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ERRATUM

In the article by George T. Becker and Arthur L. Day, published in No. 4 of Vol. XXIV of this *Journal*, the following erratum should be noted:

P. 329, line 6 from the top, the word *failure* is to be replaced by the word *presence*.

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VOLUME XXIV NUMBER 1

THE

JOURNAL OF GEOLOGY

JANUARY-FEBRUARY 1916

THE ACADIAN TRIASSIC

SIDNEY POWERS
Troy, New York

CONTENTS

PART I

PART I

INTRODUCTION

GENERAL RELATIONS

The Acadian Triassic is preserved as a rather narrow, discontinuous border to the Bay of Fundy and Minas Basin. The Bay of Fundy has a northeast-southwest trend, with the island of Grand Manan at the entrance. The Triassic extends from the southwest end of Grand Manan to Truro, a distance of 195 miles. The width of the Bay of Fundy, from Digby to St. John, is 45 miles. On both the New Brunswick and the Nova Scotia shore, the Triassic appears: in New Brunswick on Grand Manan Island, at Split Rock (Gardner's Creek), Quaco, Martin Head, and Waterside; in Nova Scotia on the island of Isle Haute, and in a quite continuous strip from Advocate around Minas Basin and down the Bay of Fundy to Brier Island at the entrance.

The field work in connection with this paper occupied a portion of the summers of 1913 and 1914. In the field work, the writer is indebted for suggestions to Professor J. W. Goldthwait, Dr.

A. O. Hayes, and Mr. W. A. Bell of the Geological Survey of Canada, and to Professor D. S. McIntosh of Halifax, Nova Scotia. Professor Alfred C. Lane of Tufts College has kindly permitted the use of thin sections and drill cores of the Cape D'Or basalt. To Professor R. A. Daly, under whose direction this paper was prepared as a portion of a thesis for the degree of Doctor of Philosophy in Harvard University, special thanks are due for helpful criticism.

GENERAL GEOGRAPHY AND GEOLOGY OF THE REGION

Topography.—The most important topographic feature of the Bay of Fundy region is North Mountain, extending from Cape Blomidon to Brier Island, 125 miles. South of North Mountain is the Annapolis Valley and the land of Evangeline, a broad fertile plain extending from Minas Basin to the Annapolis Basin. South of the Annapolis Valley is South Mountain, whose crest stands on a level with North Mountain, at an elevation of about 400 feet.

On the northern side of the Bay is the island of Grand Manan, presenting an abrupt escarpment on the west, rising 200 to 400 feet out of the sea. The tops of these basaltic cliffs is again at the level of North Mountain. On the east side of Grand Manan is a rolling lowland fronted by many islands. The New Brunswick shore is bounded by rocky cliffs rising to a height of 50 to 200 feet, but between the Triassic exposures at Quaco and Waterside, the cliffs rise to the summit level of 400 feet.

Minas Basin is surrounded by lowlands, presenting a rather flat surface at elevations of 100 to 150 feet, except for the tidal marshes. On the north, the Cobequid Mountains rise to heights of 500 to 800 feet, with "peaks" at 1,000 feet.

Geology.—The controlling factor of the topography and geology of the region is the direction of the orographic axes, from northeast to southwest (Fig. 1). The Bay of Fundy is confined between a broad belt of pre-Cambrian rocks in Nova Scotia, fronted by the Triassic; and a less broad belt of pre-Cambrian rocks in New Brunswick, fronted by Carboniferous and Triassic strata (Fig. 2). The peninsula of Nova Scotia is composed largely of pre-Cambrian strata intruded by Devonian granite.

Minas Basin is bounded by Triassic rocks, below and around which are Carboniferous and Permian strata. To the north, separated by a normal fault, are the Cobequid Mountains, which are composed of Silurian schists and quartzites with various

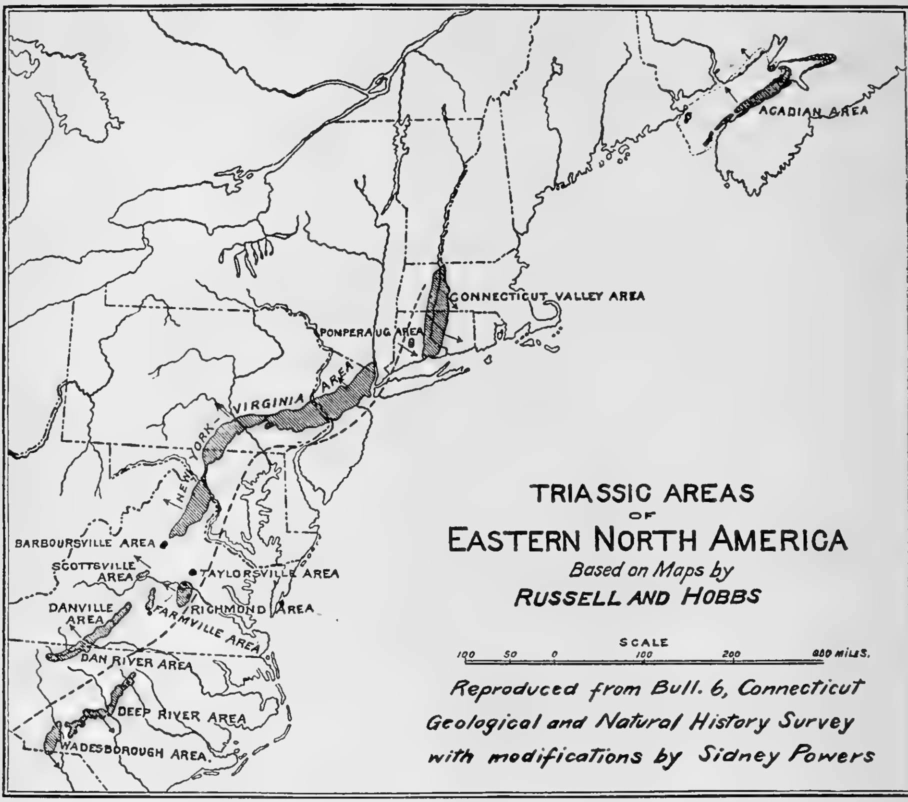

FIG. 1.—The Newark group in North America

associated igneous rocks. North and west of the Cobequids are Carboniferous and Permian strata, stretching northward over the Magdalen Islands and over Prince Edward Island.

THE NEWARK GROUP IN THE ACADIAN AREA

The first reference to the Triassic in the Maritime Provinces is by Alger, in 1827.[1] Six years later, a description of the Triassic

[1] F. Alger, "Notes on the Mineralogy of Nova Scotia," *Am. Jour. Sci.*, XII (1827), 227–32.

rocks was published by Jackson and Alger.[1] At about that time Gesner began his work in connection with the Geological Survey of New Brunswick and mentions the Triassic in each of his reports.[2]

From 1835 to the present, a number of writers have discussed the Acadian Triassic in part or in whole, and, as Russell has given a bibliography of these papers in his correlation paper on "The Newark System,"[3] only the more important and the recent papers need be noted here.

Dana gave the name "Acadian Area" to this mass of Triassic rocks in his *Manual of Geology* (2d ed., 1875). Three years later, Dawson issued the second edition of his *Acadian Geology*, in which volume is the only account of the Triassic in Nova Scotia and New Brunswick. From 1863 to 1880, G. F. Matthew and L. W. Bailey were employed by the Geological Survey of Canada in mapping southern New Brunswick. In their reports are descriptions of the outliers of Triassic strata in New Brunswick.

The more recent work on the Acadian Triassic is that published by L. W. Bailey on the Digby Neck region[4] and by H. Fletcher

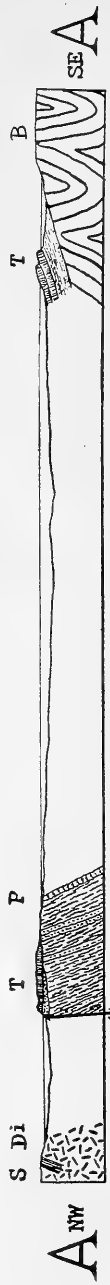

FIG. 2.—Geologic cross-section, AA, of the entrance to the Bay of Fundy, through Quoddy Head, Maine, on the northwest, the island of Grand Manan near by, and Long Island on the southeast. *P*, pre-Cambrian; *B*, Meguma series (pre-Cambrian); *S*, Silurian; *Di*, Diabase (Devonian?); *T*, Triassic. The Triassic shales under the basalt on Grand Manan appear only on the north. Note the longitudinal valley on Long Island between the flows. The Triassic sediments south of Long Island are submerged.

[1] C. T. Jackson and F. Alger, "Remarks on the Mineralogy and Geology of Nova Scotia," *Am. Acad., Mem.*, N.S., I, 217–330.

[2] The reports are given in the bibliography of all literature on the Newark System, in I. C. Russell's correlation paper on "The Newark System," *U.S. Geol. Surv., Bull. 85*, 1892.

[3] *Ibid.*

[4] L. W. Bailey, "Report on the Geology of Southwestern Nova Scotia," *Geol. Surv. Canada, Ann. Rept.*, IX (1898), Part M.

who mapped the Minas Basin region[1] for the Geological Survey of Canada.

The former extent of the Acadian area is indeterminate, but it is probable that it extended several miles in all directions beyond the present boundaries. The original form appears to have been a basin with its northern limit near the Cobequid Mountains and its southern limit not far south of Grand Manan and Brier Island. There may have been a ridge of older rock extending out into the basin where the eastern side of Grand Manan now is, provided that the interpretation of the geology of that island, as given below, is correct.

The Newark group in the Acadian area has been divided into the following formation:

		Thickness in Feet
Top, an erosion surface		
Scots Bay formation (calcareous white sandstone)		25–(2,000 ?)
North Mountain basalt (a succession of lava flows)		800– 1,000
Annapolis formation (red beds, largely calcareous)	Blomidan shale	500– 1,000
	Wolfville sandstone	2,000– 2,500
		3,325– 6,500
Base, an unconformity with Paleozoic or older rocks		

Interbedded in the Annapolis formation, near its top, are certain basalt flows: agglomerate and tuff beds near the Five Islands, grouped under the name Five Islands volcanics. At Quaco, New Brunswick, there is a conglomerate horizon in the center of the red sandstones correlated with the Annapolis formation, and this conglomerate is called the Quaco conglomerate.

DESCRIPTIVE GEOLOGY

The descriptive geology of the Acadian Triassic will be taken up by localities, giving a brief description of the lithological and structural details. A number of detailed maps and sections are introduced, which may be connected with the region as a whole, by reference to the general map (Fig. 3), and the columnar sections

[1] H. Fletcher, various papers which have been printed in the annual and summary reports of the Geological Survey of Canada from 1887 to 1907. See especially the *Annual Report*, V (1892), Part P.

(Fig. 4). The principal structural features and the details concerning the igneous rocks are summarized in a separate section.

STRATIGRAPHY

Grand Manan.—The island of Grand Manan is situated 4 miles southwest of Quoddy Head, the most easterly point in the United States. It is 15 miles long and 6 miles wide in the widest part. To the east and south are numerous islands and reefs.

Grand Manan was first visited by a geologist—Abraham Gesner—in 1838, then by Bailey,[1] Verrill,[2] and Ells.[3] Bailey visited most of the adjoining islands and gives the best description of the geology.

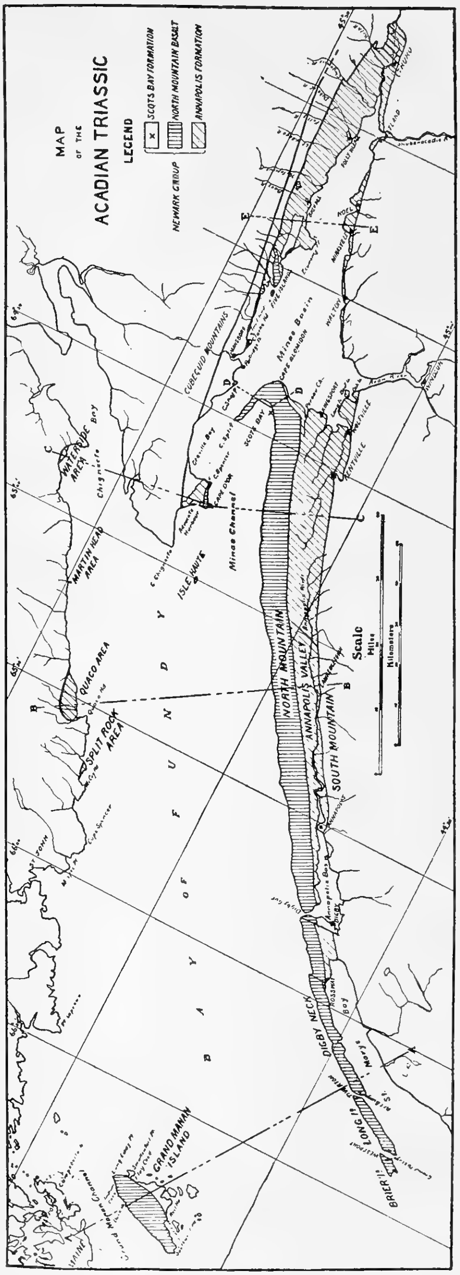

Fig. 3.—Map of the Acadian Triassic

[1] L. W. Bailey, "The Physiography and Geology of the Island of Grand Manan," *Can. Nat.*, VI (1872), 43 ff.; also see Bailey, Matthew, and Ells, "Preliminary Report on the Geology of Southern New Brunswick," *Geol. Surv. Canada, Rept. Progress* (1870), pp. 216–21.

