

Scale

1000 500 0 1000 2000 feet

exhibition of the "bands and shots" of ore in a white or gray pellucid chert. The shots are spherical masses of hematite about the size of a small buckshot, and the bands are chains of these lying side by side in a line.

The Brier slate is shown in a number of pits and in several small ledges. The rocks exposed have the typical aspect of these slates in the greater number of instances, but in others they are strongly ferruginous and cherty. This is particularly so near the west side of the northeast quarter of the northwest quarter of the section where the rocks are contorted into numerous small folds. These folds, which pitch west at angles of about 30°, indicate the presence of a larger fold in the neighborhood which may have caused an accumulation of ore in the folded rocks. The position of this larger fold can not be mapped with our present knowledge because of the lack of sufficient exposures.

The Curry belt is not as well delimited in the western portion of the section as are the other two belts of the Vulcan formation. A few pits south of the Brier slates, however, are bottomed in an iron-bearing formation which must, from its position, be the Curry member. Near the north-south quarter line, however, and east to the east line of the section, test pits that have uncovered the Curry member are frequent, and the large open pits of the Emmett and Breen mines leave no doubt as to the existence of an iron-bearing series between the Brier and the Hanbury slates. This series of rocks dips south at about 70°. Natural exposures are to be seen at the westernmost of the Emmett pits. The jaspilites and the ores associated with them are exceedingly sandy looking, and, as has been mentioned, they contain an abundance of clastic quartz grains. Nowhere in this area are the distinctly-banded jaspilites met with, except perhaps in a few of the pits in its western portion.

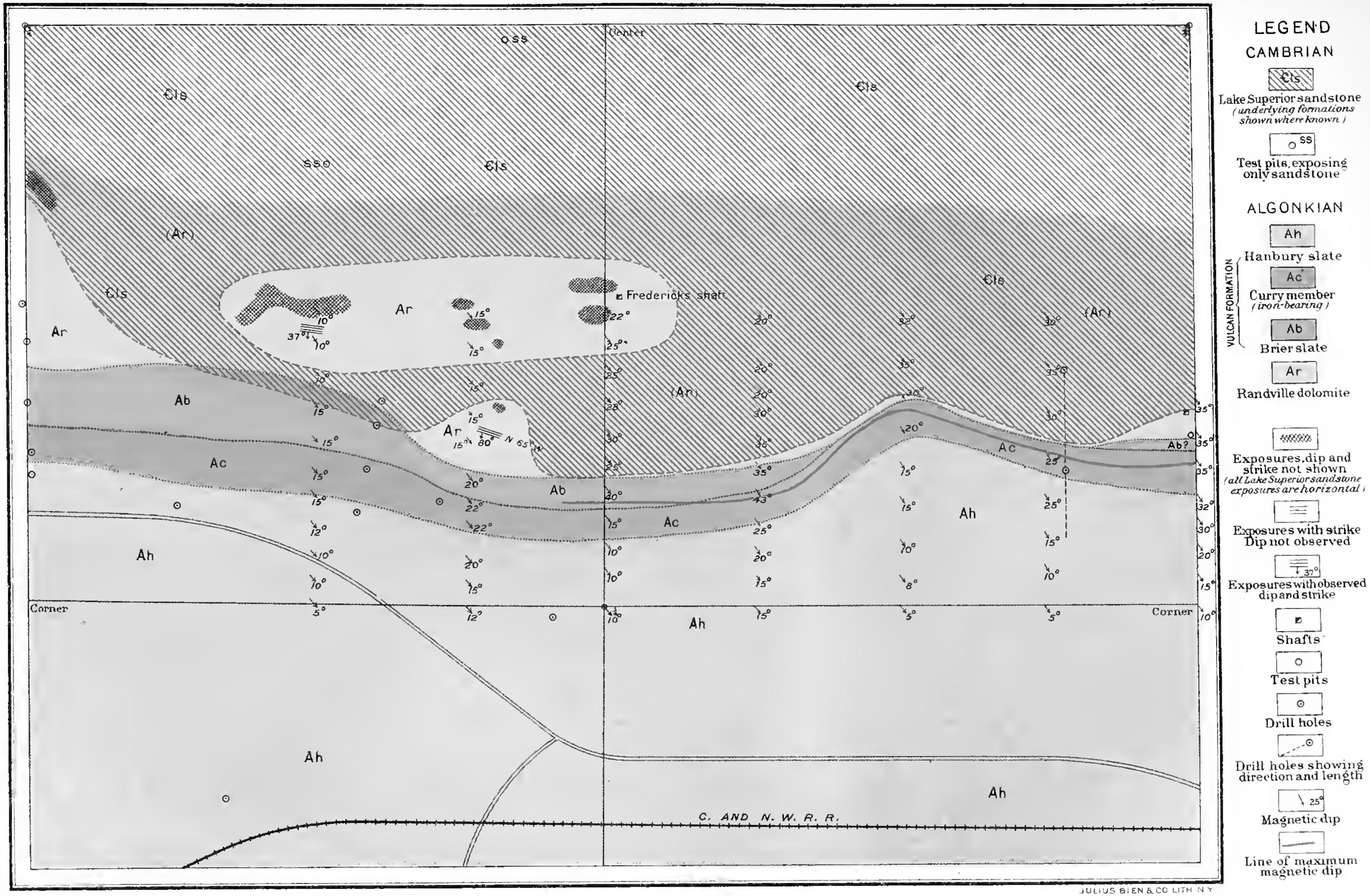
SUMMARY.

The above brief description of the mines will serve to show that the ore deposits, where of any magnitude, are situated in just such positions with respect to the surrounding rocks as might have been predicted on the assumption that the accumulation of the ores is the result of the action of percolating ground waters. The larger and richer deposits are without exception in the troughs of pitching synclines. The smaller and leaner deposits are along such contacts as would naturally be followed by descending currents. Where the rocks are brecciated near the contacts the removal of silica has proceeded with greater completeness than along contacts where there has been no brecciation and the ores are consequently rich. Where brecciation is lacking the ores are leanest. Where folding, brecciation, and other marked disturbances are lacking there the ores are lacking also.

OTHER LOCALITIES OF THE VULCAN FORMATION.

There are several other areas along the southern ore-bearing belt where the Vulcan formation is present, but from which, so far as is now known, merchantable ore deposits are absent. These emphasize the statements made above as to the manner of occurrence of the ore bodies, since they serve to show that, in the absence of marked disturbances in the jaspilite belt, there is not much hope for the discovery of valuable deposits.

Secs. 25 and 26, T. 40 N., R. 31 W.—The westernmost point at which any member of the southern belt of the Vulcan formation has been observed is at about the center of the northwest quarter of sec. 26, T. 40 N., R. 31 W. (Pl. XXXVII). From this point a series of pits and shafts extends, with short intervals between them, all the way to the east side of sec. 25, but they cover only a narrow strip of territory running through the district, and so give very little evidence as to the conditions underground. That the Vulcan formation exists from one end of the district to the other admits of no doubt. A jaspilite belt stretches throughout the entire distance, and this is bordered on the south by a series of slates. In some places the slates are red and earthy. In other places they are mottled sericitic varieties, and in still other places they resemble some phases of the Brier slates. Some of these slates are unquestionably Hanbury. Whether others are Brier or not it is impossible to say at present. The northern margin of the jaspilite belt appears to have been reached by the most northerly of the drill holes through the sandstone in the vicinity of the Federal exploration in the western portion of sec. 25 and in drifts running north from the more northerly shaft in sec. 26. In both these places the rock bordering the jaspilite is either the Randville dolomite or the cherty quartz rock lying above this. At the old Ludington mine, near the center of the southeast quarter of sec. 25, the dump contains in abundance large fragments of coarse quartzite like that at the base of the Traders member and pieces of jaspilite that are identical in appearance with the Traders jaspilites at the Aragon mine. Moreover, the situation of the old Ludington works with respect to the present



JULIUS BIEN & CO. LITH. N.Y.

GEOLOGIC MAP OF S. ½ SEC. 33, T. 40 N., R. 30 W., MICHIGAN

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 1500 2000 feet

Ludington mine indicates that both mines are at the same geological horizon, i. e., the horizon of the Traders member. Passing westward, the conditions seem to be the same at the explorations in the center of sec. 25. Farther west the jaspilite belt is narrow and is bordered on the south by slates closely resembling the Brier slates. It is probable, indeed almost certain, that near the west line of sec. 25 only one jaspilite belt is present, and this along its upper contact at the Federal exploration contains an ore body 110 to 115 feet in width. The contact dips south at 85°. At several other points lean ores have been found, but nowhere else has a distinct and well-defined ore body been discovered.

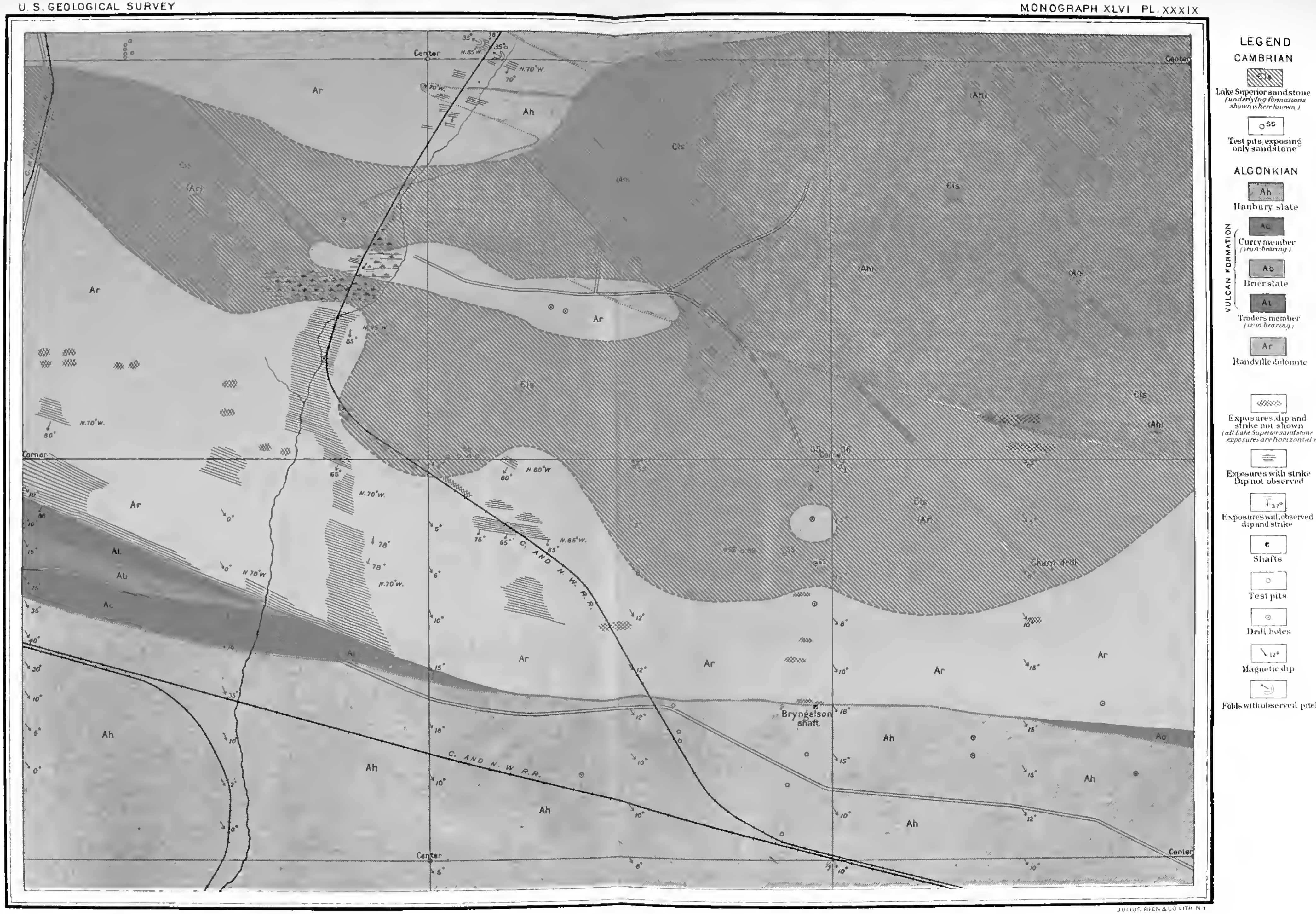
Just east of the east line of the area now being discussed all three members of the Vulcan formation are known in complicated folds that have caused a repetition of the members in several belts. These have been traced westward to within a few hundred feet of the east line of sec. 25, but have there been lost because of lack of exposures and of explorations. Until these shall have been followed continuously into sec. 25 the manner and place of their disappearance can not even be conjectured and the problem of the geology of this section and the one to the west must be left unsolved. The overlapping of the sandstone beyond the southern limit of the Randville dolomite prevents the detection of folds in this formation, if they exist, and the character of the explorations in the jaspilite belt has not been such as to develop the folds that may be present in it. It may be that folds of large size exist in the center of sec. 25, since both sharp and smooth folding on a large scale is noted in many of the jaspilite fragments on the dump of the deep shaft at this place; but, if so, there is no evidence on the surface to indicate the fact.

Sec. 33, T. 40 N., R. 30 W.—This section lies between the Keel Ridge location (Pl. XXIX) and the Quinnesec and Cundy mines (Pl. XXX). The explorations along the iron-bearing belt across the section are not sufficiently numerous to give much idea as to the distribution of the underlying rocks. An iron-bearing belt enters the southwestern corner of the section, and leaves the southeastern corner (Pl. XXXVIII). From the scanty information at hand it appears to lie between the Hanbury slate to the south and a quartzite or slate to the north. The former is believed to be the cherty phase of the Randville dolomite that lies above the more purely dolomitic beds, and the latter is thought to be a phase of the Brier slate.

This belt apparently disappears by overlap in the center of the southeast quarter of the section and gradually thickens both to the east and the west. At this place, too, there is some evidence of the northward bending of the iron-bearing belt, which may indicate a corresponding northward embayment in the dolomitic margin and a gentle fold in the entire Vulcan formation. No ore deposits have thus far been developed within the area. This is not surprising if the iron-bearing member is the Curry member, especially if, as appears to be the case, there is no sharp folding to cause brecciation in the jaspilites or to furnish troughs for the accumulation of the ores.