[2] A. E. Verrill, Appendix E to Dawson's *Acadian Geology*, 3d ed. (1878), pp. 679–80.

[3] R. W. Ells, *Geol. Surv. Canada, Summary Rept.*, VIII (1894), 271*A*.

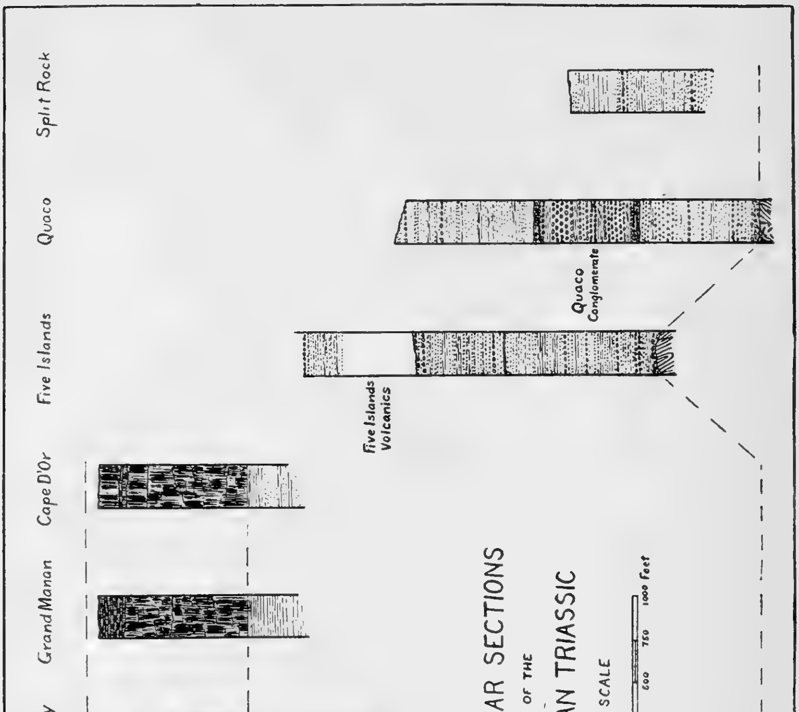

FIG. 4.—Columnar sections of the Acadian Triassic

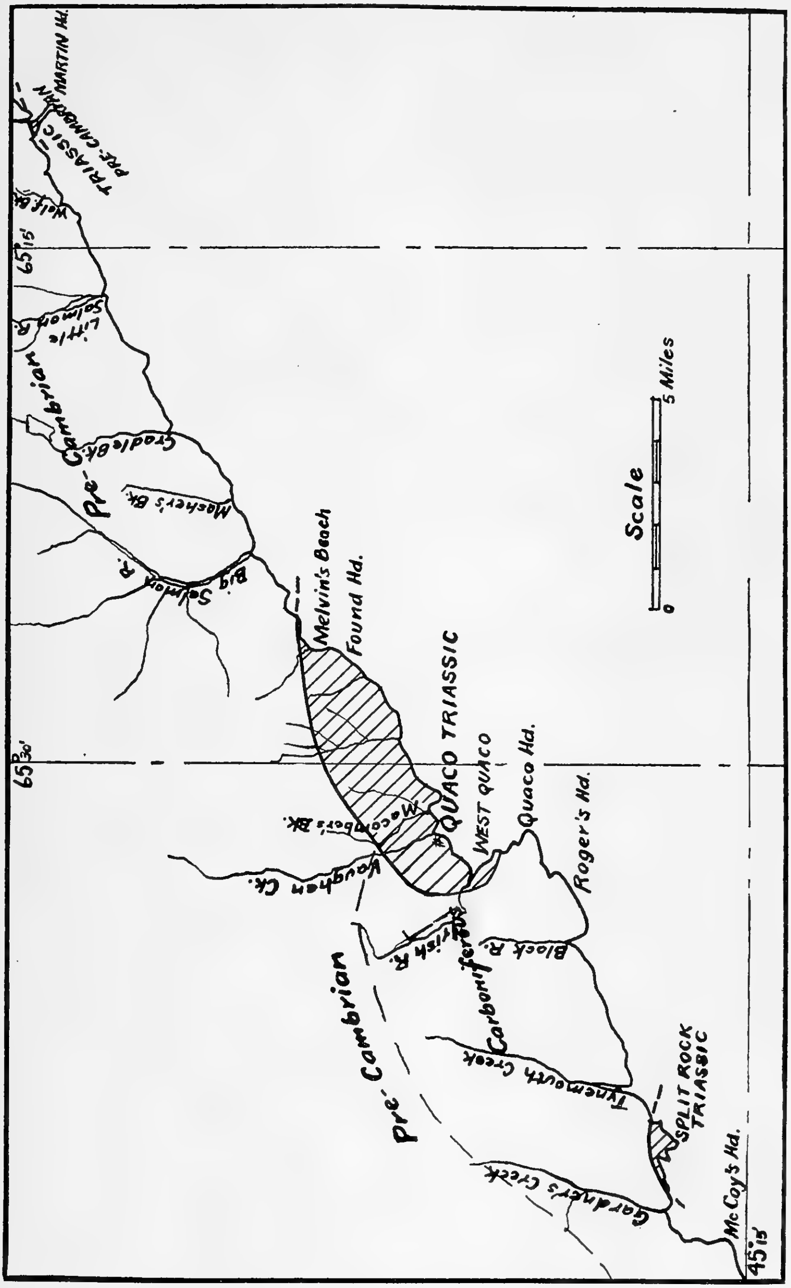

Fig. 5.—Map of the Split Rock, Quaco, and Martin Head, Triassic areas

The physiography and geology of Grand Manan divide the island into two provinces: a western upland underlain by Triassic basalt flows, and an eastern lowland underlain by pre-Silurian[1] metamorphic rocks. The upland represents the level of the Summit[2] peneplain, at elevations of 200–400 feet. The western coast of the island is fronted by cliffs rising abruptly in an almost straight line to a height of 100–300 feet.

The Triassic rocks of the island consist of basalt flows underlain by purple shale. The shale is exposed to a thickness of only 50 feet, and this exposure is at Dark Harbour, on the western side of the island. The basalts rest directly on older, metamorphic rocks on the eastern side of the island; at Red Head, on the south, and at the northwestern end of Flag Cove, on the north. At the former locality the contact dips 35 degrees, suggesting a fault, but the recent weathering of the rocks near the contact obscures the exposure.

The basalt flows are thick at the base and thin at the top. The exact thicknesses are given below with the résumé of the igneous rocks. The dip of the flows is variable. At Dark Harbour it is practically horizontal, but north of this place, the dip is down toward the north at angles of 5 to 15 degrees. It is difficult to determine the horizontal extent of any one flow. Diabase dikes are reported by Bailey at several places, one of which is Swallow-Tail Light.

The faults on Grand Manan are obscured by the massive character of the basalt. The major fault bounds the west side of the island, and the cliffs, which run in an almost straight line for 15 miles, mark the fault-line scarp. East-west faults are less prominent. One may occur at Dark Harbour, as many of the streams flowing across the Newark basalts follow fault-lines. Minor faults are seen in the shore exposures.

Split Rock.—Eighteen miles east of St. John, between Gardner's Creek and Tynemouth Creek, there is a strip of Triassic sediments

[1] The age of these rocks is probably pre-Cambrian, as they are older than the Silurian rocks of the Eastport Quadrangle. See E. S. Bastin, *U.S. Geol. Survey, Geol. Atlas*, Eastport Folio (No. 192) (1914), p. 14.

[2] The term "Summit" peneplain is used instead of "Cretaceous" peneplain in order to avoid any reference to the age of this topographic feature.

about two miles long, and three-quarters of a mile wide at Split Rock itself (Figs. 5 and 6). This point should not be confused with one southwest of St. John by the same name.

This area is bounded on the north by a fault which has brought the Triassic into contact with the Carboniferous. The dip of the

Fig. 6.—The Triassic shales near Gardner's Creek (Split Rock), dipping northward. The marine shelf has been cut at high tide level.

Triassic red sandstones, shales, and occasional conglomerates is in general northward at angles of about 45 degrees, but the beds flatten out at split rock itself. The sediments show occasional cross-bedding. The conglomerates contain only occasional pebbles, and these pebbles are subangular, with occasionally very angular, and rarely rounded surfaces. They do not show striations or sand-blasted surfaces. Fragments of silicified wood have been found near Gardner's Creek, and are noted by Dawson in his *Acadian Geology*.

Quaco.—A large area of Triassic sediments occurs at Quaco, now known as St. Martin. The Triassic extends from West Quaco to Melvin's Beach, and includes the large area mapped as

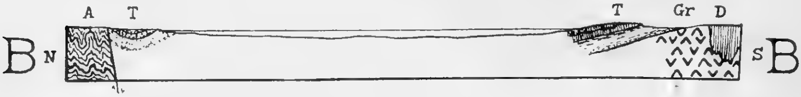

Fig. 7.—Geologic cross-section, BB, from Quaco, on the north, through North Mountain, the Annapolis Valley, and South Mountain, on the south. *A*, pre-Cambrian; *D*, Devonian; *Gr*, Devonian granite; *T*, Triassic.

Fig. 8.—The contact of the lower red sandstone and the Quaco conglomerate above, near Macomber Brook, Quaco. The contact is a conformity. There is a very sharp boundary both in lithology and in color which is obscured by a pile of talus in the center of the picture.

Lower Carboniferous on the map of the Geological Survey of Canada, issued in 1880. The length of the area is $7\frac{1}{2}$ miles and the width 3 miles, as shown in Fig. 5. The shore exposures furnish an excellent structural cross-section of the area.

The structure of the Quaco area is synclinal, with an east-west axis (Figs. 7 and 8). The contact of the Newark rocks with older rocks is shown at West Quaco, where there is an unconformity of red Triassic sandstone on greatly pointed, pre-Triassic traps. The basal sandstone contains occasional pebbles of various kinds of rock but contains no residual soil of the trap. At the unconformity there is minor cross-faulting in a northeasterly direction. At Melvin's Beach, on the northeast, the Triassic sandstones are seen, with steeply dragged dips, in fault-contact with pre-Cambrian metamorphics.

The stratigraphy of the area shows two normal red sandstone members, separated by a conglomerate of pale yellow color. Interbedded in the conglomerate are persistent beds of sandstone, a few inches in thickness, at stratigraphic distances of 10–30 feet, as shown in Fig. 8. The conglomerate is composed of rather loosely consolidated subangular to rounded stream gravels. Many of the pebbles show impressions of one pebble into another, and other recemented fractures.[1] In no other locality of the Acadian Triassic is such a conglomerate found.

The section was estimated as follows:

Upper red sandstone........................	800–1,000+
Quaco conglomerate........................	450– 700
Lower red sandstone........................	300– 300
	1,550–2,000

UNCONFORMITY WITH CARBONIFEROUS

Plant remains occur at several horizons in the Quaco series. Silicified wood was found by the writer within 50 feet of the top of the lower red sandstone, at Vaughan Creek, and by members of the Geological Survey of Canada at other localities. These fossils are correlated with the fragments of lignite from Split Rock and Martin Head. On account of the exposure of the basal unconformity of the Newark at West Quaco, it is probable that the Quaco exposure is to be correlated with the Annapolis formation,

[1] These conglomerates are similar to those of Upper Devonian age on the north side of Scaumenac Bay, Province of Quebec, described by J. M. Clarke, *Bull. Geol. Soc. Am.*, XXVI (1915).

and that it is below the horizon of the North Mountain basalt, as shown in Fig. 4.

Martin Head.—Martin Head is 20 miles northeast of Quaco. The Head itself is composed of a mass of pre-Cambrian strata, 100 feet in height, connected to a point of land by a shingle beach (Fig. 9). On the northern side of the Head is some red clay, apparently of Pleistocene age, which may be underlain by Triassic sediments.

North of the barrier beach are low cliffs of Triassic strata, exposed only on the west side of the peninsula. The bedrock is exposed for half a mile in the form of a syncline, with the longer

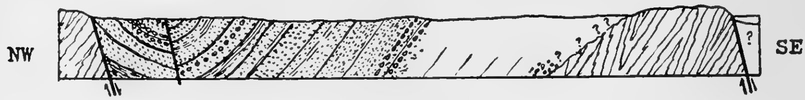

FIG. 9.—Cross-section of the Martin Head Triassic area. Martin Head itself, composed of pre-Cambrian strata, is on the right. Between it and the pre-Cambrian uplands on the northwest are the Triassic sediments. The unconformable contact of the Triassic with the pre-Cambrian on the southeast is hypothetical.

limb on the south. On the north, the Triassic is faulted against the pre-Cambrian, as shown in Fig. 9. In the southern limb 335 feet of sediments are exposed, in the northern limb 85 feet, and between these two limbs there are no exposures. A fault probably exists between the exposures, as the strata do not match on either side of the gap.

The sediments in the Martin Head area are principally yellow sandstones and shales, with occasional pale-red beds, and transition colors. The yellow is a bright-chrome shade, much brighter than that of the Quaco conglomerate, which is merely that of the common stream gravels. Conglomeratic beds occasionally appear. The sediments are characterized by a notable amount of muscovite and of calcite. The former has evidently been derived from the pre-Cambrian mica schists on the north.

Lignite occurs at several horizons in the yellow beds, as carbonized twigs, limbs, and bits of wood, often 2–3 inches in diameter. This lignite has been described by Miss Ruth Holden,[1] and the

[1] Ruth Holden, "Fossil Plants from Eastern Canada," *Annals of Botany*, XXVII (1913), 243–55.

paper is summarized below in treating of the age of the Acadian Triassic. As the plant remains appear to be similar to those found at Quaco, the sediments in the two areas may be correlated with each other.