North of the Vulcan beds the dolomite is exposed in a number of large exposures in the western portion of the section. It has likewise been found in drill holes and a shaft in its extreme eastern portion. Elsewhere north of the northern boundary of the Vulcan beds only sandstone is known. At two places this has furnished some ore from the conglomerates at its base.

Secs. 1 and 2, T. 39 N., R. 30 W.—This area is east of Quinnesec and between this village and sec. 6, T. 39 N., R. 29 W., to be referred to later. There are no natural exposures of the Vulcan formation or of the Hanbury slate in the area, although exposures of the Randville dolomite are abundant, especially in sec. 2, T. 39 N., R. 30 W., and in sec. 35 lying to the north (Pl. XXXIX). A large number of explorations have, however, been made in the area and these have afforded a large number of facts from which the geological structure may be inferred. The dolomite exposures in secs. 2 and 35 have been described in another place (see p. 263 et seq.). The southern boundary of the formation in sec. 1 is determined with a fair degree of accuracy by exposures, pits, and drill holes. Its northern boundary can be established only approximately, as the usual layer of sandstone covers all the northern portion of the area underlain by this dolomite. Drill holes in the southwest quarter of the southeast quarter of sec. 35, and a test pit near the north line of sec. 1 indicate that the boundary is north of these points. Along the line between secs. 1 and 2 the dolomite belt is shown by drill holes and test pits to be continuous from the corner to the Bryngelson shaft, about 1,600 feet south of the corner. Its southern boundary is a continuous straight line without indentations of any kind which would indicate the presence of folds.



GEOLOGIC MAP OF PORTIONS OF SECS. 1 AND 2, T. 39 N., R. 30 W. AND SECS. 35 AND 36, T. 40 N., R. 30 W., MICHIGAN

BY W. S. BAYLEY

1903

Scale

500 0 500 1000 1500 feet

South of the dolomite the Vulcan beds should normally occur. To the west of sec. 2 the three members of the formation have been observed, but there are no exposures or explorations in the western half of the section by which they can be traced across the line. The magnetic line which is so strong in the neighborhood of the Cundy mine enters the section from the west but gradually dies out within a quarter of a mile of its west line. Near the center of sec. 1, in the eastern portion of the area, a drill hole penetrated a few feet of lean ore lying between Hanbury slates and a narrow band of gray slates between it and the dolomite. The entire Vulcan series at this place is not 30 feet thick.

Between this drill hole and the western line of sec. 2 the explorations have shown only Hanbury slate south of the dolomite. This is often graphitic near the dolomite and is in some places traversed by a great many quartz veins. In the Bryngelson shaft and in a trench a few feet to the west the slate is in contact with the dolomite (see p. 366), so that there is no possibility of the presence of the Vulcan beds between them. The complete disappearance of the Vulcan formation after entering the area from the west and its gradual thinning as it enters the area from the east is explained as due to overlap of the Hanbury slate along a sinking shore line (see pp. 370–372).

Sec. 6, T. 39 N., R. 29 W.—This section has probably proved more disappointing to explorers than any other in the entire Menominee district. In the search for the westward extension of the Norway and Aragon ore deposits an immense amount of money has been expended in explorations, and even now, with the results of all these explorations in hand, we are nevertheless still very much in the dark as to the geology of the section. There seems, however, to be no possibility of the existence of undiscovered folds in the area, and therefore not much possibility of the presence of large ore deposits comparable with those of the Norway and Aragon mines.

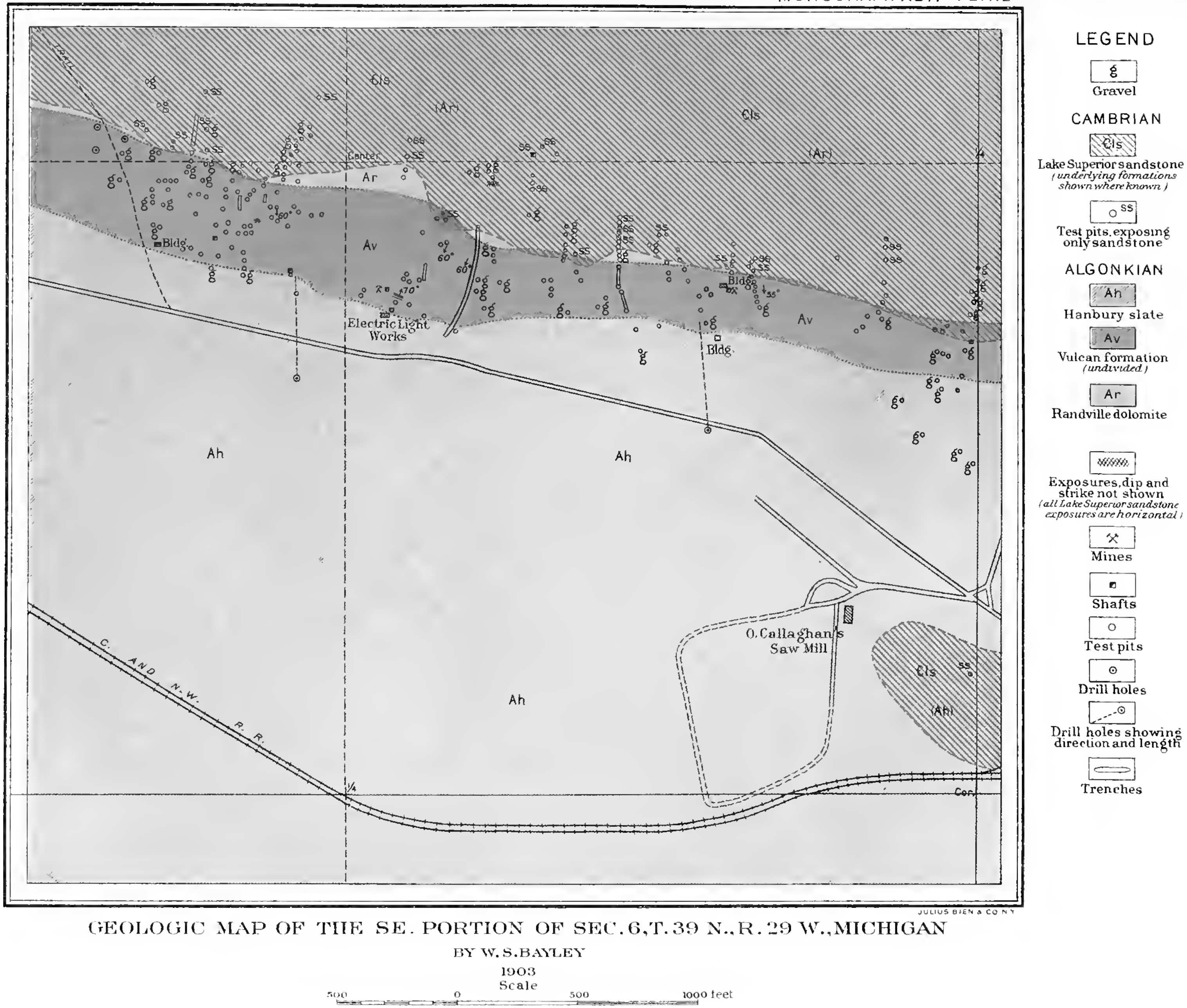
The succession, beginning at the north, is: Dolomite, followed by light-colored slates that are talcose in part, and in part quartzose; coarse quartzite, like that elsewhere near the base of the Traders beds; a jaspilite belt from 250 to 450 feet in width, and, finally, a wide belt of slate (Pl. XL). The boundary between the Lower and the Upper Menominee is drawn at the top of the talcose slates. The Vulcan beds dip south at angles varying between 55° and 70°, and strike nearly east-west. The southern slate at some places is in some respects like the typical Brier slate; at other places it is the typical gray slate of the Hanbury formation. Its maximum width, as developed by drilling, is about 400 feet. South of this point the nature of the underlying rock is unknown. It is possible, of course, that the slate is Brier and that elsewhere to the south is a second jaspilite belt, and that the Hanbury slate is much farther south. On the map the slate in which the drills were put down is placed in the Hanbury formation. This would make the jaspilite belt to the north represent the Curry member, unless this member, together with all the Brier slate, is absent, and this is not considered probable. The true age of the iron-bearing beds and the slate to the south of them can not be determined until the hiatus between the Norway and Cyclops mines and the west line of sec. 5 has been explored sufficiently to enable one to trace the three members of the Vulcan formation from the mines westward into sec. 6.

Where it enters the section from the east the jaspilite belt is about 250 feet wide. It keeps this breadth uniformly to near the center of the section, where it gradually widens to about 400 feet or 450 feet, and beyond the center it again contracts slightly. The expansion near the center of the section is evidently due partly to folding.

In the open pit east of the shaft north of the old electric-light works the jaspilites are well exposed in sharp folds pitching west. The dip in places is 70° N. Since the dip farther north is 60° S., there may be a fold in the beds between these points. Nowhere else in the belt is there any evidence of the presence of folds, although subordinate folding within the formation no doubt exists. The normal dip of the jaspilites is about 55° to 60° S. To the north near the dolomite it becomes flatter, and on the top of the hill under the sandstone it is quite flat.

The rocks are typical jaspilites composed of alternating layers of schistose hematite and dense waxy jasper. The jasper is often in flat lenticular bands, and in some cases these bands are cherty rather than jasper like.

The slate belt between the jaspilites and the dolomite appears to be much wider than it usually is, but this great width may be due to the flat dip of the upper surface of the dolomite, corresponding to the flat dip of the overlying jaspilites.



GEOLOGIC MAP OF THE SE. PORTION OF SEC. 6, T. 39 N., R. 29 W., MICHIGAN

BY W. S. BAYLEY

1903

An interesting feature of some of the deeper pits near the center of the section is the presence of an abundance of chert on their dumps. This is usually dark colored, flinty and very much brecciated, the fragments consisting very largely of a pellucid white chert. Large bowlders of the same chert are sometimes found inclosed in the basal layers of the overlying sandstone. Some of these bowlders are finely brecciated, but others consist of the dark chert traversed by veins of the white variety. The fragments in the brecciated phases are probably shattered portions of veins of this kind, and the rock is probably from a chert layer at the top of the dolomite.

Secs. 12 and 13, T. 39 N., R. 29 W.—The most easterly exposures of the Vulcan formation, with the exception of those occurring at Waucedah, are to be found on the west side of the Sturgeon River, near the north quarter post of sec. 13, T. 39 N., R. 29 W. (Pl. XLI.) The greater portion of the south half of the section to the north is occupied by the Randville dolomite, the exposures of which have been described on preceding pages (pp. 271–273). North of the dolomite the country is supposed to be underlain by a westward-pitching syncline of the Hanbury slate, and northeast by an eastward-pitching syncline of the Vulcan formation (see pp. 404–407). On the south the dolomite is bordered by a belt of the Vulcan formation about 900 feet wide, and south of this is the Hanbury slate.

The Vulcan beds are exposed by trenches and test pits, near the north-south quarter line of sec. 13 and by a group of pits near the center of the northwest quarter of the northwest quarter of the section. All three members of the formation are represented in their typical development. The jaspilites in the trench strike east-west and dip vertically. The dump of the northernmost pit near the southernmost ledges of dolomite shows the usual coarse quartzite at the base of the Traders member, and the talcose slates that usually separate the Traders quartzites and jaspilites from the dolomite. This latter rock nearest the contact with the overlying Vulcan beds is brecciated, and some specimens of the breccias look very conglomeratic Close search through the conglomeratic phases, however, revealed no foreign fragments that might indicate that the rock was water deposited.

HANBURY SLATE.

DISTRIBUTION AND TOPOGRAPHY.

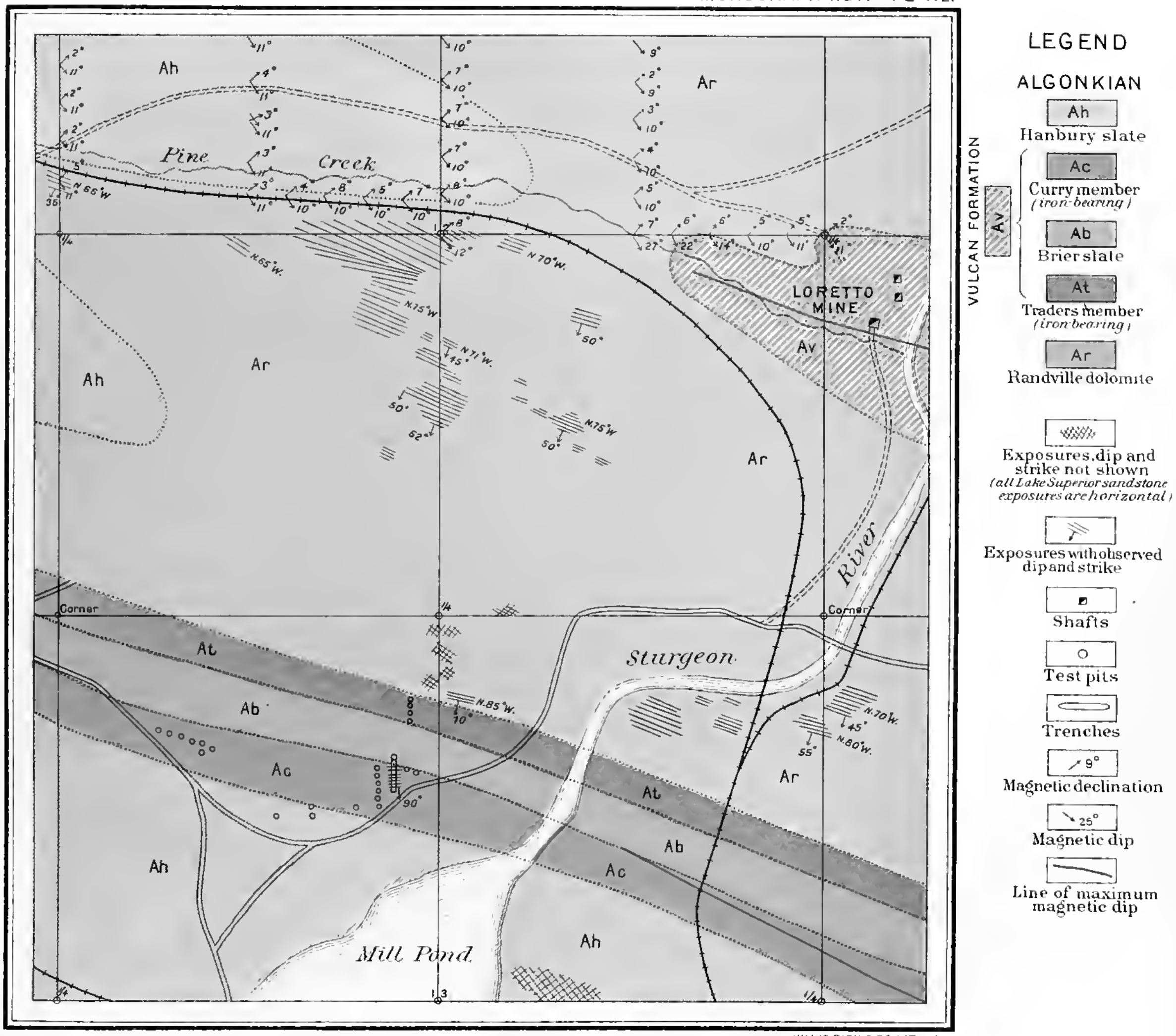
The Hanbury slate occurs mainly in three large belts constituting valleys that correspond with synclines between the older rocks. It occupies nearly all the low ground in the Menominee trough, forming a plain broken only by heaps of glacial material deposited upon it, by the protrusions of a few hillocks composed of the harder slates, or by equally resistant greenstones. Exposures in the slate areas are very rare and widely scattered. They are confined almost exclusively to the hillocks to which reference has been made and to the lower slopes of some of the stream valleys. The slates are also exposed in a number of places on the sides of cuts along the railroad right of way.

Since the main part of the Menominee trough is a westward-pitching synclinorium 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 schists. The northern part turns northwest and leaves the Menominee district at the northern limit of the area mapped, while the southern portion coalesces with the middle belt and crosses the Menominee River into Wisconsin. East of Iron Hill the two northern belts again coalesce and extend as a single belt to the Sturgeon River. Near the longitude of Waucedah all the slates disappear to the east beneath the Paleozoic beds.

LITHOLOGY.

The formation comprises black and gray clay slates, gray calcareous slates, graphite slates, graywackes, thin beds of quartzite, occasional beds of ferruginous dolomite, and rarer bodies of ferruginous chert and iron oxide. These rocks present no unusual characteristics. The argillaceous slates are like normal slates elsewhere. The quartzites and graywackes are likewise normal. The calcareous slates are either fine-grained quartzites cemented by a calcareous or dolomitic matrix, or are normal clay slates with nests and crystals of some carbonate scattered through their masses. The dolomites and cherts are like those in the Randville and Vulcan formations.

The predominant rocks of the formation are the gray clay slates and the calcareous slates. The latter are more abundant in the lower portions of the formation and the former in the upper portions, but the exact vertical



GEOLOGIC MAP OF
PORTION OF SECS. 12 AND 13, T. 39 N., R. 29 W., MICHIGAN
BY W. S. BAYLEY
1903

Scale
1000 0 1000 2000 feet

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 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.

Clay slates.—The clay slates are mostly gray or black normal argillaceous slates, in which there is always more or less ferruginous matter. Where exposed to the weather they are light in color and have a shaly character. Muscovite or sericite then becomes prominent and their iron components are decomposed to red ocherous compounds. Where most altered the rocks are light-red sericite-slates or shales. When the slates contain small quantities of calcareous components their weathering 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." A few varieties of the black slates are quartzose. These are denser and more compact than the more purely argillaceous varieties. They are not at all shaly and they possess little or no slaty cleavage. These rocks grade into the quartzites and graywackes.

Under the microscope the argillaceous varieties of the clay slates are seen to consist of small splinters and grains of quartz and an occasional grain of feldspar lying in a crystalline matrix composed of interlocking quartz, small spicules of sericite, kaolin, and chlorite, larger plates of the last-named mineral, and the usual accessories of slates, rutile crystals and needles, limonite clumps, and a few nests of calcite. In some specimens the sericite preponderates over all the other constituents; in others the chloritic component is in excess, and in yet other phases quartz is most prominent. Thus the normal slates pass on the one side into sericite-slates and on the other side into quartzite. Usually there is an interlamination of quartzose and chloritic or sericitic beds with an average thickness of not more than one-fourth inch.

The most typical sericite-slates, or perhaps more properly schists, differ from the argillaceous ones principally in the greater size of the individual sericite fibers. Because of the larger dimensions of this micaceous component the schistosity of these slates is much more pronounced than that of the gray and black argillaceous phases.

Upon exposure to weathering influences many of the argillaceous and sericitic slates, as has been stated, pass into mottled "calico" slates. The rocks are bleached in certain places by the alteration of the greenish sericite and chlorite into colorless compounds except near cracks, where the chlorite is weathered into a mass of ocher and quartz. The latter change causes red stains to spread out from the walls of all cavities into which water can penetrate, thus producing red irregularly shaped mottlings against the bleached, white background.

The graphitic varieties of the clay slates are black, very fissile, thinly laminated rocks. They appear to be limited to those portions of the formation near its contact with ferruginous beds. At any rate, they have been seen only in association with the underlying Curry member and at horizons a few hundred feet above the base of the slate formation, where cherts and ores have been developed, but they do not everywhere occur at the base of the formation. This frequent association of ore and graphitic slates suggests the possibility of a genetic relationship between them which has been referred to in another place (see p. 354). The graphitic slates appear to grade laterally into the normal gray slates, of which they seem to be local modifications. Since they occur mainly near contacts the graphitic slates have usually been tremendously sheared into very thin folia with many repeated, complicated, and irregular contortions. When stained by ocherous deposits these slates are recognizable by the curved or convex character of the plates into which they usually split.

Examined microscopically the graphitic slates are usually very fine grained. They contain an abundance of sericite and kaolin, forming an extremely fine-grained web in which small quartz grains are embedded. The graphite coats the walls of shearing joints. It is observable under the microscope only when the sections are perpendicular to the cleavage. All specimens are schistose in parallel positions, and the calcite, limonite, and most of the crystallized quartz grains are elongated in the same direction. In many sections microscopical folds are visible which are counterparts of the folds seen in hand specimens.

Graywackes and quartzites.—The graywackes and quartzites of the Hanbury formation are normal rocks of their kind, requiring no special description. They both occur in comparatively thin beds interlaminated with slates, more frequently in the lower part of the formation than in the upper portion. The quartzites are more abundant than the graywackes, but neither are common.

In one place only within the district is the quartzite present in any considerable quantity. This is near the point where the Chicago and Northwestern Railway crosses the line between sec. 19 in T. 40 N., R. 30 W., and sec. 24, T. 40 N., R. 31 W. In the cut through which the right of way runs beautifully banded slates are exposed, striking in general N. 75° W. and dipping nearly vertically. With these are interbedded narrow bands of quartzite or graywacke. The slates are distinctly ripple marked, and, together with the quartzites, are compressed into little folds pitching steeply (45° or more) to the west. The slates are green and cherty and the quartzite is gray or white and novaculitic. To the east the quartzose layers pass into cherty and ferruginous bands. The chert bands wedge out and then occur in flat lenticules surrounded by slate. Farther east the ledge disappears, but the ground is strewn with great fragments and bowlders of a fairly coarse-grained calcareous quartzite cut by a few quartz veins.

This quartzite is light gray in color and its weathered surface is pitted with little holes marking the places from which some constituent, probably calcite, has been removed. West of the railroad some few hundred steps the quartzite is exposed in place on the side of a little knob overlooking a swamp. Here it appears to have a thickness of at least 50 feet.

Although no rocks other than those described occur in the near neighborhood, which might serve to determine the relations of these, the petrographical character of the slates is so distinctly like that of the Hanbury slates elsewhere that no doubt is felt as to the stratigraphical position of the beds. They are more cherty than is usually the case, but, as will be shown later, they contain no greater proportion of cherty material than is met with at several other places in the slate area. The occurrence is particularly interesting for the great thickness of the quartzite bed.

Under the microscope the quartzite differs from the quartzite of the Sturgeon formation in containing many large and small fragments of plagioclase, orthoclase, and microcline. Moreover, its quartz grains lack the distinct clastic appearance of those in the Sturgeon quartzites. The grains seem to be corroded, and neighboring grains therefore appear to interlock by irregular sutures. Calcite or dolomite is also present in the rock, partly as little nests between the quartz grains and partly as a sparse cement. It may be due to the presence of this component that the quartz grains have the corroded outlines.

Calcareous slates and dolomites.—By the addition of calcareous material the argillaceous slates pass into the calcareous slates. These sometimes contain as much as 50 per cent of calcite or dolomite as a cement. With an increase in the carbonate the slates lose their slaty character, become more massive, and finally pass into beds of limestone or dolomite measuring from a few inches to 20 feet in thickness. On weathered surfaces both the dolomite and the calcareous slates are often coated with a skin of brown ocherous limonite, which in the case of some of the massive dolomites reaches a thickness of an inch or more. Much of the limonite is pseudomorphous after siderite. These facts show that the dolomites are sideritic, and that the siderite has partly decomposed, producing limonite.

When fresh the calcareous slates are lighter colored than the corresponding argillaceous phases, their color being usually some shade of gray. They lack the silvery luster of the sericitic varieties and their schistosity. Where their weathered surfaces are not incrusted with limonite they are pitted with little pores from which the carbonate has been dissolved.

The calcareous slates may be divided into two classes: (1) Those into which carbonate-bearing solutions infiltrated, depositing nests of calcite and dolomite, and (2) those in which these carbonates and siderite appear as original components in the form of small grains and tiny rhombohedral crystals or groups of crystals. The first class includes those slates, cut by calcite and dolomite veins, which are saturated with carbonate material. This occurs either in elongated nests arranged in lines along the cleavage planes or as a matrix in which the sericitic, quartzose, and chloritic components of the rock are embedded. In the second class the carbonate appears to be the embedded material. The matrix surrounding the carbonate is a fine-grained aggregate, with the composition and structure of the argillaceous slates. As in the first variety, the carbonate is arranged in lines that are parallel to the cleavage.

The calcareous slates grade into dolomites which vary in color through many shades of gray and pink. The majority are dark-gray, impure varieties, very different from the dolomite of the Randville formation, while a few beds consist of pink varieties identical in appearance with many specimens of the Randville dolomite. In many cases the dolomites are closely associated with cherts and sometimes with thin beds of limonite or other ferruginous compounds. Their lithological features will be referred to at greater length in the discussion of occurrences.

Cherts and ferruginous oxides.—The ferruginous cherts and iron oxides are not known to be present in the Hanbury slate in large quantity. Indeed, they are usually 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 a finely granular texture. They occur as thin seams and veins traversing the slates and dolomites, and as thin beds interlaminated with equally thin beds or seams of hard siliceous and ocherous slates and with thicker beds of dolomite.

Wherever the cherts occur there is usually found also a greater or less quantity of some iron oxide. Sometimes this appears as small veins of pure hematite cutting through the cherts, sometimes as coatings of hematite on the walls of cracks traversing the slates, sometimes as small vugs inclosed in shattered cherts, sometimes as druses covering the walls of the cavities in an extremely porous chert, sometimes in distinct bands interlaminated with bands of graywacke or quartzite, and sometimes 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 or black. Where but slightly ferruginous they still plainly exhibit their true character. When, however, the proportion of the iron oxides is large, but few traces of the original slate remain, and the rock resembles a slaty ocher or a compact siliceous ore.

At several places, more particularly at one place in the slate area near the south quarter post of sec. 21, T. 39 N., R. 28 W., the banding of the material obtained from a deep shaft appears on the weathered surfaces to be as even and as well defined as the banding of the ores and ferruginous quartzose slates of the Curry member. Close inspection of the hand specimens, however, especially where made on fresh fracture surfaces, shows that the resemblance to the Curry rock is illusory. The banded rock is mainly a graywacke interlaminated here and there with layers of slate. A set of cracks cuts the graywacke parallel to its bedding planes, and along these the percolating waters found ready passage. An earthy hematite was deposited in the cracks and in the rock mass adjacent to them, thus producing bands of ore material separated by belts of the graywacke, in which there was little deposition of ore.

Large deposits of hematite, such as characterize the Hanbury formation west of the Menominee River, in the Florence, Crystal Falls, and Iron River districts, are not known in the Menominee district; but ore bodies sufficiently large to warrant exploration have been discovered at several widely separated localities. These localities will be referred to more particularly in subsequent pages and the character of the cherts and ores in each will be briefly described.

Igneous rocks and their contact deposits.—In several places the slaty series is intruded by greenstones mainly in the form of dikes. The igneous rocks in their present condition 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.

The slates in contact with the igneous rocks are in many instances metamorphosed to a slight extent. Actinolite has developed in them as single long, slender, needles penetrating all the other components and as radial groups of needles. A few large plates of dark-green chlorite also occur in some of the metamorphosed phases and a little altered feldspar is present in very irregularly shaped masses forming a sort of matrix by which all the other constituents are surrounded. This feldspar, which is now partly changed to kaolin or saussurite and is reddened by ferruginous dust particles, must have been infused into the sedimentary rock from the neighboring intrusive. In most cases the quartz of the original slates has also suffered considerable change. Its fragmental character has largely disappeared. Its contours are rounded, its peripheries corroded, and neighboring grains interlock. The fine débris in the matrix has entirely recrystallized. In some specimens calcite is present in small quantity; in others it occurs in large quantity. In both cases it is apparently an alteration product of the feldspar.

FOLDING AND SECONDARY STRUCTURES.