Waterside.—On the north side of Chignecto Bay is a strip of Triassic at Waterside, 20 miles northeast of Martin Head. The length of the strip is about 4 miles, extending from Dennis' break-water on the west to the eastern end of the marsh at Little Rocher on the east (Fig. 10), but the length of the actual exposures of Triassic sediments is about $1\frac{1}{2}$ miles.

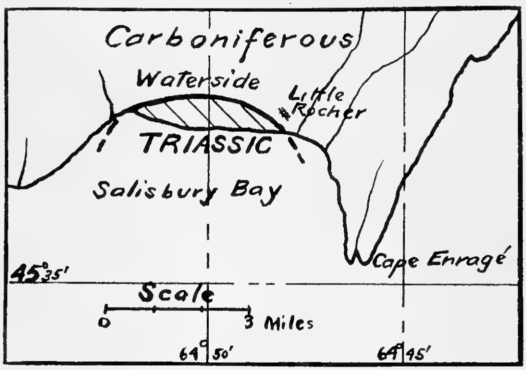

FIG. 10.—Map of the Waterside area of Triassic sediments.

The structure of this area is anticlinal on the west and synclinal on the east, with the axis of the syncline at the Waterside wharf. The dip of the folds is gentle, exposing only 320 feet on the eastern limit of the anticline. On the west,

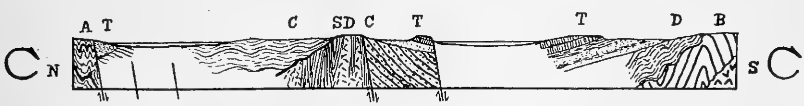

FIG. 11.—Geologic cross-section, CC, from Waterside, on the north, through Cape d'Or, across Minas Channel, and through North Mountain. *A*, pre-Cambrian; *B*, Meguma series (pre-Cambrian); *SD*, Cobequid group (Silurian, cut by Devonian igneous rocks); *D*, Devonian; *C*, Carboniferous; *T*, Triassic. The major fault of the region is shown in the center of the section, where the Carboniferous and Triassic are dropped down against the Cobequid group.

the Triassic is faulted against a sheared Carboniferous conglomerate, but the contact is concealed by a Pleistocene delta deposit. This same fault probably bounds the Triassic area on the north and east, but it is not again exposed.

The Waterside Newark strata consist of pale-red sandstones with occasional conglomerates. At the top of the series there are

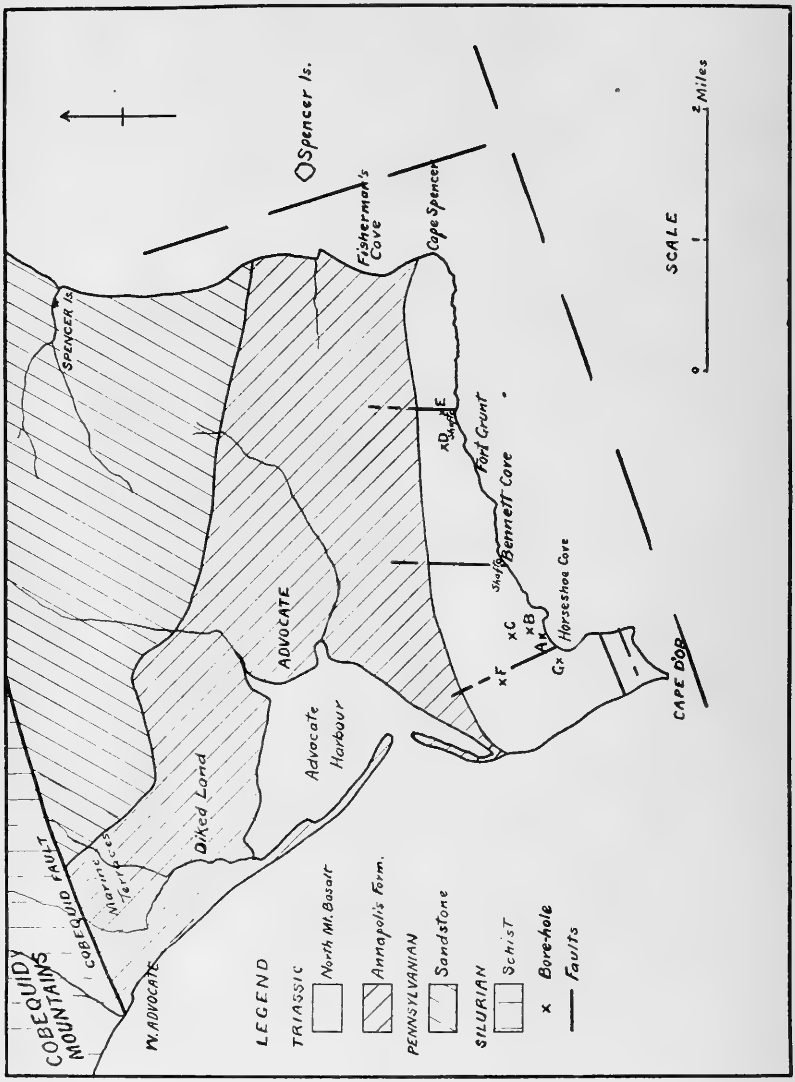

Fig. 12.—Map of the Advocate-Cape d'Or area

several calcitized sandstone beds, which weather out into peculiar forms. Persistent thin green shale or sandstone beds are present.

Contemporaneous erosion channels are seen west of the Waterside wharf.

The Waterside section is to be correlated with the Annapolis formation, but, as no plant remains have been found in it, a more definite correlation is impossible.

Advocate Harbour.—At the southeastern end of Minas Basin is Cape d'Or and north of it is Advocate Harbour. The shore from Cape d'Or to Cape Spencer (Figs. 11, 12) is fronted by basalt

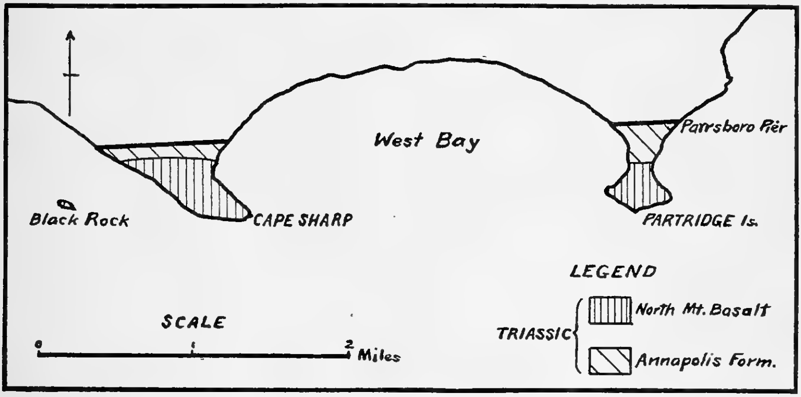

FIG. 13.—Map of the Cape Sharp-Partridge Island region

cliffs 100 feet or more in height. The lowlands on the north are underlain by Triassic sandstone, and, farther north, by Carboniferous sediments. North of the latter are the Cobequid Mountains, fronted by a fault-line scarp rising abruptly from the lowlands.

The upland from Cape d'Or to Cape Spencer, and the islands, Isle Haute and Spencer Island, are composed of basalt flows dipping southward at a low angle. Five flows are exposed at Cape d'Or in drill-cores. The base of the flows rests on Newark shale and sandstone of a white or red color. Both the basal amygdaloid and the underlying sediments are penetrated by gypsum veins.

North of Cape Spencer, very coarse conglomerates, which are probably of Newark age, are exposed. The bowlders in this conglomerate are a foot or two in diameter.

On the shore near West Advocate is the only other exposure of Newark sediments in this area. Red sandstone, with some red shale, and thin greenish or white bands of sandstone, are dipping eastward. Adjoining these sandstones, on the north, is Silurian carbonaceous schist of the Cobequid group, separated by a fault which may be traced down the beach in a S. 71° W. direction. This is the main Cobequid fault, shown in Fig. 10. Other minor faults are shown in the same map.

FIG. 14.—Partridge Island from the west, showing basalt flows overlying red sandstones. The sandstones appear along the gentle slope at the left-hand side of the cliff.

Cape Sharp.—To the east of Cape Spencer, Cape Sharp is the first promontory. It consists of basalt, as does Black Rock on the west (Fig. 13). On the north of Cape Sharp is a lowland underlain by red Triassic sandstone and shale with occasional green bands, and north of this is a rolling country underlain by Carboniferous sediments.

The basalt on Cape Sharp consists of one or more flows—probably two flows—which dip to the south at an angle of about

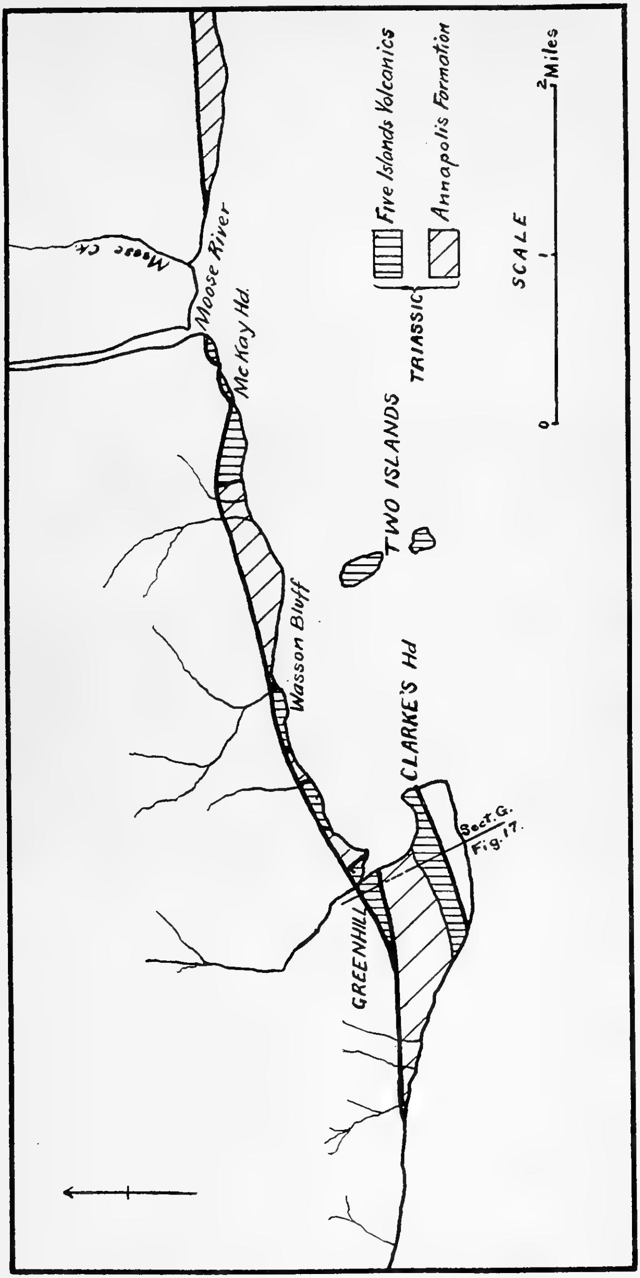

FIG. 15.—Map of the Two Islands region

5°–10°. The shale and sandstone underlying the basalt are exposed on the northeast side, for a short distance only. The sandstone

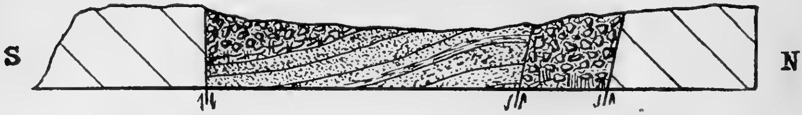

FIG. 16.—Structure section, G, through Clarke's Head, on the south, and Swan Creek, on the north. The structure of the pre-Triassic rocks is not shown. Overlying the Triassic red sandstone is a bed of tuff, overlain, in turn, by agglomerate. At Swan Creek only agglomerate appears, but it is probably a part of the same flow.

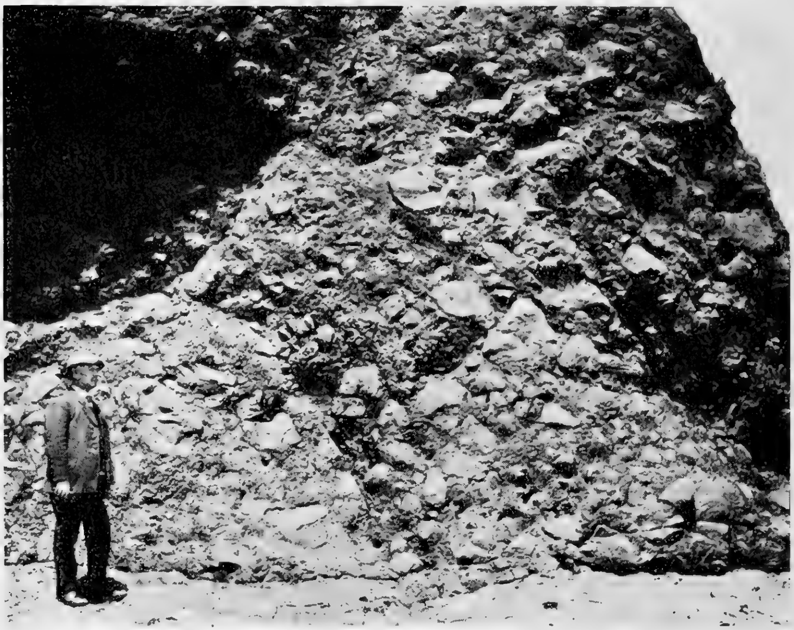

FIG. 17.—A detailed view of the agglomerate which comprises a large portion of the Five Islands volcanics. The photograph shows the center of a 100-foot bed of the agglomerate east of Blue Sack. The angular blocks are composed of basalt, and the matrix is tuffaceous.

is seen to be in fault contact with the Carboniferous shales and sandstone to the north.