The major folding of the Hanbury slate corresponds with that of the underlying formations. Along a north-south cross section there are three major synclines with east-west axes, the major anticlines having been eroded save at the ends of the central dolomite belt and at the east end of the western area of Quinnesec schist. At these places the slates should present plunging anticlines. The exposures necessary to confirm this inference are lacking. The north-south major folds corresponding to the broad north-south folds of the Randville dolomite are not easily recognizable. The slate belts, however, widen to the west and wrap around both ends of the central dolomite area and around the east end of the western Quinnesec schist area. There must be anticlinal arches over the dolomite and the schists with a syncline between, and there must also exist a second syncline between the eastern end of the central dolomite belt and the Loretto mine. The slates must likewise pass over the ore-bearing beds at this place in an anticline and beneath the Paleozoic beds to the east by another syncline. Thus the formation must be affected by three broad anticlines and three broad synclines with north-south axes.

Within the major folds the slates are crowded together in many close minor folds, here pitching in one direction, and there in another. No definite system has been discovered in the minor folds, chiefly, perhaps, because outcrops are so scarce. In general, however, the pitch of these folds in the western portion of the district is to the west, and in its eastern portion toward the east. On one or two of the hillocks on which exposures are fairly plentiful it was observed, moreover, that, as a rule, the little folds at the east ends of the hillocks pitch to the west, and those on the west ends to the east, at angles varying between 20° and 45°. These hillocks thus constitute open cross synclines with approximately north-south axes, corresponding to the broad north-south folds of the formation as a whole.

The east-west minor folds, on the other hand, are extremely close folds. Frequently on ledges that show cross sections 10 or 12 feet across several small anticlines or synclines may be plainly seen, so closely compressed that the dips of their opposite limbs vary but a few degrees. Frequently, too, the folds are overturned so that the dips of the limbs are in the same direction. On horizontal exposures these close folds are often very difficult, if not impossible, to detect, so that in many cases the closely folded beds appear to be consecutive. The strikes of the folds are usually a little north of west, and, consequently, the strike of the bedding is approximately in the same direction, and this is also the direction of trend of the Menominee trough. Departures from this strike are noticeable in many instances, but the variations are not great except in a few restricted areas where the pitch due to cross folding is marked. Small folds with dimensions of an inch or two are present everywhere. These often cause flutings and puckerings of the strata to such an extent that even approximate strikes and dips can not be obtained. In some places lens-shaped deposits of quartz have been found between the layers of the slate at the apices of the little anticlines and in the troughs of the little synclines.

The strong north-south compression of the slate beds, producing the close east-west folds, also impressed upon all the weaker members of the slate 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. In addition to this cleavage there was also often produced a set of fracture planes or joints at right angles to the cleavage. These latter 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 flat horizontal surfaces two sets of these joints are sometimes seen cutting each other at acute angles, and about each slight faulting has occurred. All of the phenomena presented by the slates indicate that they were subjected to powerful north-south stresses acting nearly at right angles to the axis of the Menominee trough and producing the close east-west folds, the cleavage, and the jointing; and that at the same time they were influenced by less powerful east-west stresses acting along the axis of the troughs, and producing the open north-south cross folds.

THICKNESS.

No approximately correct estimate of the thickness of the Hanbury slate is at present possible. 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 can be no doubt that the Hanbury slate is much thicker than any of the other formations in the district, but that it is as thick as the corresponding formation in the Penokee district—12,000 feet—is not probable. Indeed, it is extremely doubtful whether its maximum thickness is more than 2,000 or 3,000 feet, though, as has been said, this estimate is not founded on sufficient data to make it of much value.

RELATIONS TO PALEOZOIC BEDS.

The relations of the Hanbury slate to the underlying Vulcan formation, the Randville dolomite, and the Archean schists have already been fully discussed (pp. 289, 365–372). The relations of the formation to the overlying Paleozoic sediments are those of a much-deformed, closely folded, highly tilted set of beds to a set of undisturbed horizontal deposits laid down upon them. No actual contacts of the slates with the overlying sediments have been seen, but from the nature of the structural differences exhibited by them there is no doubt as to the existence of a profound unconformity between the two. During the interval represented by the break the Upper Huronian beds were raised above the sea, closely folded, deeply eroded, and again lowered beneath the water's surface.

INTERESTING LOCALITIES.

The most interesting points at which to study the Hanbury slate are (1) those at which the formation is exhibited in its typical development, and (2) those at which its unusual cherty and ferruginous phases occur. The latter are of interest because of the light they may throw on the problem of the origin of the jaspilites and ores of the Vulcan formation, and because they suggest the possible presence of ore deposits in the slates like those in their western extension across the Menominee River.

TYPICAL LOCALITIES.

Exposures of the Hanbury slates are so scarce that only in a few places may more than one phase be seen. In several places, however, all the lithological types of the formation are well exhibited. Two such localities are described below and two others in which the slaty phases are best shown.

Sec. 13, T. 40 N., R. 31 W.—The exposures along both sides of the Menominee River in sec. 13, T. 40 N., R. 31 W., have already been referred to on a former page (p. 289), in discussing the relations between the Quinnesec schists and the Huronian sedimentaries. The slates form the banks of the river and the bottom of its channel for a distance of about 300 paces. Between the slate exposures and the nearest ledge of green schist, which is immediately under the railroad bridge of the Florence branch of the Chicago and Northwestern Railway, is an interval of about 150 paces free of exposures of any kind. The slates are cut through by the stream, leaving little perpendicular walls about 8 feet high bordering both sides of the channel. The rocks in these walls are silvery-gray sericitic slates with a well-marked cleavage dipping high (80°) to the north, and a jointing at right angles to this direction. Their strike is nearly east-west across the stream, the water of which flows across their upturned edges in a little rapids.

At about the middle of the exposure on the Michigan side of the river the slates are fluted in a series of small wave-like folds and are crossed by joints at right angles to the general dip of the fluting. Near the joint cracks there has been movement in a narrow shear zone which has produced a distinct schistosity which is inclined to the joints at angles of about 60°.

Hanbury Hill.—Hanbury Hill, situated just south of Lake Hanbury, furnishes the best exhibition of the Hanbury slates and their associated greenstones found anywhere in the district. The hill is the most marked topographic feature within the slate area. It rises about 140 feet above the surrounding plain, its apex reaching an altitude of a little over 1,040 feet above sea level. From a physiographic point of view it is a monadnock, which has resisted erosion because there are associated with the soft slates at this place large dikes and sheets of intrusive basic rocks which are now represented by greenstone-schists.

The predominant rocks exposed on the hill, in addition to the greenstones, are dark-gray argillaceous slates, light-gray calcareous slates, graywackes, and quartzites. These are folded in a most intricate manner in the central portion of the elevation, but on its east side the pitch of the folds is uniformly toward the west and on the west side toward the east. Where folding it not pronounced the strike of the beds is about N. 78° W., but there are many places where the strike departs widely from this, especially on the higher points of the hill. In one place near the west end of the top of the hill a strike was measured and found to be nearly north-south. At this place the folding is very distinct. The little folds, where the proper observations could be made, were found to pitch east at 20° and to strike N. 85° W. In other portions of the hill near its west end the folds are very close. Their axes usually pitch east at angles varying between 20° and 45°, but in a few instances the angle of pitch is much higher, reaching 90° in a few cases. The general dip of the beds in the hill approximates 70° S., showing that the folds are frequently overturned to the north, but of course dips of all angles and in all directions are met with, as must be the case in a series of folded beds. Northern dips are, however, rare, and where observed they are always much steeper than the southern ones.

All the beds are crossed by a schistosity that strikes about N. 75° W. and dips from 80° S. to 90°, irrespective of the folding. It therefore sometimes corresponds with the bedding of the slates, but more frequently the two structures are discordant.

The greenstone-schists are limited almost exclusively to the northern part of the hill, although a few ledges have been observed on its south side, especially where the hill is widest, i. e., near the section line between secs. 15 and 16. The relation of the schists to the surrounding slates is not always easy to ascertain. In most instances the greenstone appears to intrude the bedded series in the form of large dikes, but in the northwest part of the hill the igneous rock appears to underlie slates, both on the north and on the south sides of a minor elevation; consequently the rock in this case may be an intruded sill. In all cases the greenstone is strongly schistose in the same direction as the neighboring slates. In composition it is an aggregate of fibrous hornblende and the decomposition products of feldspar. None of the original constituents remain. In structure the rock was apparently granular, although the presence of small white spots sprinkled over the dark-green weathered surfaces of some of the schists may indicate that these were originally porphyritic. The greenstone occupies some of the higher peaks of the hill and forms a little cliff about 20 feet high with a northern face overhanging the lake.

The various phases of the slates, the quartzites, and the graywackes are interbedded. The quartzites and graywackes are usually in comparatively thin beds, but in one case at least a quartzite bed measures 20 feet in width. These quartzites are nearly all calcareous, and gradation phases between them and the calcareous slates or impure dolomites are common.

The slates, as before stated, predominate over all other rocks. They form not only thicker beds but more numerous ones.

The calcareous phases occupy distinct horizons toward the north side of the hill They are interbedded with the argillaceous phases, but the former greatly predominate. The argillaceous phases, on the other hand, are more common to the south. Near the center of the hill thin beds of the calcareous slates may alternate with the argillaceous ones, but farther south on its southern slope the calcareous forms are entirely lacking. Here the gray slates exclude all other rocks. While the exact stratigraphical position of the calcareous slates is not certainly known, on account of the complicated folding of the series, it is nevertheless believed that, together with the graywackes and the quartzites, they occupy low horizons and that the argillaceous phases occur above them.

Under the microscope the gray and black argillaceous slates are seen to be typical clay slates, composed of fine quartz grains, spicules of chlorite and sericite, flakes of kaolin and the usual accessory particles. Some of the quartz is plainly in fragmental grains, but most of it has been recrystallized. Near the contacts with the greenstones a little brown biotite has been developed in them, otherwise the contact phases are not essentially different from the normal ones. Where most contorted, both normal and contact varieties, more particularly the latter, are traversed by an intricate system of veins and veinlets of quartz.

The argillaceous slates pass into the quartzites by increase in their quartzose components. The most distinct quartzites are dark-gray or black varieties that are usually covered on their weathered surfaces by a crust of brown, earthy limonitic material that indicates the presence of siderite in the fresher portions of the rock. Here and there they are cut by quartz veins, and near contacts with the greenstone they are gashed and jointed into polygonal blocks, many of which are bounded by curved surfaces. The quartzites are much less schistose than the other rocks in the hill, but all specimens show some indications of the structure. Under the microscope the rocks present two types. In both types the quartz grains have more or less ragged outlines in place of the sharp ones characteristic of clastic quartz, as though they had been partly dissolved and new quartz had added itself to the undissolved nuclei. The two types differ in the amounts and character of their matrices. In one type the matrix is in comparatively large quantity, constituting perhaps 50 per cent of the rock. It has the usual character of the matrix of the argillaceous slates, except that it contains a great deal of a light-brown carbonate in small grains and groups of grains, and in large pieces that look as though they might be pseudomorphs after some other mineral, or the fillings of pores or cavities. In the second type the matrix is sparse. It consists of an occasional plate of chlorite and sericite and many small rhombohedra of a yellowish-brown carbonate that is locally changed into limonite. The carbonate crystals in this type of quartzite are plainly ferruginous. The carbonate in the first type seems to be partly a ferruginous carbonate and partly calcite or dolomite.

The calcareous slates differ from the quartzites mainly in the absence of the large quartz grains and the presence of more abundant carbonate. They are essentially like the matrices of the quartzites of the first type, except that they contain even more of the carbonate. This mineral often makes up by far the greater portion of the rock. It is an aggregate of granules, many of which have a rhombohedral habit. When the texture is extremely fine the rocks resemble slates more than they do quartzites; when coarser they graduate into the latter rocks.

Sturgeon Mills.—East and southeast of Sturgeon Mills, in sec. 13, T. 39 N., R. 29 W., are several small knobs of black slates that are easily accessible from the railroad track east of Sturgeon Mills station. On the east side of the mill pond (see map, Pl. XLI) the slates form a considerable knoll in which the most typical phase of the black variety is beautifully exposed. The rocks are dense and homogeneous and are crossed by a well-marked cleavage that is vertical. No bedding is noticeable. Farther south, alongside the railroad track, the same rock occurs in two flat ledges with a vertical schistosity striking east-west. In the northern ledge the bedding is much contorted, the little folds in every instance pitching about 55° E.

On or near the banks of the river are other ledges in which slates and quartzites are interlaminated. Here, too, the bedding is much folded, and again the folds pitch to the east, the angle of pitch being between 30° and 40°. Greenstones are associated with the slates in the southern ledges, and in several instances the knobs rising above the plain expose only the intrusive rock.

Secs. 29 and 30, T. 39 N., R. 28 W.—In the central portion of sec. 29 and the eastern part of sec. 30, in T. 39 N., R. 28 W., the slates of the Hanbury formation are well exposed in a number of little knobs and flat ledges on both sides of the road running southwest from Waucedah. In sec. 30 the slates are calcareous in part, and in part sericitic, and are associated with schistose greenstones of the usual types. In nearly all the ledges folding is very apparent. The axes of the sharp, close folds strike N. 75° W. and pitch 15° E. The slates are also schistose, with the schistosity striking parallel to the axes of the folds, and consequently in some places across the bedding, and in other places parallel with it. Farther east, in sec. 29, the gray argillaceous slates predominate, although a few beds of calcareous slates are interbedded with them. Here, too, the rocks are contorted and schistose. The schistosity strikes east-west, crossing the numerous little folds at inclined angles. The strike of the axes of the folds is about N. 45° W. and their pitch is to the east.

LOCALITIES AT WHICH CHERTS OCCUR.

The second group of localities within the Hanbury area that are of special interest are those in which cherty and ferruginous rocks occur. Comparatively only a few of these are known at present, all of which are briefly referred to below.