Partridge Island.—East of Cape Sharp is a peninsula called Partridge Island, formed of a mass of basalt connected with the shore by a low, swampy area which is covered by the sea at very high tides. On the northwest is Gilbert's Cliff, rising to a height of 60 feet, and on the northeast Parrsboro Pier (Fig. 13).

The basalt on Partridge Island (Fig. 14) is partly columnar and partly vesicular. It probably consists of two flows. Stilbite is very abundant in geodes in the amygdaloid. At the base of the lower flow the highly weathered amygdaloid is 15 feet thick.

The Triassic shales and sandstones are seen underlying the basalt on the west side of the island, dipping southward at an angle of 10 to 35 degrees. Near Gilbert's Cliff are red clays of Recent age, overlying the beveled, upturned edges of the ripple-marked Pennsylvania shales. The Triassic is not exposed to show whether this surface was the one on which the Triassic was deposited or whether it was the one made by the Pleistocene ice-sheet.

Greenhill–Five Islands.—From a point 3 miles east of Parrsboro, near Greenhill, to Five Islands, there is an almost continuous strip of Triassic, faulted down against the Riversdale–Union series of Pennsylvanian age (Fig. 15). The entire region has suffered extensive faulting and, with these movements, gypsum veins have been introduced.

The Newark comprises red sandstones and some shales, with occasional beds of green sandstone or shale; tuff and agglomerate beds; and basalt flows. The distribution of these rocks is very irregular, owing to the faulting, and is disturbed by extensive landslides in the volcanics.

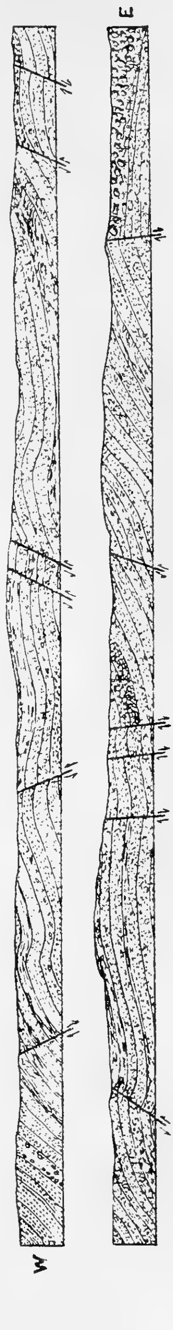

Fig. 18.—Structure section from Moose Creek toward Blue Sack, a distance of about 2 miles, showing the character of the folding and faulting in the sediments as seen in the shore exposures. The height of the cliffs is 150–200 feet. On the extreme right, a bed of agglomerate of the Five Islands volcanics is shown, overlying sandstone.

West of Clarke Head is an excellent exposure showing sandstones overlain by black ash, and this by agglomerate, the whole being cut off by a fault (Fig. 16). North of Clarke Head, agglomerate is exposed, and copper has been sought at this locality.

East of Swan Creek, sandstone appears, overlain by a volcanic conglomerate—a mass of fragments 6 inches to 2 feet in diameter, of various kinds of basalt and agglomerate, imbedded in a red sandstone matrix. Above this, with a gradual transition, comes a true agglomerate of angular blocks imbedded in a tuffaceous matrix (Fig. 17). Sandstone appears above the agglomerate, and the contact is locally cross-cutting.

At Wasson's Bluff, agglomerate appears above red sandstone, with a conformable contact. East of Wasson's Bluff the agglomerate rests unconformably on the sandstone. Another local unconformity is found at McKay Head, where the sediments are overlain by agglomerate with columnar basalt above. East of McKay Head are two remnants of the same basalt, with faulted contacts. The cross-cutting nature of some of the contacts may indicate volcanic vents.

Two Islands, known also as The Brothers, consist of basalt flows dipping gently northwest. The islands are probably separated from each other and from the mainland by faults.

East of Moose River the sediments reappear and extend from this point around Minas Basin, continuously as far as the Shubenacadie River. The structure of the sandstones between Moose River and Five Islands may be seen in Fig. 18. Near Blue Sack (see Fig. 19) they are greatly slickensided, as shown in detail in Fig. 20.

On the top of the cliffs east of Moose River, tuff, overlain by agglomerate, forms a capping for the sandstone. The thickness of the volcanics varies, but is only 100 feet at a maximum. Near Blue Sack are two beds of agglomerate interbedded with sandstone, the lower being 100 feet or more, the upper 20 feet, with 10 feet of intervening sandstone. One of the contacts is cross-cutting, but there can be little doubt that the volcanics were formed contemporaneously with the sandstone, as blocks of basalt occur in the latter.

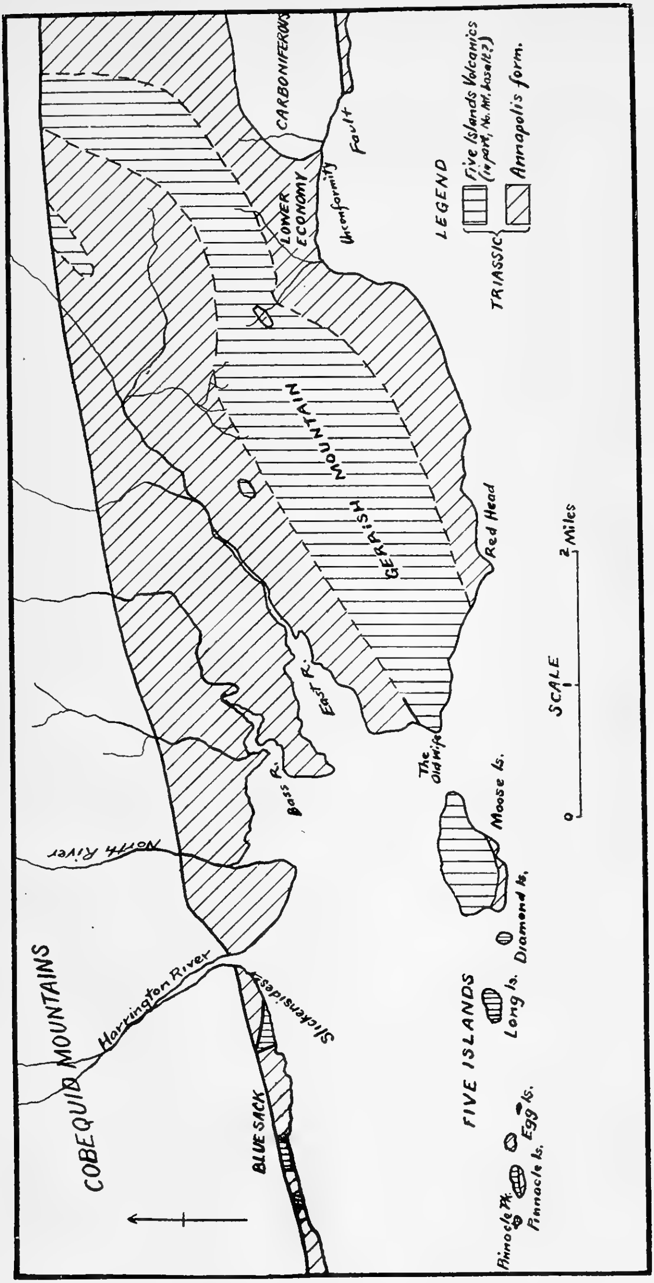

Fig. 19.—Map of the Five Islands region

This strip of Triassic is bounded on the north by a fault which probably continues east almost as far as Truro. The fault may be seen near the town of Two Islands, and between Moose Creek and Blue Sack the older rocks may be seen in one place at the top of the cliffs, in contact with the Triassic volcanics.

FIG. 20.—A detailed view of the slickensides north of Long Island of the Five Islands. The polished surfaces strike at right angles to the beach and the movement has been horizontal. Little or no vertical displacement is shown, but the slickensided surfaces strike toward the Five Islands between each of which there is a fault. It is impossible to determine which are the major fault-planes.

Five Islands.—The Five Islands are situated west of Gerrish Mountain. Their names, from east to west, are: Moose, Diamond, Long, Egg, and Pinnacle islands, and Pinnacle Peak (Fig. 21). Moose Island is nearly a mile in length and half a mile in width. The highest point on it is 350 feet above sea-level. Diamond Island is a small, round island, Long Island is one-quarter of a mile long and 180 feet in height at the center. Egg Island is smaller and round. Pinnacle Island is a quarter of a mile long and 130 feet in height in the center. Pinnacle Peak is merely an erosion pinnacle. East of Egg Island at ebb tide is Egg Rock. At low tide, with a high run of tides, the sea-bottom between the islands and the mainland is left dry except for numerous deep river channels through the soft red clay.

Moose Island consists of basalt flows on the north, underlain by red sandstones on the south. On the west end there is a fault between red amygdaloid and the sandstone, with a number of gypsum veins near the contact. On the east side the amygdaloid and basalt above dip north at angles of 45° above the sandstone. At the base of the amygdaloid is greenish-white ash, 2 feet thick, similar to that at Gerrish Mountain. Fletcher's mapping of Moose Island and of the other Islands is largely incorrect.

Diamond Island consists of a portion of the same basalt flows as on Moose Island and the other islands. The dip of the basalt is about 40° northeast.

Long Island consists of basalt on the north and sandstone on

FIG. 21.—The Five Islands. On the left is Gerrish Mountain. The Five Islands are, from left to right: Moose, Diamond, Long, Egg, and Pinnacle islands, and Pinnacle Peak. Complex block-faulting separates these islands.

the south, with the contact striking nearly east and west. The dip of the sandstone and basalt is variable owing to minor folds, but is in general in a northerly direction about 20°.

Egg Island and Egg Rock on the east consist wholly of red sandstone, dipping northwestward about 15°. Pinnacle Island consists of red sandstone on the south and basalt on the north, dipping northwest at angles of 20°–40°. Pinnacle Peak consists of basalt.

Each of the islands is separated from the others by a fault, and they are probably bounded on the north by a continuation of the Gerrish Mountain fault. On each island the flows or sandstones dip northward, but at different angles.

The basalt flows of the Five Islands were undoubtedly originally connected with the flow on Gerrish Mountain and with those on the Two Islands. They do not, however, appear to be directly connected with the agglomerate and tuff which are exposed along the shore. Probably the dike in Gerrish Mountain was the source of most of the igneous material, part of which flowed out, and part of which was blown out. The relative age of the pyroclastic material and the flows could not be determined.

[*To be continued*]

AVERAGE REGIONAL SLOPE, A CRITERION FOR THE SUBDIVISION OF OLD EROSION SURFACES[1]

LEOPOLD REINECKE
Geological Survey of Canada

CONTENTS

INTRODUCTION

During the four field seasons from 1908 to 1911 the writer was engaged in topographic and geologic work in the southern part of the Interior Plateaus of British Columbia. Certain questions which arose in the study of the physiography of that region are discussed in this paper.

Information regarding the physiography was acquired from a study of the Tulameen and Beaverdell map areas at the Southern end of the Plateaus, of the Kamloops and Shuswap[2] map sheets covering 9,000 square miles to the north of them, and from the

[1] Published by the permission of the Director of the Geological Survey of Canada.

[2] The geological work upon the Tulameen map area was done by C. Camsell, and upon the Kamloops and Shuswap areas by G. M. Dawson of the Geological Survey of Canada. Explorations in the country between these areas have been made by the same men.

descriptions of the region lying between. The locations of the areas in question and of the Interior Plateaus are shown on the index map, Fig. 1. No detailed work has been done to the north of the Kamloops area, but explorations have indicated that the

FIG. 1.—Index map

character of the surface resembles that farther south although the general elevation is said to be less.

The southern part of the Plateaus consists of an old erosion surface or upland, dissected by younger deep valleys (Figs. 2, 3, and 4). The region appears to have been overridden by a conti-

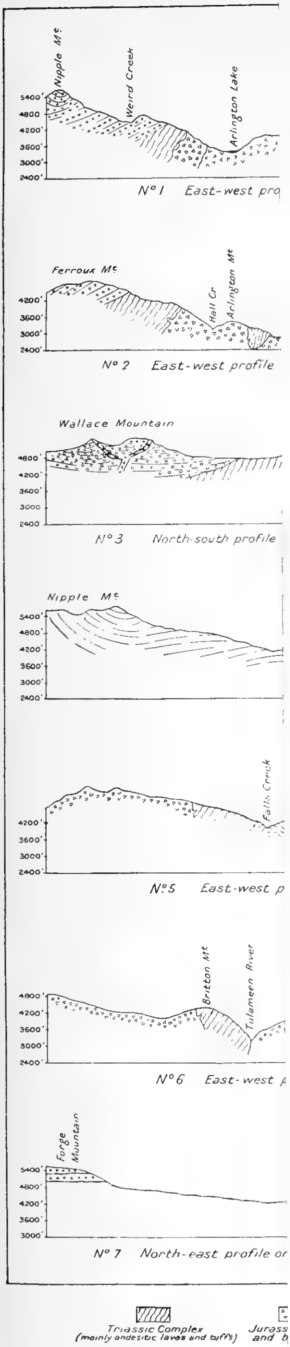

FIG. 2.—Character

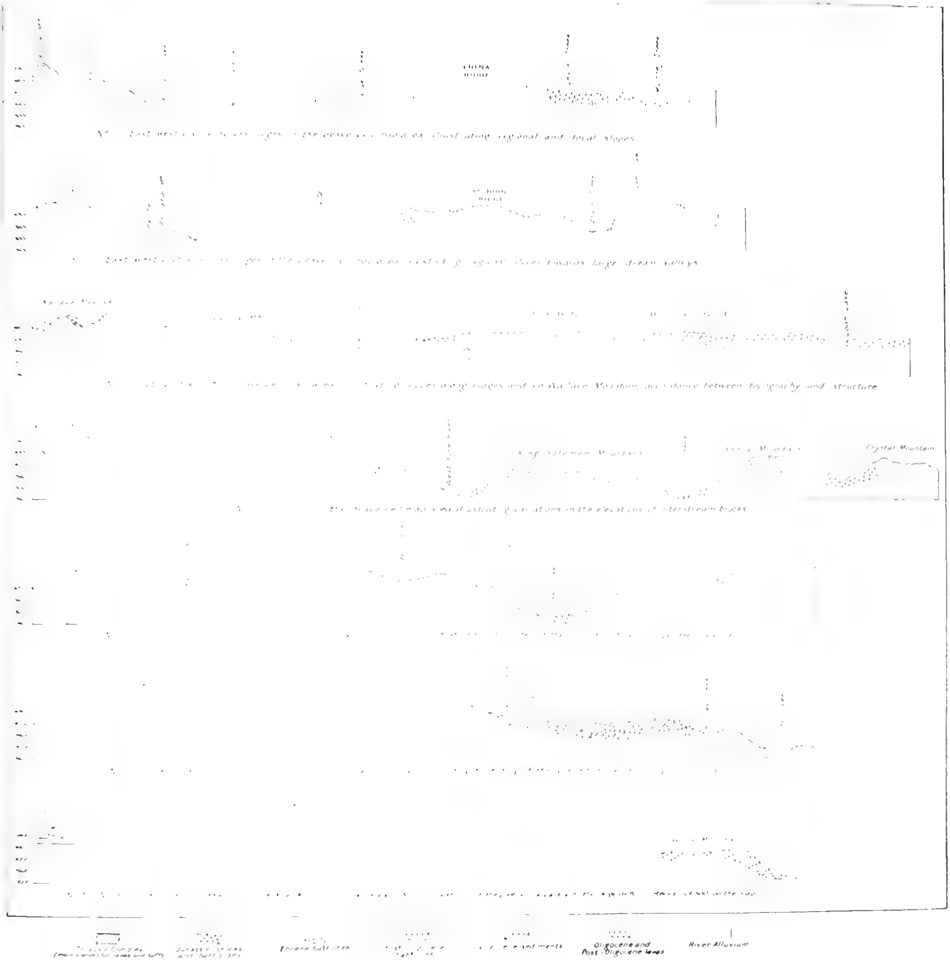

FIG. 2.—Character of the surface in the Interior Plateaus of British Columbia. Horizontal scale: 1 in.=about 2⅞ miles

nental ice sheet which removed the soil covering from the upland, carved a few shallow rock basins, and left a thin irregular blanket of drift upon its retreat, but which does not appear to have modified the upland slopes in any essential manner. This old upland surface has all the essential characters which are commonly used as criteria to distinguish peneplains, but the average slopes on it, measured from the higher areas or ridges toward main drainage lines, vary from 150 to over 300 feet to the mile, and these slopes

FIG. 3.—View of a portion of the Interior Plateaus near the Tulameen Valley

are found on the surface as a whole, not merely on isolated portions of it.

If the slopes on this land form had not been measured, the dominant discordance of topography and structure and the general evenness of sky line would have caused it to be classed as a peneplain. The degree of slope present, however, led to a search for indications that would point to the fact that in this instance the stage of old age had just begun. It was found that the drainage system upon the upland was apparently related to a system of shear zones in the underlying rocks, and that in some of the areas underlain by certain Tertiary sediments and lavas, topographic form was governed by geological structure. The accordance of topography and structure might in this case be described as a dimmed and accessory character, while the discordance was sharply defined and extensively developed, an essential character. It was found that on an old surface, with slopes of 3 to 6 per cent, the characters developed in maturity were just disappearing and those related to peneplanation were strongly developed but had not yet entirely supplanted the others.

According to the hypothesis of the geographic cycle this land form, if it had been left undisturbed, would have been gradually worn down; that is, its average slopes would have been gradually diminished, the characters of maturity have gradually disappeared, and the characters of peneplanation have prevailed everywhere. It seemed possible then, by using the criterion of regional slopes, to subdivide old land forms on a quantitative basis.

The primary object of this paper is to point out the importance of the measurement of average regional slopes upon "old erosion surfaces," and to show that such data assist materially in the more accurate study of the physiographic development of the region in which these surfaces occur, and of the diastrophic movements which have taken place there. The writer believes that it will be possible eventually to subdivide old land surfaces on the basis of their average slopes, and has attempted to do so here. The subdivision proposed is necessarily imperfect, partly because of the lack of accurate data regarding the slopes of old erosion surfaces, and largely because of the writer's imperfect knowledge of the literature describing such surfaces. As more data upon the slopes of old surfaces become available, however, the imperfections of a subdivision of this kind can be remedied.

METHOD OF MEASURING REGIONAL SLOPES

By regional slope is meant the general slope of the land toward main drainage lines. Slope is stated here as the percentage of vertical to horizontal distance rather than as an angle, because the measurement of the angles of slope on a land form of moderate relief is generally impracticable in the field, and for that reason the degree of slope stated as an angle, especially if the angle is small, does not

FIG. 4.—View of the Interior Plateaus looking northeast across the valley of the Tulameen River

carry a suggestion of the actual land form to the mind of the reader. For the measurement of such slopes either topographic maps or a number of traverses across the region to be examined are essential. An appreciation of the significance of the slopes can, however, be attained only by traveling over them.

The following is an outline of the methods followed in obtaining data from topographic maps of portions of the southern section of the Interior Plateaus of British Columbia. These methods were applied, in part, to the measuring of slopes upon topographic maps of certain sections of the United States, with satisfactory results.

The first step to be taken is the drawing of a number of profiles, some in the direction of the main drainage and others at right angles to it. The profiles should include as many of the pertinent topographic features of the region as possible. If they are plotted with a vertical scale somewhat larger than the horizontal, they will assist both in determining whether the land form under consideration is the result of one or more cycles of erosion, in discovering whether processes other than subaërial erosion have been responsible for existent forms, and in detecting tilting or warping of the crust subsequent to the formation of the surface. The usefulness of profiles is discussed more fully farther on. If forms due to more than one cycle are present, slopes should of course be measured on each of those forms separately. In the Interior Plateaus two cycles are represented, an older upland and younger valleys intrenched in it. There is a distinct break or topographic unconformity between the upland and the valley forms (Fig. 2, profiles 1 to 7). In this instance the measurements of slopes on the older land form, the upland, were made by taking a large number of horizontal measurements on the topographic map from a dominant ridge line to the bottom of a large upland valley. If a deep valley of the younger cycle occupied the site of the bottom of the old valley, the measurements were made to the point where the break in slope occurred between the old and the young forms (profiles 1 and 2). Horizontal measurements were made as long as possible, and never less than one mile. The vertical difference was read directly from the topographic map. Measurements were taken in both directions at right angles to the trend of the ridge, and also along its crest. Variations in the slopes along ridge crests in the Beaverdell map area of southern British Columbia are illustrated in Fig. 2, profiles 3 and 4. The average slope measured on four or five ridges in this area lay between 100 and 300 feet to the mile, and averaged over 200 feet except in places where certain Tertiary formations occurred over which the slopes ranged between 500 and 900 feet to the mile, and averaged 600. The Tertiary areas occupied less than one-eighth of the area of the whole upland; the average slope along ridges therefore averaged between 200 and 300 feet to the mile. Slopes across ridges were in this area of very nearly the same magnitude and did not average over 300 feet to the mile.

Slopes as high as 900 to 1,000 feet to the mile were found in a few places only, and could have been omitted from the general average without changing the result to any great extent. Such local irregularities of slope are more likely to occur in land forms with fairly high slopes than in those which are of a plainlike character. Of twelve measurements on the Caldwell, Kansas, map sheet for instance, six lay between 14 and 21 feet to the mile, four between 32 and 35 feet, one was 47 feet, and one 10 feet to the mile.

VALUE OF THE MEASUREMENT OF REGIONAL SLOPES

The study and determination of the regional slopes upon old erosion surfaces is both useful and necessary. It is useful: (*a*) in helping to determine the agencies which have carved and molded the topography to its present form, and (*b*) in separating forms due to different erosion cycles. It becomes necessary (*c*) when an old erosion surface is to be used as a datum for measuring diastrophic movements.

a) The study of regional slopes often will indicate the agencies which have carved or assisted in carving a land form. This is illustrated by Barrell's[1] work along the New England coast. He found that certain flat-topped ridges in the interior sloped gently toward the coast, and the plainlike surfaces, of which the ridge tops were residuals, occurred in terraces of successively higher

[1] Joseph Barrell, "Piedmont Terraces of the Northern Appalachians," *Bull. Geol. Soc. Am.*, XXIV, No. 4 (December, 1913), 688–90.

elevations, each being separated from the next by a shorter and steeper slope. Further study proved that a number of flat hill-tops in this region, which have for a long time been regarded as residuals of a tilted peneplain formed by subaërial erosion, were in reality parts of a series of wave-cut marine terraces.

b) The measurement of slopes and the study of profiles were found very useful in determining the number of cycles of erosion through which the uplands of the Interior Plateaus of British Columbia had passed. The older uplands and younger valley cycles were separated with comparative ease, but detailed study of the slopes was needed to show that no remnants of an older plain-like surface existed within the upland itself.

c) The measurement and recording of regional slopes will be of the greatest value, however, in cases where old surfaces and their residuals are used to determine the manner in which earth movements have taken place or the amount through which a section of the crust has moved. The manner in which movements of the crust have taken place sometimes can be brought out by profiles (see Fig. 2, profile 6), but it is necessary to determine the original internal relief and average slope of an elevated or warped old erosion surface before such a surface can be used for quantitative measurements of movements of the earth's crust.

In the uplands of the Interior Plateaus, for instance, the relative relief of points within 10 miles of each other quite commonly is from 1,500 to 2,000 feet. If such a surface be uplifted and dissected until only remnants of it remain, the difference of elevation between them could be 1,500 feet without the section of the crust within which they occur having been either warped or tilted. Calculations of earth movements based on the assumption that such a surface was plainlike before uplift would be liable to errors of 1,500 feet or more. If the slopes are not measured, however, old surfaces of marked relief are likely to be thought nearly flat or of much lower relief than actually is the case. For instance in describing an old erosion surface in the Colorado Front Range, Davis[1] says: "In the highland west of Palmer Lake, between Denver and Colorado Springs the sky line seems to be essentially

[1] W. M. Davis, "The Colorado Front Range," *Ann. Assoc. Am. Geog.*, I, 42.

level; much more so in the actual view than would be inferred from the crowded contours of the Platte Canyon map sheet."

Value of certain criteria of peneplanation.—The reasons for mistakes of the kind referred to are, first, that an uplifted old erosion surface of moderate relief is often seen in juxtaposition to younger topographic forms upon which the slopes are much steeper, so that by contrast the relief on the older surface appears much less than it really is.

A second and less obvious reason is that certain of the more important characteristics of plainlike erosion surfaces with average slopes of less than 10 feet to the mile are found also on old erosion surfaces with slopes as high as 300 feet to the mile. The criteria referred to are a general flatness of sky line and the planing of a rather flat topographic surface across rocks of different hardness and texture without any apparent change in the character of the topography.

Flat sky lines: In a rolling hill country ridge lines sloping from 100 to 300 feet to the mile may appear quite flat and the completeness of the illusion will depend partly on the position of the observer and partly on the distance of the ridge line or lines from him. Flat sky lines often are caused by the blending of more than one ridge line of entirely different elevation in the observer's line of sight, the irregularities of one being neutralized by the other (Figs. 3 and 4). The writer knows of at least one locality in the Beaverdell map area of British Columbia where an observer, climbing up one side of the West Fork River valley and looking across to the opposite side, would see first a flat sky line on a ridge with an elevation of 4,000 feet, and as he climbed higher another flat ridge line would come into view with an elevation approximately 700 feet higher and lying 3 miles farther away. The two ridges are shown in cross-section in Fig. 2, profile 2, the flat top of the higher, the St. John ridge, in profile 3. Between the two positions there is doubtlessly one where both ridge lines would blend and appear as one. The flat sky line in this instance evidently does not mean that the ridge tops represented in the sky line are remnants of one nearly flat plain, for the lower one is next to a large river, the higher 3 miles from it, and the slope between them over 200 feet to the mile.

Nor can the lower and flatter of the two ridges be considered a peneplain remnant. Both ridges are, in fact, part of one surface in the stage of early old age, a surface with average slopes of about $2\frac{1}{2}$ per cent. Their nearly flat surface is doubtlessly due to their lying between nearly parallel drainage lines.

Measurements made along apparently flat ridges, moreover, often show that they slope at a quite appreciable rate. The slopes upon St. John ridge, one of the ridges referred to in the preceding paragraph (Fig. 2, profile 3), vary from 100 to 300 feet to the mile. In Fig. 4, an apparently flat sky line is shown between the points *a* and *b* which are about $7\frac{1}{2}$ and 6 miles respectively, from the camera. From the photographic work done at this place it is known that a vertical shift of $\frac{1}{100}$ of an inch in the sky line of the picture represents an actual fall of 90 feet in the topography, and that between *a* and *b* there is a broad upland draw which is 250 feet deep, and whose sides slope at the rate of 100 feet to the mile. If the sky line in Fig. 4 were farther away, it would, without doubt, appear much flatter. In the clear western air, ridges 20 miles away often are plainly visible.