Sec. 15, T. 40 N., R. 30 W.—In the southeast quarter of the southwest quarter of sec. 15, T. 40 N., R. 30 W., near the point where the road crosses the little stream flowing north, are two deep test pits or exploring shafts, from which a large quantity of material was taken many years ago. The rocks on the dump piles are much weathered, but there can be distinguished among them various slates, cherts, and lean ores. At the pit about 200 paces west of the stream the material on the dump is principally a sheared pink ferruginous slate, containing considerable talc or serpentine along the shearing planes between the laminæ. It looks extremely like the talcose slates lying between the Randville dolomite and the base of the Vulcan beds. The other pit is about 200 paces south of the same stream. Here the principal material on the dump is a ferruginous slate not very different from that at the western pit. In addition to this, however, there are many fragments of a red and gray cherty quartzite, some fragments of a well-characterized jasper, and a few pieces of a very heavy brecciated jasper in which the fragments are cemented by a porous crystallized mass of hematite. The cherts or jaspers are very much more like some varieties in the Vulcan formation than like those in the Hanbury slates. There are no exposures of any kind in the vicinity of the pits, and consequently there is no way of learning what the relations of these rocks are to those north and south.

The nearest rocks outcropping to the north are the Quinnesec schists of the western area. Those to the south are the sandstones covering the hill north of the Cuff mine. If, as has been reported, a drill put down in the northeast corner of sec. 21 penetrated the Randville dolomite, then the dolomite is but a short distance south of the southern pit. If this latter condition is true, the jasper and ores reached by the pits may belong in the Vulcan formation and the talcose slates may be the slates on the top of the Randville formation. In this event there would be a narrow syncline of Vulcan beds between the Quinnesec schists on the north and the Randville dolomite on the south. There is no possible method at present of deciding whether this view of the case is correct or not, and so, in the interests of conservatism, the jaspers and ores are regarded as portions of the Hanbury formation and the general map (Pl. IX) is colored accordingly.

Sec. 11, T. 39 N., R. 30 W.—Another place within the area of the Hanbury slate at which cherts are found is near the center of sec. 11, T. 39 N., R. 30 W., on the top of the terrace just west of the point where the railroad to Little Quinnesec Falls crosses the highway running from Quinnesec to the same point. Here there are several exposures of typical Hanbury slates and several test pits. The pit nearest the railroad is in the normal clay slates of the formation. These strike east-west, as shown by exposures near by. About 150 paces east and 150 or 200 paces north is another pit, south of a large ledge of slates striking also east-west. The slate is strongly schistose, and this structure strikes in the same direction. Its dip is vertical.

On the dump of the pits are rocks some of which are unlike anything else seen in the district. A few of the pieces seem to be a network of quartz veins, with its meshes filled by a mass of hematite and chlorite. A few others are slate. The greatest number consist of a streaked and mottled red and dark-green chert. The dark portion has the texture and the general appearance of flint. The red portion differs from jasper in having a duller luster. Both the red and the green portions are composed principally of a very fine-grained crystalline aggregate of quartz, but the former contains, in addition, a large quantity of hematite and the latter a large amount of chlorite. The hematite is in small granules between the quartz grains and the chlorite is in streaks forming a matrix in which the quartz grains are embedded. Here and there a quartz vein traverses the chert, and the rock is moreover incipiently schistose. The near proximity of the slate ledges to the pit showing these cherts would appear to indicate that these rocks were formed in some vein-like crevice, but of course no proof of this conclusion is at hand. The cherts, however. are clearly in the Hanbury slates.

Southeast quarter of sec. 7 and southwest quarter of sec. 8, T. 39 N., R. 29 W.—West and a little north of Hanbury Hill, i. e., nearly on the general strike of the bedded rocks forming this elevation, is a little hillock on which are exposed not only the siliceous and calcareous forms of the Hanbury slates, but also dolomites and cherts better developed than anywhere else in the Hanbury formation. In the southeast quarter of sec. 7 the rocks form a distinct hill 80 feet high, overlooking a swamp which lies to the north, east, and west. On the top of the hillock the various slaty phases of the formation are well exposed in a complicated series of small folds. Between the slate layers there is occasionally a thin layer of coarse grit or conglomerate, containing granite, chert, and quartz pebbles, and in the trough of some of the folds the slates are brecciated. In some places the rocks are cut by ramifying veins of white quartz, but usually veins are absent. The bedding of the slates in the western part of the hill strikes fairly uniformly N. 65° to 75°, but the dips vary from 63° S. to 65° N., indicating the presence of a syncline. Farther east the bedding is much more contorted and small folds are numerous. Moreover, in some cases a few of the layers constituting the larger folds are folded within themselves into minute crinkles and crumplings. Near the east end of the hillock the little folds are well enough defined to enable one in several instances to determine the direction of their pitch. In one case noted the pitch of a small fold near the center of the elevation was found to be east at 20° to 30°. Farther east the pitch is almost uniformly to the west at widely different angles. This hill, thus, like Hanbury Hill, is a synclinorium with the axis of the fold transverse to the axis of the elevation. Its presence as a hill is undoubtedly due to the close folding to which its rocks have been subjected and their consequent compactness.

All the slates, whether sharply folded or not, are markedly schistose, but the direction of the schistosity is uniformly N. 80° to 85° W. and its dip is 75° to 80° S. Thus the secondary structure is inclined to the bedding at all angles. It is parallel with the same structure in the slates of Hanbury Hill, and departs only slightly in direction from the corresponding structure observed in nearly all the sedimentary rocks of the entire district. Hence this structure is not of local origin, but is probably connected with some general cause which was active throughout the entire Menominee trough. The only general cause capable of producing the effect was that which at the same time produced the major folding of the district and gave rise to the great synclinorium that constitutes the Menominee trough.

Nearly all the slates composing the hill contain iron carbonate to some extent, as is shown by the almost universal existence of a brown, earthy limonitic weathering crust. On its north slope the carbonate is especially abundant, some of the beds consisting of a well-characterized ferruginous limestone 10 feet or more thick. This limestone is dark gray in color and finely granular, and is covered by a limonitic skin or crust one-tenth inch in thickness. Under the microscope can be detected a few grains of quartz, a number of small plates of brown mica, an occasional flake of muscovite, and a few spicules of kaolin. The major portion of the section consists of an intricately interlocking mass of carbonate and crystallized quartz.

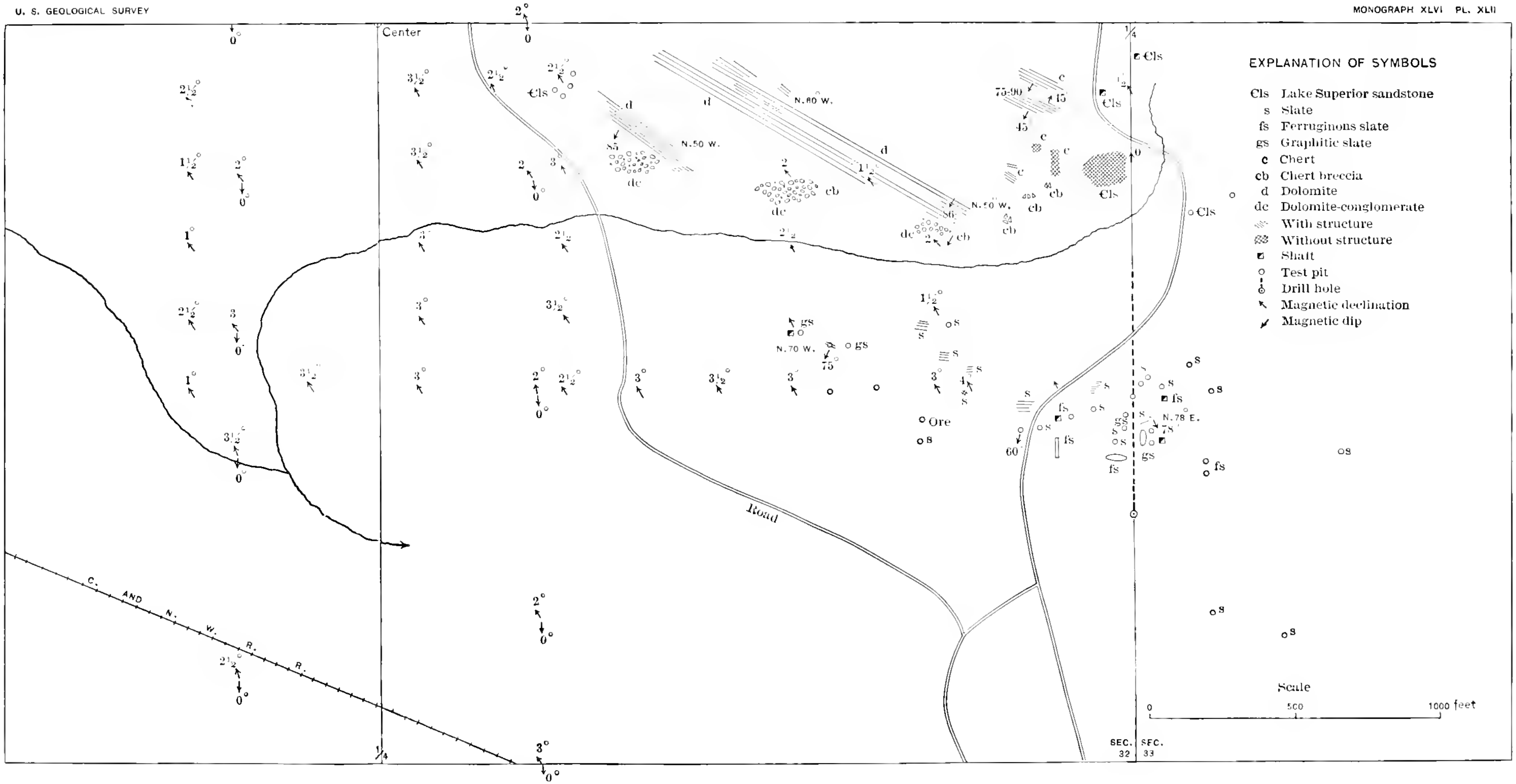
An analysis of one of the best specimens of the ferruginous limestones from this place was made by Mr. George Steiger, of the Survey laboratory, with a view to the determination of the nature of the cementing carbonate

Analysis of ferruginous dolomite in Hanbury formation.

	Entire rock.	Soluble in HCl (dil.).
SiO_2	36.71	2.28
Al_2O_3	5.34	1.27
Fe_2O_3	.35	3.61
FeO	3.37	
MgO	10.78	8.83
CaO	15.11	15.20
Na_2O	.12	....
K_2O	2.40	....
H_2O at 105°	.55	....
H_2O above 105°	1.61	....
TiO_2	.27	....
CO_2	23.22	....
P_2O_5	.05	....
MnO	.23	....
Total	100.11	....

The soluble portion includes the carbonates and a small portion of some aluminous silicate. If all the iron, magnesia, and lime are assumed to be in the form of carbonates the proportions of these in the rock are 5.43 $FeCO_3$, 18.54 $MgCO_3$, and 27.15 $CaCO_3$, which require the presence of 23.72 per cent CO_2. The total amount of the carbonate present must be about 51 per cent of the entire rock and its composition must be about as follows: $FeCO_3$, $4\frac{3}{4}$ $MgCO_3$, $5\frac{3}{4}$ $CaCO_3$—or the carbonate is a dolomite in which about 17 per cent of the $MgCO_3$ is replaced by $FeCO_3$.

In some places the limestone bears layers of chert several inches wide. This chert is a dark-gray variety clouded with irregular patches having a light-gray or white color and marked by bedding lines. In some places the chert grades on both sides into the limestone. In others it forms a distinct band separated from the limestone by a very sharp line. In the latter cases the siliceous rock appears to occupy a fissure and to partake somewhat of the nature of a vein. In both cases the composition and structure of the chert are simple. The major part of those phases that are most intimately related to the limestone is an aggregate of finely granular, interlocking silica. In this there are embedded abundant little rhombohedra of a light-yellow carbonate, probably siderite, an occasional



MAP OF EXPOSURES AT IRON HILL, IN SEC 32 AND NEIGHBORING PORTION OF SEC. 33, T. 40 N., R. 29 W.

grain of hematite or magnetite, and a few flakes of biotite. The bedding observed in the banded specimen is due to the greater richness in carbonate of some portions of the sections than others; the darker bands containing a greater proportion of carbonate and the lighter ones a greater excess of quartz. Tiny quartz veins intersect the rock, sometimes forming a complicated network traversing the thin sections in all directions. The quartz in these veins is much coarser grained than that in the mass of the chert, and through it are interspersed little nests of calcite or other carbonate, streaks of a black substance that may be carbonaceous, and a few wisps of muscovite. The carbonate is usually near the walls of the vein and frequently when in this position it occurs in rhombohedra. Those varieties of the chert that are distinctly separated from the limestone, and that have been said to be vein-like in character, differ from the cherts just described in being almost free from carbonate except on the selvages of veins. In many places the slates near the chert bands are highly ferruginous, and in one or two instances distinct veins of hematite can be seen penetrating them.

About a quarter of a mile east of the east end of the hill the same kinds of rocks outcrop in little ledges scattered through the swamp. Black slates, quartzite, and impure limestones occur interbedded with one another in such a way as to show that the general strike is N. 85° E. and the dip about 55° S., but the beds are affected by minor folding, which naturally causes many departures from these directions in both strike and dip. In the midst of the slate outcrops is one of greenstone-schist, in which the schistosity is parallel to the cleavage in the slates, which, of course, is not always coincident with the bedding in these rocks.

Iron Hill, southeast quarter of sec. 32, T. 40 N., R. 29 W.—Near Iron Hill, in the southeast quarter of sec. 32 and the adjoining portion of sec. 33, T. 40 N., R. 29 W., is the most extensive exhibition of ores and cherts seen anywhere in the Hanbury slate area. The ledges and pits in which they are exposed are dotted over a plain lying south and east of the end of the central dolomite belt, from which they are separated by a narrow swamp (see Pl. XLII). The dolomite has been described on a previous page. The fact that a drill hole cutting under the pits along the east line of the section encountered only gray slates, like the typical clay slates of Hanbury Hill, indicates conclusively that none of the cherts and ores are in the Vulcan formation.

On the little terrace south of the swamp, and hence south of the dolomite ridge, are numerous outcrops of well-defined slaty rocks striking about N. 70° W. and dipping approximately 70° S. Some of these are clay slates, others are graywackes, and others are impure quartzites. Most of the slates are like the argillaceous Hanbury slates, but some of them are slightly ferruginized. Graphitic varieties have also been met with in test pits sunk in this portion of the area, and here, as elsewhere, they are associated with heavily ferruginous beds. In one pit a fairly good lean ore was encountered.