Discordance of structure and topography: Discordance of topography and structure must also not be considered a final proof that the land form being examined is at all plainlike. Relatively flat surfaces planing across the contacts of rocks of different hardness are quite common in the Interior Plateaus, but sloping surfaces which plane across the structure are much more common. The flat areas are local developments on the rolling-hill type of Interior Plateau topography. In one instance a flat surface was seen planing across a centroclinal basin of relatively soft rocks which were protected on the outside by hard layers. The flat surface is shown in Fig. 2, profile 6, just east of the point marked Hamilton Hill, and a part of the same surface in the foreground of Fig. 4. This is undoubtedly a case of local base-leveling and not a proof of universal peneplanation. In another locality a flat ridge top lying next to a large river at an elevation of 3,800 feet was found planing across the structure. The ridge, a part of King Solomon Mountain in the Beaverdell area, is shown in cross-section in Fig. 2, profile 4, but the change of structure is not shown in the profile. This ridge top represents the lowest part of the upland within an area of several hundred square miles and within 10 miles of it there are numerous ridges from 1,000 to 2,000 feet higher. The flat surface is a small but integral part, not of a plainlike, but a decidedly hilly, land form. Discordance between topography and structure is, moreover, as well developed on the sloping hillsides of that land form as on the few flat surfaces that are present within it.

Neither approximately even sky lines, nor flat or nearly flat areas planing across the structure, are therefore in themselves a proof that the land form within which they occur is of more moderate relief than the upland of Interior Plateaus with average slopes as high as 6 per cent. The measurement of the slopes on old erosion surfaces must therefore be made before one can venture to judge of its actual relief or use it in quantitative measurements of earth warping.

PROPOSED SUBDIVISION

The following subdivision is concerned only with the stage of old age in the normal cycle of erosion as outlined by Davis.[1]

An old erosion surface is for the purposes of this discussion defined as a geographic unit worn down by subaërial processes alone to a state of moderate relief. By geographic unit is meant a portion of the earth's surface over which topographic conditions and the underlying rock structure were essentially similar at the beginning of the erosion cycle, and over which conditions of erosion remained essentially the same while the cycle was in progress. It is proposed to treat all surfaces in this stage as varying from two types, those of plainlike forms of peneplains and forms corresponding in general features to the uplands of the Interior Plateaus of British Columbia which may be referred to as "beveled hills." Following Smith[2] and Davis[3] peneplains are defined as geographic units worn down by subaërial processes alone to a condition of very moderate relief. The theory of the formation of such plainlike land forms does not necessarily imply that all parts of them lay

[1] W. M. Davis, "The Geographic Cycle," *Geog. Jour.*, XIV (1899), 481.

[2] W. S. Tangier Smith, "Some Aspects of Erosion in Relation to the Theory of the Peneplain," *Univ. of California Bull. Dept. of Geol.*, II (1899), 155–77.

[3] W. M. Davis, "The Geographic Cycle," *Geog. Jour.*, XIV (1899), 486.

near the ocean at the time of their formation. If the geographic unit be large, parts of it must lie far from the ocean and may be at a considerable elevation above it.[1] The "Almost plains" are characterized as presenting absolute discordance between topography and structure, graded streams and hill slopes, that is, practically a lack of cliff and local flat surfaces, and by deep soil covering. These are the commonly accepted criteria for determining peneplanation. In addition, we suggest that the term be restricted to surfaces with average slopes of less than 2 per cent, 105 feet to the mile. For examples of peneplains one may cite the Laurentian peneplain[2] of Canada, and a peneplain in the Mississippi Valley illustrated by the Caldwell, Kansas, topographic map sheet.[3] The Laurentian peneplain has an area of about two million square miles, with average slopes of about one-tenth of 1 per cent. It differs from an ideal type in that it has been modified by the accident of glaciation in removing the residual soil, in substituting an irregular drift mantle, and in slightly altering the form of the original surface. Upon the Caldwell area, average slopes vary from 10 to 50 feet to the mile, that is from one-fifth of 1 per cent to 1 per cent.

"Beveled hills" are characterized as geographic units worn down to moderate relief by subaërial processes alone. Their "essential" characters are discordance of topography and structure, graded slopes, smooth sky lines and contours, and a deep soil covering. Their "accessory" characters are local accordance between topography and structure, and the local occurrence of cliff faces and flat areas, that is, of ungraded slopes. In this instance the terms "essential" and "accessory" are used in the same way as they are in petrography, essential characters being those which predominate within the land form, accessory those of which but few examples can be found and which may be entirely absent.

"Peneplains" and "beveled hills" are distinguished therefore by their degree of slope and also by the occasional finding in the

[1] W. M. Davis, "The Colorado Front Range," *Ann. Assoc. Am. Geog.*, I, 42.

[2] A. W. G. Wilson, "The Laurentian Peneplain," *Jour. Geol.*, XI (1903), 628–29.

[3] Henry Gannett, "Topographic Atlas of the United States. Physiographic Types," *U.S.G.S.*, Folio 1, Caldwell, Kansas, sheet, 1898.

"beveled hills" type of characters which are characteristic of the stage of maturity.

It is suggested that the upland portion of the Interior Plateaus of British Columbia be taken as a type of the "beveled hills" form, and that the term therefore be restricted to old erosion surfaces upon which the average regional slopes are from 3 to 6 per cent. The upland of the Plateaus differs from an ideal type in that glaciation has removed the soil covering and substituted an irregular mantle of drift.

The term "beveling" was introduced into physiographic literature by Tarr.[1] He applied the term to the process of the cutting down of certain of the peaks and ridges on a land form, by differential erosion, to approximately uniform elevations. According to Murray's *New Dictionary* one of the meanings of "to bevel" is "to reduce (a square edge) to a more obtuse angle." As used in this paper the adjective "beveled" is meant to suggest that the land form so designated has been reduced to one on which nearly uniform sky lines are a common characteristic, and one upon which ridge tops have broadened or become rounded in cross-section; that is, the angles which ridge sides make at their crests have been increased to obtuse angles. "Hills" are meant to suggest that the land form is composed of numerous eminences of moderate relief and of smooth and rounded contours. Except in so far as it suggests reduction from a higher and more rugged form, the term "beveled hills" is intended to be descriptive, and is not meant to suggest the agencies by which reduction was effected.

GENETIC SIGNIFICANCE OF REGIONAL SLOPES

The desirability of a subdivision of this kind is that it will stimulate the gathering of data on the slopes of old erosion surfaces, and that it places definite limits on the term "peneplain." The value of such data and of such a restriction have been referred to before. An added argument in its favor is that the subdivision is based upon a factor which is of genetic significance in the development of land forms. For the slopes of a topographic form are not only one of the results of its development, but the amount of slope

[1] R. S. Tarr, "The Peneplain," *Am. Geol.*, XXI (January–June, 1898), 351–70.

present is also a factor in the rate of its further development. Moreover, the rate of development decreases so rapidly with decrease of slope that "beveled hills" are probably chronologically closer to forms in early maturity than to peneplains.

It is proposed in the following section to give proofs for the hypothesis that the rate at which a land surface progresses through the geographic cycle is dependent on its average regional slope, and that its progress becomes slower as the slopes become less. This hypothesis has of course been accepted by physiographers[1] for a long time, and is discussed only because of the emphasis placed in this paper on "average regional slope" and because the writer has found no presentation of evidence to prove this hypothesis.

The products of erosion in the normal geographic cycle are practically all removed from the land by streams. The rock waste is moved downstream partly as débris and partly in solution, and, if one could compare the amount of load carried by the streams on any land form during two stages of its progress, when average slopes were known, a measure would be furnished of comparative changes in the rate of erosion as the geographic cycle progresses toward old age.

The load consists of débris dragged along the stream bed, débris carried in suspension, and rock matter carried in solution, each of which will be considered in the order named.

A series of experiments have been made by Gilbert[2] on the relations between the load of débris that a stream can drag along its bed, and its slope.

The experiments proved that the quantity of load dragged by a stream varies in a complex manner with a set of controlling factors—such as slope of stream bed, discharge of water per second, fineness of débris, and form of stream channel. The changes, in amounts carried, vary at a different rate for each of the factors concerned. Under the conditions of the laboratory, the load dragged along the stream bed varied with the slope, but at a greater rate.

[1] W. M. Davis, "The Peneplain," *Am. Geol.*, XXIII (January–June, 1899), R. S. Tarr, "The Peneplain," *ibid.*, XXI (January–June, 1898), 354, 365.

[2] G. K. Gilbert, "The Transportation of Débris by Running Water," *U.S.G.S., Professional Paper No. 86*, pp. 10–54, 120, 121.

If, for instance, the slope, expressed in percentage of fall to horizontal distance, was doubled, the load dragged was, in the experiments, increased three to more than tenfold. Conversely as the slope decreased, the load decreased, but at a greater rate.

The load carried in suspension is partly a function of the stream's velocity, and depends partly upon the fineness and amount of débris supplied. In experiments made on streams without load, the velocity was found to vary approximately as the 0.3 power of the slope, and the 0.25 power of the discharge.[1]

The size of pebbles which can be carried in suspension varies as the fifth power of the velocity; that is, if velocity were unaffected by the addition of débris, it would vary approximately as the $\frac{5}{3}$ power of the slope. Velocity is diminished by suspended matter, but not enough to make the factor of $\frac{5}{3}$ less than unity. It is probable that in the majority of cases the grading of débris supplied to a stream is such that, if the slope be increased, the maximum load of suspended material carried by a stream will increase at a rate comparable to the rate of increase of the size of débris carried; that is, it will increase at a slightly greater rate than the increase in slope. Conversely if the slope be decreased, the maximum load carried in suspension will be decreased but at a greater rate than the slopes.

If discharge and fineness of débris supplied remain the same, therefore, both the maximum load dragged along a stream bed and that carried in suspension decrease at a greater rate than the slope, and the difference in the rate of decrease of the two functions becomes greater as the slopes decrease. This law of variation is applicable to natural streams as well as to those in the laboratory.[2]

But changes in discharge and fineness of débris as old age progresses, both tend to reduce further the load carried. For the rainfall on a land form, the size of a geographic unit is likely to decrease as the land becomes lower, and the proportion of runoff to rainfall will also decrease so that the discharge of the streams would decrease. The débris supplied to the streams, moreover, becomes

[1] *Ibid.*, 225. Discharge is defined as the number of cubic feet of water passing a given point per second.

[2] Gilbert, *op. cit.*, p. 233.

finer with old age and its increasing depth of soil. But suspended matter added to a stream retards its velocity, and the rate of retardation becomes greater as the débris becomes finer.[1] Hence as the slopes became lower, both the factors of decreased discharge and increased fineness of débris would help to a further and more rapid rate of decrease of maximum load carried.

Obviously also the amount of creep and wash of débris down hillsides into the stream beds is smaller on gentle than on high slopes. The rate at which a land form is worn down by mechanical erosion must therefore diminish very rapidly as the slopes decrease. On the other hand, lower slopes may aid chemical erosion, in that more rain water is absorbed and the solution of the rock materials near the surface is increased. Chemical erosion must, however, be a very small factor in the wearing down of a land surface, for the matter dissolved in river waters is derived from surface rocks in the process of weathering, and the greater bulk of the rocks at the surface lose on an average less than one-third of their original weight by the process of solution when weathering is complete. Moreover, part or all of this loss is compensated for, both in weight and in bulk, by gains in the form of oxygen, water, and carbon dioxide obtained from the atmosphere, and recombined as insoluble mineral products in the residual soil.[2]

If the average slopes of a land surface, therefore, be reduced in the progress of the geographic cycle from, say, 4 per cent to 2, the rate of reduction of the land surface by erosion will be less than one-half what it was before, and as the slopes decrease, the process becomes slower and slower.

The final stages of old age in which the surface is reduced to slopes as low as one-tenth of 1 per cent must therefore represent a very much longer period of time than the stage of maturity or of early old age. Chronologically, therefore, "beveled hills" are probably closer to land forms in early maturity than to "peneplains," and for that reason alone the subdivision proposed in this paper should be justified.

[1] Gilbert, *op. cit.*, p. 228.

[2] F. W. Clarke, "The Data of Geochemistry," *Bull. 491, U.S.G.S.*, pp. 462 and 465.

OBJECTIONS TO A SUBDIVISION BY AVERAGE REGIONAL SLOPES

The objections which may be urged to a subdivision of this kind are: (*a*) that it is an arbitrary one; (*b*) that the slopes on a land form vary widely, and two observers may come to different conclusions regarding it; (*c*) that it requires a greater amount of detailed field and office work than is necessary when the average slopes are not taken account of.

a) The subdivision is arbitrary, for as far as we know there is no distinct change in the cycle at either of the two limiting points of 2 and 3 per cent, which is placed on the two type forms proposed here. Moreover, it is probable that there are old erosion surfaces to represent all stages of average regional slope from 6 per cent to less than one-tenth of 1 per cent, and there may be as many examples lying between the two types proposed as within the limits of the peneplain type.