North of the dolomite exposures, near the north quarter post between secs. 32 and 33, are three or four deep shafts and a tunnel leading from the bottom of one of them to the side of the hill on which they are situated. These shafts are all in sandstone. A large quantity of ocher is found on their dumps, but this it is believed must have come from a ferruginous bed at the base of the sandstone. Indeed, on some of the dumps pieces of conglomerate were seen that resemble strongly the ore conglomerate found at the base of the sandstone at many places within the district.

The pits and shafts southeast of the dolomite bluffs are plainly in a heavily ferruginized zone. They are at the base of a high hill on which no exposures have been found, but which is probably composed mainly of the Lake Superior sandstone. The pits have disclosed a great variety of rocks. Red ferruginous schistose slates predominate, but in addition to these there are also on the dump heaps graphite-slates, cherts, thin beds of hematite, interbanded cherts and ores, and a few specimens of conglomerate. The latter is from a thin bed interlaminated with slates.

In places the slates approach graywackes in composition and structure, and in other places they approach quartzites. In some places shearing has been so severe as to produce fissility. The slates nearly all contain visible quartz grains. On fracture surfaces their original color can be seen to be green. Their present red color is due to a stain that started along the fissility planes and extended inward from these. In composition the slates of this kind are very near to graywacke. Their quartz grains are often crushed into mosaics or mashed into long, flat lenses. These are embedded in a schistose aggregate of chlorite, muscovite, and crystallized quartz. The brown stain is due to the decomposition of the micaceous constituents and the development within them of limonite and hematite. Others of the red slates contain considerable dolomite. These on a fresh fracture are light-yellowish gray. They are schistose and stained in the same manner as are the quartzose slates.

The cherts and ores are naturally the most interesting of the rocks encountered in the explorations. Indeed they look so promising in a number of instances that the general view as to the existence of a narrow belt of the Vulcan formation at this place is not to be wondered at. However, the cherts are all sandy textured and the ores are very dense, hard, brownish-red varieties unlike anything seen in the Vulcan beds. Most of them are also porous. In some specimens the pores are little, irregularly shaped, vug-like cavities, lined with tiny hematite druses. In other specimens narrow, crack-like cavities, with druse-covered walls run through the centers of the bands as do the longitudinal cavities so often seen in veins. All the ore layers are minutely banded and many of them are divided longitudinally into two or more parts by very fine lines, as though the ore material had grown from both sides of the band inward until the opposite portions joined. The only conclusion as to the origin of the ore that can be reached from a study of the fragments thrown out on the dumps is that they are vein fillings in a fragmental rock which has been partly silicified, and which, therefore, has lost some of its fragmental features. Some of the siliceous bands associated with the ores are distinct cherts, but these may be veins. All the cherts and ores are jointed, and along some of the joints slight faulting has taken place.

Again, there is no opportunity to study the relations between the different rocks because of the impossibility of seeing them in place. It can scarcely be doubted, however, that the jointing and ferruginization of the beds is connected in some way with the folding that terminated the central dolomite belt.

Sec. 17, T. 39 N., R. 29 W.—In about the center of the southeast quarter of the northeast quarter of sec. 17, T. 39 N., R. 29 W., several test pits have been put down in low ground near a swamp. Most of the pits have exposed the normal black siliceous slates of the Hanbury formation, but a few of them, apparently along a crushed zone in the slates, have yielded a red, porous mass of hematite and chert that might be regarded as a lean ore. On the dumps of several other pits fragments of a brecciated chert are also noticed. In these the cement is a red, earthy hematite, and the fragments are small angular pieces of light-gray chert, very similar to the chert on the hill in sec. 7 of the same township. The relations of the cherts and ore to the slates are not known. No exposures are visible in the vicinity, and the pits are now partially filled with débris. The location is referred to simply because it is one of the places within the Hanbury slate area at which cherts have been found.

Northwest quarter of sec. 26, T. 39 N., R. 29 W.—The only place near the southern Quinnesec schists at which cherts and ferruginous beds have been seen is in the southwest quarter of the northwest quarter of sec. 26, T. 39 N., R. 29 W., near Sturgeon Falls, on the Menominee River. On the north side of a little hillock not more than 200 feet north of the State road (see map, fig. 22) running east from the New York farm are exposures of fissile slates containing layers of white, gray, and pink chert, and bands of dense black and dark-purple ores. The rocks are jointed, and in the joint cracks are often thin deposits of hematite. Some of the slates are graphitic. Northeast of this again, at a distance of about 300 feet, is another very similar ledge on the escarpment of a terrace, and this deflects the compass needle to a very noticeable extent. Still farther north, about 250 paces north of the last-mentioned ledge, is a third low ledge in which the rocks are plainly distinctly fissile slates interbedded with bands of chert. In this ledge the beds are contorted. In all these cases the slates are undoubted members of the Hanbury formation, and the cherts and ores are secondary deposits.

Sec. 21, T. 39 N., R. 28 W.—In the center of the south half of sec. 21, T. 39 N., R. 28 W., is another group of pits which show the presence of ferruginous bands in the slates. The pits are comparatively old, but quartzites, graywackes, and slates can be recognized on their dumps. All the rocks are more or less ferruginized, and some of the slate presents the appearance of a very lean banded ore. Reference has already been made to this ore-like slate in another place (p. 467). The relations of the different rocks to one another are not known. There is little doubt, however, as to their being a part of the Hanbury formation.

Sec. 19, T. 39 N., R. 28 W.—In sec. 13, T. 39 N., R. 29 W., the Hanbury formation is represented by exposures of black slates cut by greenstones (see p. 471). Between this place and the center of sec. 19, T. 39 N., R. 28 W., there are no exposures except here and there a small knob of greenstone. Within the last few years, however, the formation has been opened up by a series of test pits and shafts extending along the east-west quarter line of the last-named section for a distance of about 2,000 feet. (See map, fig. 54.)

This exploration, which was made under the direction of Mr. Turner, of Vulcan, has shown the presence of a ferruginized belt inclosed between normal Hanbury slates, extending in an east-west direction entirely across the explored region. Associated with the slates at several places is a greenstone which is occasionally fresh and dense, but which usually is much decomposed. On the north side of the ferruginized belt the slates dip north at high angles. On the south side they apparently dip high to the south. On both sides the slates are light-gray, much-sheared clay slates, cut by many gaping joint cracks. With these are interbedded a few layers of quartzite or graywacke, the thickness of which has not been

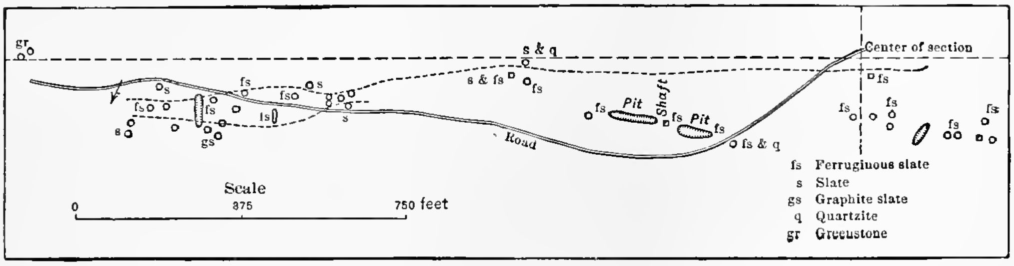


FIG. 54.—Sketch map of explorations at Turner's location, near center of sec. 19, T. 39 N., R. 28 W.

determined. Nearly all of the quartzite is sheared, and in one instance considerable muscovite or other light-colored mica has been developed. One of the pits on the south side of the ferruginized belt has also disclosed the presence of a well-defined graphite slate. The existence of this material so near the ferruginous beds recalls the presence of similar material in association with the ore-bearing beds of the Curry member of the Vulcan formation, and suggests the interesting possibility that it may signify that the same processes were active here, which, in the Vulcan beds gave rise to the ore deposits.

The ferruginous band averages about 60 feet in width. In many pits the material of the bands looks as though it were a brecciated chert or fine-grained quartzite, cut by numerous quartz veins and by thin veinlets of dense hematite. At other places it is a porous, cherty, ocherous mass containing crystalline hematite, forming druses on the walls of its pores and on the sides of joint cracks. In the deepest shaft the ocherous mass seems to be a superficial layer covering a bed of hard hematite ore. This ore appears in two varieties. In one it is a dense black or dark-red hematite, interlaminated with thin layers of yellowish-gray chert, or a dense, banded ore, made up of layers differing slightly in texture. The second variety is porous and crystalline, and the pores are studded with crystals of hematite. The ore that has been seen differs in character from that of the great ore deposits in the Vulcan formation, but is similar to that of the vein-like material that sometimes occurs in the jaspilites as narrow bands, which are interpolated parallel to the bedding. While it is not possible to see the relations of the ferruginous belt to the slates on both sides, it seems probable that the ferruginous zone is along a line of crushing and fracture, and that the hematite was deposited within it in the same manner as that in which the ores were deposited in the brecciated zones within the Vulcan formation.

POSSIBLE IRON-ORE DEPOSITS.

From very early times in the exploration of the Menominee district there has been much speculation as to the possibility of discovering workable ore deposits in the great slate area between the Chicago and Northwestern Railway and the southern area of Quinnesec schists. The discovery of valuable ore beds at Commonwealth and Florence, in Wisconsin, in slates resembling those of the Hanbury formation, has given rise to the belief that similar ores will sometime be found in the slates east of the Menominee River. That so few explorations have been made in this area is explained by the fact that few clues have been available to guide the explorer in locating drills and test pits. Exposures are scarce, and the mantle of drift is so thick that explorations can not be intelligently undertaken. Even if ore bodies exist, they would be very difficult to find. Nevertheless, as has been indicated above, at a number of places within the slate area groups of test pits have been sunk, and from these lean ores have been obtained. In some cases the material is only ferruginous slate, and in other instances it appears to be red ocher. In a few cases, however, mixtures of chert and iron oxide have been found that resemble some of the mixed cherts and ores from the Michigamme slates of the Marquette district, and in several cases these are banded. Thus far, however, nothing has been discovered that would lead to the belief that large ore bodies exist at any of these places. But notwithstanding the unfavorable results hitherto reached by explorations, the conclusion that no ore bodies exist in the slate areas should not be assumed. The slates have been pierced at only a few places, and at these places there has unquestionably been deposited some ore material. That ore bodies of workable size have not been discovered may be due to the fact that the explorations were not made in situations that presented conditions favorable to the accumulation of the ores, or it may be due to the absence of sufficient ferruginous material in the slates at these places to furnish large quantities of iron oxide.

In describing the lithological features of the Hanbury slate reference was made to the presence of iron carbonates in the calcareous slates and dolomites in the lower portion of the formation and to their alteration products. Under favorable conditions these carbonates have partially or completely changed into oxide. Crusts composed largely of the hydrated oxide, limonite, are noticeable on all their exposed surfaces, and gradations between the dolomites and ferruginous cherts are observable in several places. Under favorable conditions of environment and with suitable basins furnished in which to accumulate the ore produced, there seems to be no valid reason why there should not be formed in the Hanbury slates of the Menominee district ore deposits of equal size to those formed in the slates of the Florence and Iron River districts. It is probable, however, that the ores would be non-Bessemer, and therefore quite unlike those in the Vulcan formation.

The same rules to be followed in exploring the Vulcan beds for ore deposits should also be followed in exploring the Hanbury slates. In the latter case, however, there is much greater difficulty in selecting favorable sites for the location of the explorations than in the case of explorations in the Vulcan area. In the latter area the possible positions of the ore deposits are in a narrow belt limited on the one side by the Randville dolomite and on the other by the Hanbury slate. Moreover, marginal folds in the dolomite are comparatively easily detected.

The Hanbury areas on the other hand are broad, and the folding of the slates is of an exceedingly complicated character. Before locating exploring plants in this area the ground should be closely examined with a view to securing the most favorable environment possible, for it is a well-established fact that it is only in exceptionably favorable situations within the slate area that ore deposits of workable size have been developed, and that explorations in any other than the most favorably situated locations will result in a waste of money and energy. If possible, the following conditions should be met by the sites selected:

First. Since the ore material is derived from iron carbonates, and these are known to exist only in the dolomites, cherts, and calcareous slates, the explorations should be confined to areas near those known to be underlain by these rocks, which, when exposed to the weather, may be identified by the coating of limonite that covers their weathered surfaces.

Second. The most favorable situations for ore concentration are the troughs of pitching synclines with impervious bottoms. Hence search should be made for pitching folds. If such folds can be found, and it can be further determined that the folding involves beds of argillaceous slates or other impervious rocks, these furnish conditions favorable for ore concentration.

Third. In the Crystal Falls district carbonaceous shales are often associated with the ore bodies, and in the Menominee district graphitic slates are often associated with the Curry ores, some of the material of which is almost certainly original. Therefore, if situations can be found where carbonaceous slates occur in pitching synclines below rocks containing iron carbonate, the conditions may be regarded as exceptionally favorable for the accumulation of ore deposits.

Fourth. Percolating waters are the agents of the process of concentration; consequently localities at which the rock masses have been shattered, thus affording easy passage to the water, are places particularly desirable for testing.

In a set of slates as closely folded as are the Hanbury there may somewhere be found places where the conditions outlined are fulfilled, and in such places ore bodies will be found, if they exist anywhere in the slate area.

Thus it appears that, although no ore bodies of value have thus far been discovered in the slates, the possibilities of the formation have not by any means been exhausted. A more extensive exploration of the slate formation is, perhaps, warranted before the field is finally abandoned as worthless.

CHAPTER VI.

THE PALEOZOIC SYSTEM.

Limited areas of Paleozoic sediments in approximately horizontal sheets are found to lie on the eroded edges of the Huronian and Archean rocks within the Menominee trough, and a wide expanse of the same sediments is known to cover all the older rocks at the eastern border of the trough and to extend uninterruptedly eastward to Green Bay.

The Paleozoic rocks may be divided into two formations. The lower beds are mainly red sandstone, which is known in the region as the Lake Superior sandstone. The upper beds are porous arenaceous limestones, identified by Rominger as corresponding to the Chazy and Calciferous formations of the Ordovician in the Eastern States. This formation is designated the Hermansville limestone on the map forming Pl. IX. The sandstones and possibly the limestones at one time must have spread continuously over the entire Menominee district, as they now do over the region to the east. West of Waucedah, however, they have been generally eroded from the valleys, leaving remnants as isolated patches on the tops of the higher hills. East of Norway both the sandstones and the limestones can still be found at many points, but west of this place the limestone has been identified at only one locality. The apparent absence of the limestone from the western portion of the district may, however, be due to the fact that exposures are rare, indeed practically unknown, on the tops of the hills where the limestone would naturally occur.

SECTION 1. LAKE SUPERIOR SANDSTONE.

CHARACTER AND RELATIONS.

The Lake Superior sandstone, according to Rominger, 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. Its total thickness is estimated at 300 feet.

The relations of the sandstone to the underlying formations are always practically the same. Whether on the tops of hills or in the depressions between the hills the horizonal beds of the younger rock always rest unconformably upon the upturned and truncated layers of the older series. In the mines and open pits visible contacts between the sandstone and the underlying rocks are numerous, and in every case the contact is an unconformable one. Perhaps the best of these is at the west end of the Quinnesec pit (see Pl. XLIII), where the shore-line conditions that prevailed at the time the sandstone was deposited are very clearly exhibited. Similar contacts are to be seen at several places within the Pewabic and the Cuff mines and in the open pits of the Norway and the Cyclops mines.

Moreover, not only is the sandstone separated from the Huronian rocks by a discordance in bedding, but its basal layers always contain a great deal of material derived from the immediately subjacent formations. Where the underlying rocks are those of the Randville formation the inclosed fragments consist of bowlders of cherty quartzite and dolomite. 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 occasional pebbles of white quartz, of granite or of other members of the Archean system. Some of these conglomerates are exceedingly handsome.

In a few instances 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 southeast quarter of 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 (Pl. XXII, *B*). In the summer of 1898 the yield of ore from the concentrator was 5,000 tons.

PLATE XLIII.

PLATE XLIII.

VIEW OF UNCONFORMITY BETWEEN THE TRADERS JASPILITES AND THE LAKE SUPERIOR SANDSTONE.

West side of Quinnesec open pit. The rocks to the left are even-banded Traders jaspilites dipping north. Above these, and to the right, is the Lake Superior sandstone. Its top layers are practically horizontal, but near the contact with the jaspilites the dip is steep to the north, conforming with the dip of the surface of the underlying rock. The lower layers of the sandstone series consist of coarse conglomerates containing abundant angular fragments of the jaspilites. Interlaminated with these are layers of fine sand. All beds thicken with increasing distance from the contact, and their included fragments become less angular. Cross bedding can be detected in the sandstone layer beneath the heavy bed of conglomerate.

VIEW OF UNCONFORMITY BETWEEN THE TRADERS JASPILITES AND THE LAKE SUPERIOR SANDSTONE WEST SIDE OF QUINNESEC OPEN PIT.

AGE OF LAKE SUPERIOR SANDSTONE.

Although Rominger states that there is no record of any recognizable fossils from the sandstone, nevertheless, because of its position beneath the limestones, he correlates it with the Potsdam of New York. Since the publication of Rominger's report several pieces of fossil-bearing sandstone have been obtained, which, according to reliable authority, came from the ledge through which the Pewabic mine shafts near Iron Mountain were driven. One of these contains numerous fragments of trilobites, some of which were determined by Dr. Walcott as "the heads of small trilobites, probably *Dikellocephalus misa;*" others are "fragments of a large species of *Dikellocephalus.*" According to Walcott, "these indicate the Upper Cambrian horizon of the Mississippi Valley section." Other pieces are filled with fragments of brachiopod shells. In most cases these are ground up into very small portions, but occasionally a layer is found in which whole valves, and indeed entire shells, are abundant. In every case seen the shell-bearing layers are interbedded with coarsely conglomeratic layers, indicating that they must have been formed in shallow water near a shore line. Mr. Schuchert, of the United States National Museum, has been kind enough to examine some of the best preserved of these shells and has pronounced them to be *Lingulepis pinniformis.*

The discovery of these fossils in the sandstone at Iron Mountain is particularly interesting, since they furnish the data by which the rock is identified as a portion of the St. Croix series of the Upper Mississippi Valley, which in turn is stratigraphically equivalent to the Potsdam sandstone in the Adirondack region. Through the Menominee rock is likewise established the age of the sandstone bordering the south side of Lake Superior, since the Menominee sandstone is traceable directly by almost continuous exposures into the sandstone at Ashland, Marquette, and other points on the south shore of the lake. Therefore this sandstone likewise must be the equivalent of the St. Croix sandstones. This view has been consistently maintained by nearly all writers on the geology of the Lake Superior region, but it was based exclusively on stratigraphical arguments, since the rock had nowhere been seen to contain fossils that it was possible to identify. Walcott, in his review of the literature of the Cambrian series,[a]

[a] Walcott, C. D., Correlation papers—Cambrian: Bull. U. S. Geol. Survey No. 81, 1891, p. 338.

concluded that the Lake Superior sandstone "occupies the exact stratigraphic position of the fossiliferous St. Croix or 'Potsdam' sandstone of Wisconsin." He continues: "Although not considering it proved that the two sandstones are exactly contemporaneous, I think that for all practical geological classification they may be considered equivalent deposits." The discovery of a portion of the St. Croix fauna in these sandstones removes the doubt as to their contemporaneity with the St. Croix beds and enables us to correlate the two sandstones without much fear of error.

SECTION 2. 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 Hughitt Bluff, east of Iron Mountain, on the north side of the road between the Pewabic and the Walpole mines, and also on the bluff northeast of Norway and at several places on the hills north of Waucedah. Its maximum thickness, according to Rominger, 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 gasteropod, and several other fragmentary forms found in the top layer on the bluff northeast of Norway.

The areas within which the limestone is known to occur are so small that no attempt has been made to differentiate them from the Cambrian areas on the general map.

CHAPTER VII.

OUTLINE OF GEOLOGICAL HISTORY.

RÉSUMÉ OF FORMATIONS.

Before giving a brief outline of the history of the district it may be well to recall the general succession of formations and their distribution. The district is bordered by areas of Archean schists and granites. The Huronian sediments of the district are in a trough between these older rocks. Structurally this trough is a synclinorium, composed of several important anticlines and synclines. The Lower Menominee series comprises 1,050 to 1,250 feet of quartzites and conglomerates that have been called the Sturgeon quartzite, 1,000 to 1,500 feet of dolomites, with subordinate amounts of calcareous slate and chert, designated the Randville dolomite, and possibly small patches of the iron-bearing Negaunee formation. The Upper Menominee series comprises the Vulcan formation, 650 feet thick, and the Hanbury slate. The Vulcan formation includes three members, the iron-bearing Traders member, consisting largely of detrital ores and jaspilites, but having basal layers of slate, quartzite, and conglomerate; the Brier member, composed of ferruginous and siliceous slates; and the Curry member, consisting of quartzites, ferruginous quartzose slates, jaspilites, and ores. The Hanbury slate is mainly argillaceous, but in places is calcareous, and includes small beds of dolomite and ferruginous chert.

SUCCESSION OF EVENTS.

Archean.—The history of the Archean rocks is an extraordinarily complex one, which will not here be analyzed. It is sufficient to say that the ancient Quinnesec schists, wholly of igneous and largely of volcanic origin, were intruded in a most complex fashion by various igneous rocks, of which granite was the most abundant. This complex of rocks went through a long series of epeirogenic and orogenic movements, with attendant metamorphosis and deep denudation, before Algonkian time.

Lower Menominee deposition.—By transgression of the sea, due to subsidence of the land or rise of the sea, or both, the Menominee district was finally covered by water, and Lower Menominee Algonkian deposition began. Originally the sediments were laid down as a set of approximately horizontal beds on a basement composed of Archean rocks similar to, if not identical with, the material constituting the rims of the trough. The first deposit of the advancing sea was the basal conglomerate of the Sturgeon quartzite. Following this conglomerate was a thick layer of sandstone, which later was consolidated into quartzite. The deposition of a considerable thickness of sand, which at several horizons is ripple marked, shows that the district must have continued to subside during Sturgeon time. Apparently toward the end of the Sturgeon epoch the water became too deep for sandstone formation, and the nonclastic sediments of the Randville dolomite were deposited. These are now cherty crystalline dolomites and marbles, but there is every reason to believe that the original form of the material was an ordinary siliceous magnesian limestone. The time represented by the Randville dolomite was probably long, for the thickness of limestones deposited was 1,000 feet or more. Possibly, as a result of upbuilding with shallowing of the sea, or other unknown conditions, the carbonates being deposited changed in character and bore a large amount of iron. At this time the cherty iron-bearing carbonates and greenalite nodules were produced. Later these were transformed into the ferruginous cherts and jaspilites of the Negaunee formation. Whether or not later formations were deposited during Lower Menominee time upon the Negaunee formation is uncertain.

The formations of the Lower Menominee series were certainly deposited over a considerable area in the Menominee district, and the equivalents of these formations were deposited north of the Menominee district in the Crystal Falls and Marquette districts. Whether or not the Lower Menominee formations were deposited upon the Quinnesec schists is uncertain. It is possible that the Quinnesec schists were land areas during a large part of Lower Menominee time and that the iron for the Negaunee formation was derived from these heavily ferruginous rocks within and bordering the district mapped. The apparent entire absence of the Lower Menominee formations about the western area of Quinnesec schist is difficult to understand. The most plausible explanation for this area, and possibly for the southern area, is that the Lower Menominee formations were there deposited and were subsequently removed by erosion. These formations, resting upon the Quinnesec schists, might have been composed of softer material than the resistant formations adjacent to the granite area on the north side of the trough, and therefore may have been more easily erodible.

In any case, it is highly probable that the different formations were not deposited in uniformly thick layers throughout the district. If all the formations, or the lower ones, were not deposited upon the Quinnesec schist, each higher stratum overlapped the one next below it in passing toward the land areas of Quinnesec rocks.

Inter-Menominee unconformity.—Following the long-continued deposition of Lower Menominee time the district was raised above the sea. Apparently this uplift was accompanied by only very gentle folding. The reason for this belief lies in the apparent conformity of strike and dip of the Upper and Lower Menominee series. However, it is explained in another connection that such an erosion interval, with no great discordance in strike and dip, may mark a very great hiatus, and such is believed to have been the case in the Menominee district. The evidence that such a hiatus exists between the lower and the upper iron-bearing series is not found in the Menominee area, but in other areas south of Lake Superior. In the Marquette district, for instance, the inter-Huronian orogenic movements and denudation were of a most profound character. As soon as the Menominee area rose above the water, erosion began and continued until all the Negaunee formation was removed through the central and northern parts of the district, and probably also all of the Lower Menominee formations from that part of the district adjacent to the areas of the Quinnesec schists. However, as has already been said, these schist areas may have been above water during much of Lower Menominee time, in which case it would not be necessary to suppose that denudation removed from them the Lower Menominee formations.

Upper Menominee deposition.—During the later stages of the inter-Menominee denudation the sea again gradually overrode the district. Evidently at this time the area was uneven, though not mountainous, for the first formation laid down by the Upper Menominee sea does not extend over the entire district. These first deposits constitute the iron-bearing Traders member of the Vulcan formation. The material of which this member is composed was largely derived from the iron-bearing Negaunee formation, although material was furnished by other formations, and a portion consisted of iron carbonate and greenalite. Therefore the basal layers are composed of quartzites and conglomerates, the bowlders and smaller detritus of which consist largely of iron oxide and jasper, with some quartzite and dolomite. Since these bowlders could have come only from a land mass, it is certain that the Lower Menominee beds at this time had already been consolidated and were at least partly above the sea. Following the deposition of the basal, somewhat coarse, clastic member of the Vulcan formation, there came a time of relative quiescence, during which the muds that afterwards solidified into the Brier slate were laid down. Following the deposition of the Brier slate the mingled fragmental and nonfragmental sediments of the Curry member were deposited. At the end of the time of the deposition of the Vulcan formation—that is, at the close of the deposition of the iron-bearing Curry member—the sea had not as yet spread over all of the district. The area covered has not been accurately determined, and the Vulcan formation may have a wider distribution than that shown on the map, but it is certain that the sea had not covered the entire district and that some areas were still land, especially those occupied by the hard, resistant dolomite. This is shown by the fact that the Hanbury slate, the next deposit of the advancing sea, at various places rests directly upon the Randville dolomite, there being no intermediate belt of Vulcan formation. The deposition of the Hanbury slate required a long time, during which the physical conditions varied, for mingled with the ordinary slates are subordinate amounts of calcareous slate, dolomite, and chert, marking brief stages of partial or complete nonfragmental sedimentation.

Folding and metamorphism.—Following the deposition of Upper Menominee time the district was again raised above the sea and was subjected to very great orogenic forces. The major compressing force was nearly north-south. As a result of compression in this direction the areal extent of the mass of Menominee sediments was shortened considerably, probably as much as one-half. Consequent on this folding two great anticlinoria were formed, bordering the northern and southern sides of the area, and a great central synclinorium constituting the Menominee trough. The northern and southern anticlinoria naturally expose the oldest, or Archean, rocks. The intermediate synclinorium is occupied by the Huronian sediments.

This central synclinorium consists of three synclines and two anticlines. Superimposed on these folds of the first order is a set of folds of the second order, on these a set of folds of the third order, and on these folds of higher orders to those of microscopical dimensions. The major folds of the Menominee synclinorium are illustrated by the anticlines of dolomite; the folds of the second order by the synclines within the Vulcan formation, in which such mines as the Walpole, Pewabic, and Aragon occur; the folds of the third order by the two separate ore deposits of the Walpole. From an economic point of view, therefore, it is necessary to take into account at least the three major orders of folds.