A parallel might be drawn between the classification of igneous rocks and the subdivision proposed here. In 1886 or thereabouts, when geologists of the United States Geological Survey found large areas in the Sierra Nevada Mountains underlain by intrusive masses of approximately similar composition lying between the quartz-diorite and granite families, they suggested the name granodiorite for them. Thirteen years later Lindgren[1] proposed definite limits for the "granodiorite" family in regard to both its chemical and mineralogical composition. The bulk of the rock masses referred to in the Sierras, and later found to occupy great areas in Canada, fall within the limits proposed by him. His quantitative restriction of the term granodiorite is therefore justified, for it represents a natural group of rocks. The term gains stability, moreover, because of the occurrence of this group within a definite and accessible region.

This definition of granodiorite is of great value to petrographers because it furnishes a clear-cut standard of comparison and datum point within the scheme of classification. The occurrence of rocks intermediate in composition between granodiorite and granite on the one hand, or granodiorite and quartz-diorite on the other, does

[1] Waldemar Lindgren, "Granodiorite and Other Intermediate Rocks," *Am. Jour. Sci.*, IX (1900), 269–82.

not detract from the usefulness of the quantitative definition of the family, but rather adds to the necessity of such a definition. In the same way the term "beveled hills" proposed here represents a land form which actually occurs over the known portion of a large geographic unit, the Interior Plateaus of British Columbia, and the quantitative limits proposed for the type are those measured upon the land form in question. The value of the establishment of a subdivision centering about a quantitatively defined physiographic type should also not be seriously impaired by the occurrence of numerous intermediate forms.

b) The slopes on a land form vary widely, and an accurate average is not easily obtained. Variation in slope will cause trouble only in old surfaces of fairly high relief, that is, in the "beveled hills" type. In the work in the Interior Plateaus, it was found that the greater part of the surface within areas of about 200 square miles lay between 3 and 6 per cent, and where slopes of a mile or more in length varied greatly from the general average they occurred over small areas. By estimating the relation of the size of these areas to the whole, irregularities of slope were calculated into the whole, and found to change the general average very slightly. If care is taken first carefully to separate forms due to different cycles, and then to note the frequency of the occurrence of irregularities varying from the average, the final results will be found to be fairly consistent.

In land of lower relief, that is, in the peneplain division, the results will be found to agree much more closely for the variation in slope is very much less.

c) The amount of field work is greater than is necessary when slopes are not measured.

This is true even when the measurements are made on topographic maps, for in order to appreciate the meaning of the forms shown on a topographic map it is necessary that one examine them closely at first hand. The extra time and energy which physiographers will of necessity have to spend in traversing old land surfaces before they can obtain data upon the nature and extent of their slopes is one of the best arguments for the adoption of this classification instead of an objection to it. The geologist knows that rocks must be cracked if results are to be obtained, and the physiographer who depends largely upon distant views will miss a great deal of the detail which helps to prove or disprove field hypotheses.

SUMMARY

In the study of the physiographic development of the Interior Plateaus of British Columbia, certain characteristics commonly accepted as criteria for peneplanation were found well developed upon an erosion surface with regional slopes of 3 to 6 per cent.

Stress is laid on the value of the study and measurement of the regional slopes of old erosion surfaces, and a quantitative subdivision of old erosion surfaces on the basis of their average regional slopes is suggested. Regional slope is defined as the general slope of the land toward main drainage lines, and an outline is given of the methods of measuring regional slopes, as followed in the work on the Interior Plateaus of British Columbia.

The determination of the regional slopes of a land form is of value in furnishing clews to the agencies which have affected its development, and in separating the products of the different cycles of erosion through which it may have passed. The measurement of regional slopes is essential if a land surface is used as a datum for the measurement of movements of the earth's crust. For if such measurements are not made, an uplifted old erosion surface is very likely to be considered of much lower relief than is actually the case. Such an assumption leads to serious errors in estimates of the manner and extent of movements of the crust. It is caused partly by optical illusions, and partly from the fact that the characteristic flat horizon lines and the discordance of topography and structure which prevail over old erosion surfaces of plainlike form are also found well developed upon surfaces of much greater relief.

It is proposed that old erosion surfaces be divided into two central types "peneplains" and "beveled hills." Peneplains are to be characterized by average regional slopes up to 2 per cent by discordance between topography and structure, by the absence of local irregularities of slope, such as cliffs and flat areas, and by deep soil covering.

"Beveled hills" are old erosion surfaces with dominant discordance between topography and structure, with a general absence of irregularities of slope, and with deep soil covering. In addition, one may expect to find on them the accessory characters of partial accordance between topography and structure and occasional cliffs and flat areas. It is proposed that the term be confined to forms with average regional slopes of from 3 to 6 per cent and that the upland portion of the Interior Plateaus of British Columbia be considered the type of this land form.

The subdivision is desirable because it will stimulate the measuring of regional slopes and thus assist in working out the physiographic development of the surface and diastrophic movements of the crust after its formation. It is not contrary to the accepted hypotheses of the genesis of a land form through the normal cycle of erosion, for the degree of slope is a factor in the manner, as well as the rate of development, of an erosion surface.

The objections to the subdivision are that it is arbitrary, that a true average of the regional slopes on a land form are hard to get, and that it involves more field and office work than are otherwise necessary. The objections are met in the following manner.

The type form "beveled hills" is represented by an old erosion surface, which is found throughout the southern portion of a large geographic unit, the Interior Plateaus of British Columbia. The subdivision is therefore not entirely arbitrary. The difficulty of obtaining a true average of the regional slopes on a land surface can be met by taking account of the relative area occupied by slopes departing from the general average. It is thought, finally, that the extra field work involved in traverses over the region will be of advantage in calling attention to details of physiographic interest which can be obtained in no other way.

It is well to repeat here that the object of this paper is first of all to point out the importance of the study and determination of regional slopes on old erosion surfaces, and that the particular form of subdivision proposed is not considered final.

CAIMANOIDEA VISHERI, A NEW CROCODILIAN FROM THE OLIGOCENE OF SOUTH DAKOTA

MAURICE G. MEHL
University of Wisconsin

In the summer of 1911, Mr. S. S. Visher, then connected with the Geological Survey of South Dakota, collected some interesting crocodilian material from the Oligocene of Washington County, South Dakota. Some time ago, the attention of the writer was called to these remains by Dr. Visher, and recently through the courtesy of Mr. W. H. Over, director of the museum at the University of South Dakota, the collection was loaned to the writer for study.

The material herein described consists of a goodly portion of a skull, a nearly complete mandible, two femora and other limb bones, a nearly complete series of vertebrae, many dorsal scutes, and numerous fragments. According to Dr. Visher, the collection was made from the Titanothere zone of the Lower White River beds, perhaps 20 to 30 feet above their base.

THE SKULL

Of the skull, nearly the entire right half is preserved as well as portions from the left side including the quadrate region, the posterior half of the cranium roof from the median line to the middle of the orbit and supratemporal vacuity, and fragments of the maxilla along the alveolar margin. Of the base of the skull but little remains save the separate occipital condyle and portions of the exoccipitals.

In general shape and appearance it is quite similar to that of the alligators. A lateral expansion of the maxilla in the region of the third to fifth maxillary teeth produces a marked break in the otherwise regular outline of the muzzle, more prominent, perhaps, than in most of the Crocodilia. The width of the skull in the region of this maxilla expansion is 72 mm. Immediately back

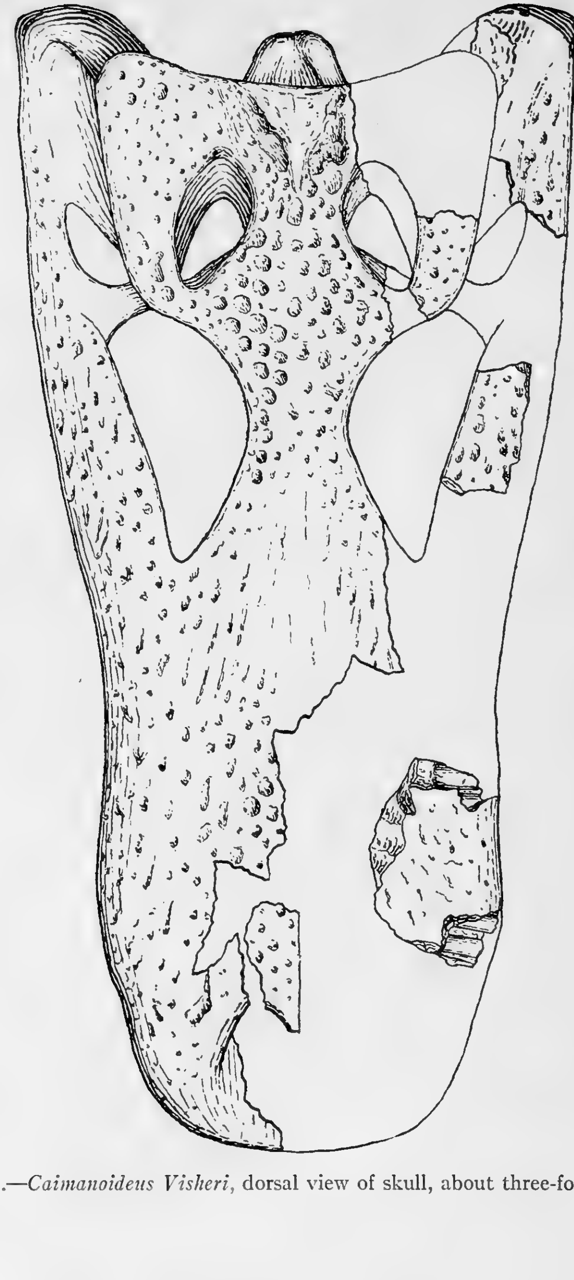

FIG. 1.—*Caimanoideus Visheri*, dorsal view of skull, about three-fourths natural size.

of the expansion, the width is but 66 mm. The greatest width, across the quadrates, is approximately 100 mm. The length of the skull, along the median line from the posterior border of the supraoccipital to the tip, is some 180 mm. From the posterior edge of the quadrates to the tip of the muzzle the measurement is 203 mm. Unlike the most of the Crocodilia, the inter-orbital region is flat, or essentially so, rather than presenting the marked concavity.

All the bones of the facial region of the skull are sculptured by more or less pronounced rounded pits or longitudinal grooves except the posterior ends of the nasals. In the maxillary region, the markings are more or less ill defined and, for the most part, take the form of long and narrow longitudinal grooves. The pits of the posterior frontal region are round, well defined, and deep. They are crowded close together and separated by narrow ridges only. The pits average 2.5 mm. in diameter, perhaps, in this region. On the jugals and squamosals, the

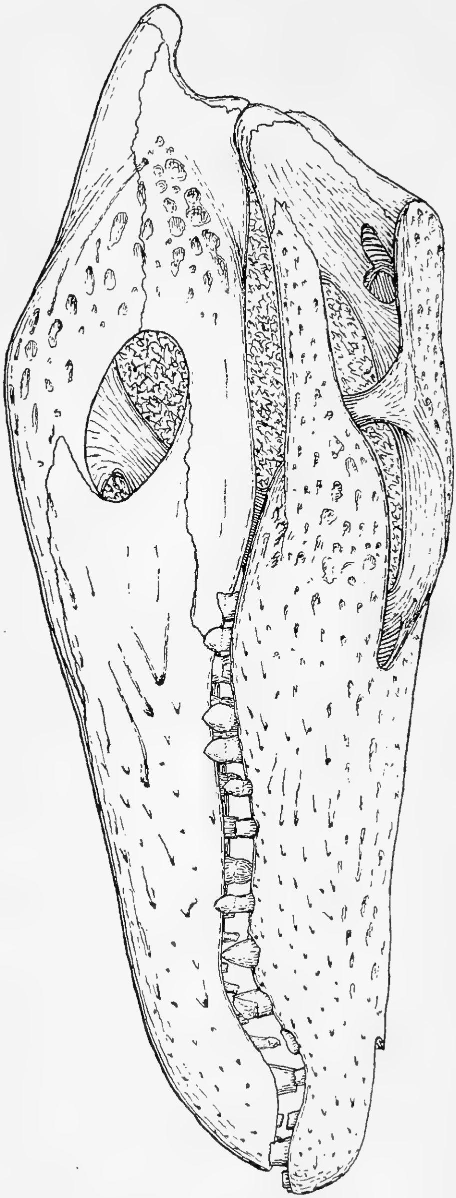

FIG. 2.—*Caimanoideus Visheri*, right lateral view of skull and mandible, three-fourths natural size

pits are shallow and varying in size, for the most part minute, but well defined.

The relations of the various bones of the skull are quite alligatoroid, as are their general proportions with few exceptions. The prefrontal is relatively longer than in the genus *Alligator* and extends at least half the length of the lachrymal in advance of the latter element. The nasals are relatively broad, the two making nearly half the total width of that part of the skull.

Unfortunately, part of the anterior border of the snout is missing, but the portions present are sufficient to show some of the important characteristics. Unlike the condition in all the true alligators, the nasals, while projecting slightly into the external narial opening, do not form a more or less complete bony septum. Furthermore, the premaxillae do not form an arch over the anterior border of the opening as is the case in all modern and extinct alligators with one or two exceptions, perhaps. In this respect, the skull simulates that of *Brachychampsa Montana*, an alligatoroid form described by Gilmore from the Upper Cretaceous of Montana.[1] To quote: "In the absence of a roof-like covering formed by the premaxillaries over the anterior part of the external nares, *Brachychampsa* differs from all known alligators, both recent and extinct."

The anterior border of the nares in the described form differs from that of *Brachychampsa*, however, in that the premaxilla in the former are still further reduced till the nares are directed slightly forward and lack entirely the definite ridgelike anterior border. This is the condition pointed out by Loomis in a specimen described by him from the Oligocene of South Dakota and referred to the genus *Crocodilus*.[2] Quoting Loomis on this point: "The undivided nasal opening is very far forward, and differs from that of the other crocodiles in the lack of a distinct anterior border, this portion of the nasal cavity having a smooth, rimless boundary on the premaxilla. The nostril opening would seem, therefore, to have been directed to the front, rather than upward on the snout.