In addition to the intense north-south compression there was very strong compression in an approximately east-west direction, or, to speak more exactly, parallel to the direction of the trough. This compression produced folds at right angles to the longitudinal folds, so that the east-west folds of the various orders have a pitch. In some cases this pitch is comparatively slight, but in other cases it is very steep, as high as 40°, 50°, 60°, or even 70° or more. It is therefore clear that the east-west compression was of great importance. While the north-south compression produced the subordinate synclines holding the ore bodies, the east-west compression gives these folds a pitch, and thus supplies the chief final condition for the production of the ore deposits.

During the uplifting and folding of the rocks of the Menominee series the harder formations were fractured in a most complicated fashion, and all were profoundly metamorphosed. The sandstones were transformed to quartzites, the limestones to crystalline dolomite or marble, the iron-bearing formation to ferruginous slates, jaspilites, and ores, the muds to slates.

Post-Huronian unconformity.—Contemporary with the uplifting and folding of the district, which must have produced mountain masses, denudation was steadily going on. It was during this complex series of transformations that iron oxide was concentrated in the pitching troughs and the ore deposits were produced. The period of post-Huronian folding and erosion occupied the great length of time represented in other parts of the Lake Superior region by the unconformity between the Upper Huronian and the Keweenawan, the formation of the entire Keweenawan series, and the great unconformity between the Keweenawan and the Cambrian.

Paleozoic deposition.—During the later stages of this great period of denudation the Cambrian transgression was slowly making its way in

North America from the southeast toward the northwest. Finally the Cambrian sea reached the Menominee district, but not until Upper Cambrian time. At this time the topography of the Menominee area was rough, even bluffy. The Cambrian deposits filled the depressions in the preexisting rocks and capped even the highest hills of the district. Where the sandstone lies adjacent to or upon the Vulcan formation the basal member of the Cambrian contains quantities of iron-ore pebbles, and where the topography furnished depressions for concentration of the heavy material these beds are so strongly ferruginous as to furnish detrital iron ores. Sandstone deposition continued to the end of the Cambrian period, at which time the water had become sufficiently deep for limestones to be deposited, and at this stage of the history the Hermansville limestone was laid down. Whether Paleozoic rocks later than the Hermansville limestone were deposited in the Lake Superior region is uncertain.

Post-Paleozoic history.—Following the Paleozoic period of deposition the area was again elevated above the sea, and then another long period of denudation began. So far as known, this erosion period continued until late in Cretaceous time. Possibly later Cretaceous sediments were laid down over the Menominee areas; but in any case, following Cretaceous time the region was again elevated, and, so far as we know, denudation has since continued. Nearly all of the Silurian limestone has now been removed from the district, and only a subordinate amount of the Cambrian sandstone remains capping the higher hills and filling the depressions in some of the subordinate valleys. During this period of erosion the present topography of the district was largely produced. The exact extent to which this topography follows the pre-Cambrian topography can not be accurately determined, but apparently the pre-Cambrian topography has had an important influence upon present topography. As the result of the removal of the greater part of the Paleozoic rocks, the Huronian and Archean rocks were again brought to the surface.

The final important episodes in the history of the Menominee district were the successive advances of the North American ice sheet, which modified the topography of the district by erosion and by deposition. The glacial deposits constitute a mantle which subsequent river erosion has only partially succeeded in removing, and which has prevented fully satisfactory determination of the distribution of the Vulcan and other formations.

CORRELATION WITH OTHER IRON-BEARING DISTRICTS OF THE LAKE SUPERIOR REGION.

The attempt to correlate the various formations of the two Huronian series in the four different iron-bearing districts south of Lake Superior shows very significantly that the geological history of pre-Cambrian time was extraordinarily complex. From Archean to Upper Cambrian time, in the Marquette, Crystal Falls, and Menominee districts, the areas three times emerged from the sea and were three times overridden by the sea. In the Penokee district there was a fourth emergence and transgression of the sea. The epeirogenic or land-making movements were accompanied by orogenic movements, or mountain growths of varying power, but some of them exceedingly intense. In Huronian time, in all the districts except the Menominee, there were important and long-continued periods of volcanism. The erosive forces at periods when the districts were land areas found rocks of very different characters. Here they were resistant, there easily denuded. As a consequence, when the sea encroached at the close of Archean, Lower Huronian, and Upper Huronian times, the country in detail was very irregular—was in fact bluffy, but not mountainous. Therefore certain areas were covered by the sea, while other immediately adjacent areas were above the water and were being actively eroded. As a consequence of all these complex conditions we have unconformity, overlap, changes in the characters of contemporaneous sediments along the strike and across the strike, disturbances in the successions due to volcanism, close folding, and attendant metamorphism, and all of these phenomena in a region which is largely covered by glacial drift.

A more precise correlation of the Menominee formations with those of the other iron-bearing districts south of Lake Superior as well as with those to the north of the lake is left for discussion in another monograph which will treat of the geology of the entire Lake Superior Basin.

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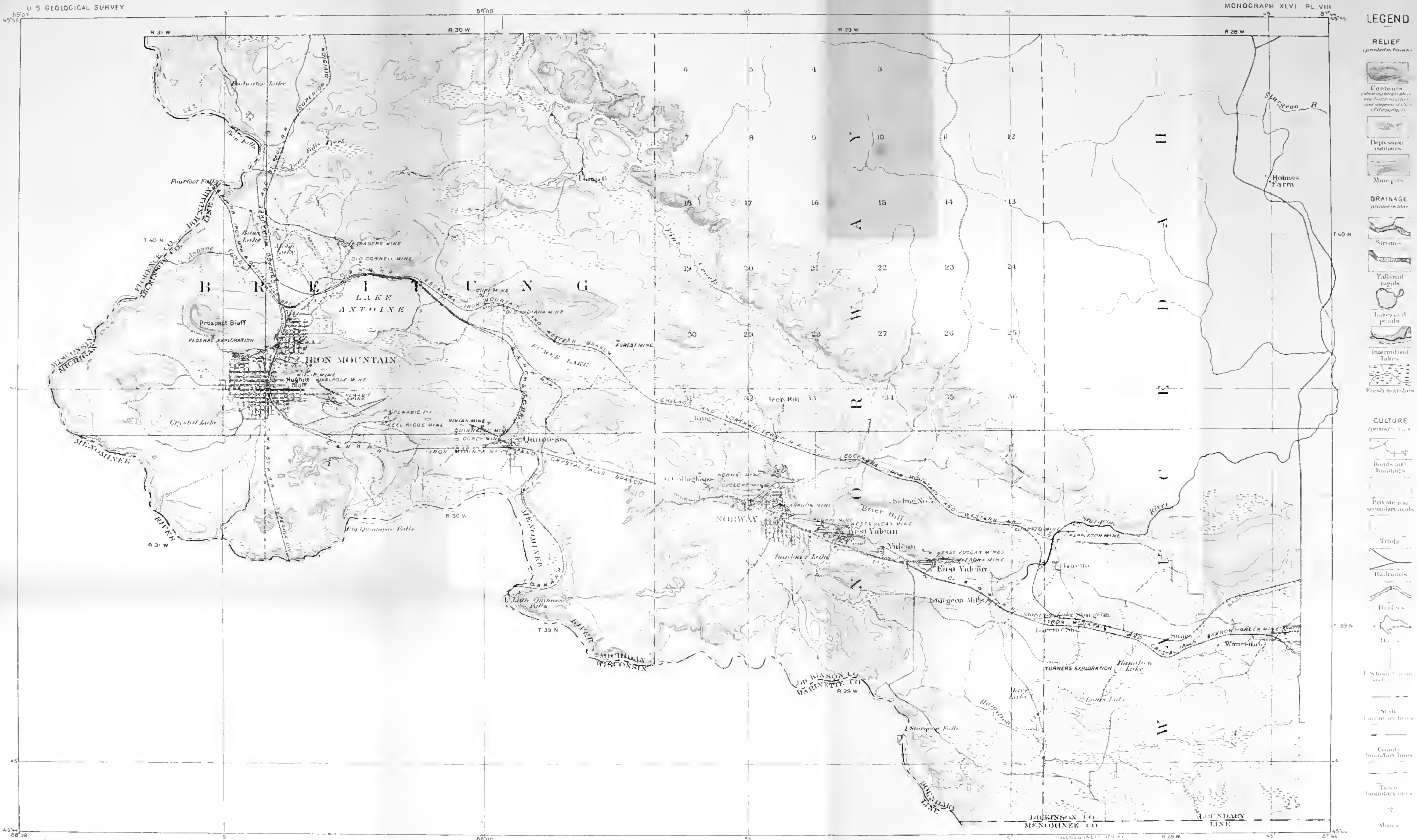
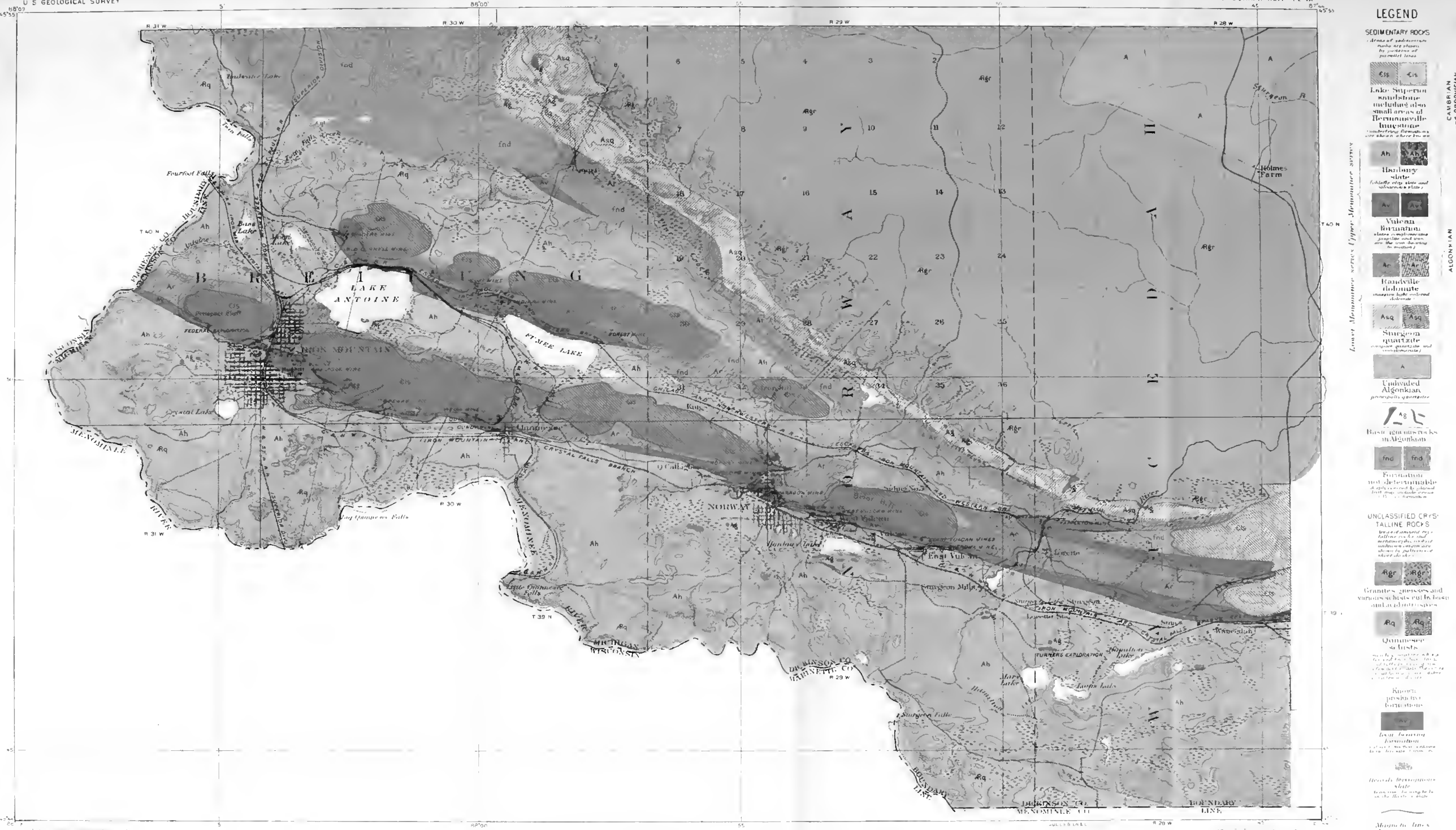


TOPOGRAPHIC MAP OF MENOMINEE IRON DISTRICT, MICHIGAN

Jno H Renshawe, Geographer in charge
Topography by E.C. Bebb
Surveyed in 1898

Scales

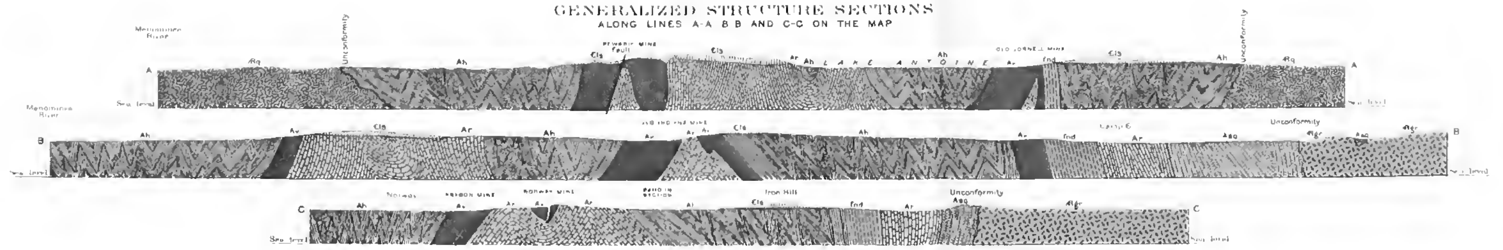
Contour interval 20 feet
Datum is mean sea level
1903



GEOLOGIC MAP OF MENOMINEE IRON DISTRICT, MICHIGAN

Contour interval 20 feet

GENERALIZED STRUCTURE SECTIONS
ALONG LINES A-A B-B AND C-C ON THE MAP



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