[1] "A New Fossil Alligator from the Hell Creek Beds of Montana," *U.S. Nat. Mus.*, XLI (1914), 299.

[2] "A New River Reptile from the Titanothere Beds," *Am. Jour. Sci.*, CLXVIII (1914), 429.

(The lack of a rim gives the snout a distinctly mammalian appearance.)"

The teeth are well preserved for the most part and, with few exceptions, have the crowns preserved entire. On the right premaxilla, there are preserved four alveolae. On the portion of the premaxilla broken away, there is apparently space for two additional alveolae, but there is possibly only one. In the latter case, the total number is five, the number in the specimen described by Loomis. Concerning this series but little can be said, as only the circular roots of four remain. Of these the next to the last is the largest, 5.5 mm. in diameter. In each maxilla there are apparently thirteen teeth, a smaller number than is usually found in the alligators. Of these the fourth is much the largest, fully 8 mm. in diameter at the base and approximately circular in section. The posterior maxillary teeth are all more or less laterally compressed. The roots are oval in cross-section and in measurements range from 2.5 mm.×4 mm. to 4 mm.×7 mm., the more posterior teeth being the larger in general. The crowns of the first four maxillary teeth are somewhat flattened on the inner side and present a slight trenchant anterior and posterior edge. They are sharply conical and very slightly incurved, perhaps. The crowns of the posterior teeth show a rapid transition from this type to those with swollen crowns, rather sharply conical in the first of the series and more blunt or even of a rounded form posteriorly. A brief description of the well-preserved eleventh maxillary tooth will serve well to characterize this type. The crown is subglobular and is flattened somewhat on the upper, inner surface. It is sharply set off from the root by a marked necklike constriction. The apex is marked by an indistinct, antero-posteriorly placed carina that does not extend down on the sides.

Of the posterior part of the skull but little remains except the basi-occipital. The condyle is more or less spout-shaped and is divided into two distinct surfaces by a well-marked median groove.

The palate is almost entirely lacking except for a small portion along the maxilla-premaxilla union. At this point there is a deep, sharply outlined pit for the reception of the fourth mandibular tooth. The pit does not perforate the facial surface of the bone, however, as is occasionally the case in the alligators.

The lower jaws are represented by an almost perfect right ramus and a goodly portion of the left, including the symphyseal and articular regions. The sculpturing of the mandible is much the same as in any of the alligators; the dentary is marked by small, deep pits and more or less prominent longitudinal grooves. In the region back of and below the external mandibular foramen the surface is dotted with deep rounded pits, irregular in size but distinct. In the relation of the various mandibular elements there is nothing of particular interest except perhaps in the unusual forward extent of the splenial. This element extends far forward and takes an ample part in the symphysis. Each ramus bears nineteen teeth, very similar, in general, to the maxillary teeth. The fourth tooth is the largest in the series, round in section, and measures fully 6 mm. in diameter at the base. The crown is largely missing, but was apparently sharply conical, and the indications are that there was a faint anterior and posterior carina extending down the sides. This was probably the condition of the anterior four teeth in each ramus. The root of the first tooth indicates that it was somewhat larger (about 4 mm. in diameter) than the two subequal teeth that follow.

Immediately following the fourth tooth is a series of seven, all comparatively short and slender and averaging about 2 mm. in diameter at the base and 4.5 mm. in height. These small teeth have slightly swollen crowns and a faint suggestion of anterior and posterior carina. The posterior eight teeth are subequal in size and quite like the eleventh maxillary tooth described above.

The nature of the bite is alligatoroid in that the teeth of the mandible all close within the teeth of the upper jaw and the fourth mandibular tooth fits into a deep socket in the palate surface.

THE VERTEBRAL COLUMN

Eight of the cervical vertebrae are present, all but the atlas. With the exception of the axis, they are all very pronounced procoelous. Although the union between the centrum and the arch is clearly distinguishable, the two parts are as a rule closely united.

There is nothing distinctive in this series that serves to set them off from the other Crocodilia save perhaps in the atlas. The odontoid process is very prominent, and in a superficial way resembles the spout-shaped process of some of the mammals. The total length of the series, allowing for the missing atlas, is approximately 18.5 cm. Of the dorsal series all are preserved. As the cervicals, they are of the pronounced procoelous type. The total length of the series is about 23.7 cm. The five lumbar vertebrae are well preserved. The posterior articular faces of the centra are all highly convex and round in outline except the fifth. In this the posterior face of the centrum is fully twice as wide as high. The lumbars together measure 11.7 cm. The two sacrals measure 4.7 cm. A noteworthy feature is the shifting of the sacral ribs. The posterior rib forms a small part of the posterior concavity into which the first caudal fits. The anterior rib is shifted forward to such an extent that it might be said to articulate intercentrally, for although it is solidly fused to the first sacral vertebra, nearly half of its diameter extends beyond the anterior face of that vertebra and articulates broadly with the last lumbar. Of the caudal vertebra, there are 23 preserved. There are probably about 11 missing, almost entirely from the posterior end of the series. The vertebrae present measure about 23.7 cm. To this should be added perhaps 16.5 cm. for those missing, making a total of 40.2 cm. for the caudal series.

Of the numerous appendicular bones indiscriminately preserved the femora alone, perhaps, deserve special mention. Both of these bones are nearly complete, but the right is the more nearly perfect (Fig. 3). The head is broad and much flattened. The articular surface extends entirely around the end and on the side of the pronounced rounded cone that rises from the concave lower surface close to the proximal end of the bone. The trochanteric ridge on the flexor surface is very pronounced, more so than usual. At this point, about 45 mm. below the head, the shaft is bent abruptly back and from there sweeps backward in a broad, anteriorly concave curve to the distal end.

The dorsal armor consists of a large number of pitted plates, sub-rectangular in outline for the most part. Of these there are several distinct types and a great variation in size. All bear a more or less prominent antero-posteriorly directed carina on the dorsal surface and are concave below from side to side to some extent at least and often sharply so. The dorsal surface of all is deeply sculptured by small, rounded, closely crowded pits. While the anterior and posterior edges are smooth, the lateral edges of

FIG. 3.—*Caimanoideus Visheri*, right femur; *a*, from below; *b*, from above; *c*, from behind; three-fourths natural size.

most of them indicate a more or less firm union with an adjacent plate. In some plates, this union is indicated on one margin only, and a few apparently were entirely free. The plates were probably arranged in more or less rigid transverse rows of five units at least, and, in much probability, seven units for certain regions of the back. Fig. 4 indicates the apparent arrangement of the plates.

As pointed out above, the affinities of this form with the genus *Alligator* are marked. This is shown chiefly in that the fourth mandibular tooth fits into a deep pit in the palate instead of closing in a notch, as in crocodiles. Furthermore, all the mandibular teeth close within those of the upper jaw. In the lack of a division of the anterior nares and the lateral union of the dorsal scutes, the form is quite similar to the genus *Crocodilus*. It apparently stands much nearer to *Caiman*, however, than to either of the genera mentioned above inasmuch as this group combines the alligatoroid bite, the undivided anterior nares, and the lateral union of the dorsal scutes. One of the striking differences from *Caiman* is to be seen in the entire lack of the anterior border of the external narial opening in the form here described. A new genus, *Caimanoeda*, is proposed to include this form *C. Visheri*, which may be considered the type, and *C.* (*Crocodilus*) *prenasalis*, Loomis,[1] a form that a careful examination of the type skull has shown to be very similar to *C. Visheri*.

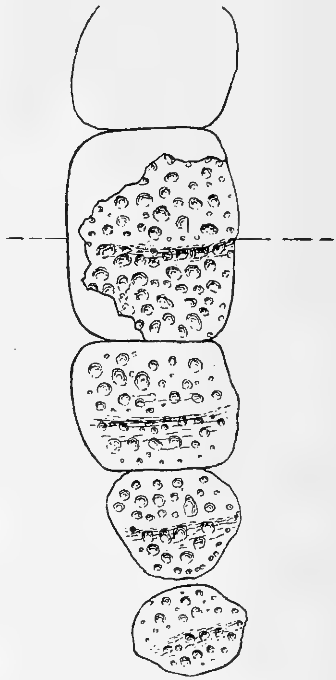

FIG. 4.—*Caimanoideus Visheri*, apparent arrangement of dorsal armor in transverse rows, about three-fourths natural size.

If one may depend on the figures of *C. prenasalis* there is a noticeable difference between the dorsal scutes of this form and those of *C. Visheri*. In the latter, all the scutes are more or less strongly keeled, and are much more finely and regularly pitted than in the former. Greater differences are to be noted in the vertebrae. Of the vertebral column of *C. prenasalis* Loomis says: "The vertebrae are all deeply procoelous. Those of the lumbar region have heads (posterior) which are short, wider than high, and rectangular in outline. Those of the dorsal region, however, are smaller and have prominent conical, rounded heads."

As pointed out above, in the lumbars of *C. Visheri*, the posterior face of the centra are regularly convex and round in outline and the

[1] *Op. cit.*

centra differ but little in size from those of the dorsals. The vertebra figured and described as a dorsal of *C. prenasalis* is apparently very similar to the anterior caudals of *C. Visheri* and may well belong to the caudal series. This being the case, the vertebrae of the two forms are not very different.

The remains of *C. Visheri* represent a creature approximately five and a half feet from tip to tip. The skeleton is probably not that of a young individual, but it is possible that it had not reached its greatest length. It is probably a good average for the species, and is apparently somewhat smaller than *C. prenasalis*.

While any record that indicates the former distribution, the relative abundance, and the diversity of the extinct Crocodilia is noteworthy, there is, perhaps, a special interest in the form here described in the light that it throws on the ancestry of the caimans. To the writer's knowledge, there is no record of extinct caimans and the history of the alligators is almost as obscure. While the genus *Caimanoidea* is perhaps too highly specialized in the external narial opening to stand in the direct line of the caimans, in other respects, especially the moderate size of the supratemporal fenestrae, it is very similar to what one would expect in their primitive ancestors. The genus stands close enough to the modern forms to indicate a very ancient history for this group.

The writer wishes to take this opportunity to thank Professor Over, through the courtesy of whom he was permitted to study the material here described, and President C. C. O'Harra of the South Dakota School of Mines for the loan of the type skull of *Caimanoidea* (*Crocodilus*) *prenasalis*. The writer is also greatly indebted to Professor Ruthven, director of the zoölogical museum, University of Michigan, for the loan of *caiman* material and for valuable information concerning that group.

The type of *Caimanoidea Visheri* is number 1,044 in the University of South Dakota geological collections.

ON THE STRUCTURE AND CLASSIFICATION OF THE STROMATOPOROIDEA[1]

M. HEINRICH

In the course of my studies on the numerous stromatoporids from the Rhenish Devonian which are in the Geological Institute of the University of Bonn, among them the types of Goldfuss and Bargatzky, I have come to hold a view concerning the structure and especially concerning the classification of the Stromatoporoidea which is not in harmony with the one now generally accepted.

Since the publication of my complete work, which will appear under the title, *Studien in den Riffkalken des rheinischen Mitteldevon. I. Teil: Biologie, Morphologie und Genesis der Riffe des rheinischen oberen Mitteldevon. II. Teil: Revision der Stromatoporen* is still somewhat distant, I will present here the results of the second part, leaving the detailed evidence to follow in the complete work.

It is apparent from all textbooks on paleontology and also from the often exhaustive works of recent students of this debatable subject (Parks and others), that since 1886–92 the view of Nicholson has been generally followed and the Stromatoporoidea therefore divided into two groups. The "milleporoid" group includes the forms which possess the so-called "zoöidal tubes"; and the other or "hydractinoid" group, those without such structures. To the first group are referred the families Stromatoporidae Nicholson and Idiostromidae Nicholson; to the second, the families Actinostromidae Nicholson and Labechidae Nicholson.

It now appears: (1) that the families Labechidae Nicholson and Idiostromidae Nicholson should be taken out of the order Stromatoporoidea, since their organization has scarcely anything in common with that of the remaining Stromatoporoidea. By means of this division, a simple, clear definition is obtained for the

[1] Translated from the German (*N. Jahrb. für Min.*, etc., 1914, No. 23, pp. 732–36) by Clara Mae LeVene, Peabody Museum, Yale University.

"true" Stromatoporoidea. (2) That the division into a "milleporoid" and a "hydractinoid" group must give way to another, since the distinction on which it rests is not present.

Next should be discussed the families which in my opinion have been incorrectly referred to the Stromatoporoidea, i.e., Idiostromidae Nicholson, with the genera *Amphipora* Schulze, *Stachyodes* Bargatzky, and *Idiostroma* Winchell, and Labechidae Nicholson, with the genera *Labechia* Edwards and Haime, *Rosenella* Nicholson, and *Beatricea* Billings.

In *Amphipora*, the old conception is to be replaced by that of Felix (1905), which I found confirmed in hand specimens from Letmathe and elsewhere in which the fossil had not yet been weathered out. According to this, around a non-tabulate axial canal, about 0.75 mm. wide, are grouped closed cells, which increase in size outward.

In *Stachyodes*, the original view of Bargatzky (1881) must be restored, which stated that from a non-tabulate axial canal there branch off non-tabulate lateral canals which in turn branch repeatedly. The wall structure of the canals is massive but seems to be perforated in places.

Idiostroma also has a non-tabulate axial canal, arising out of the openings, which bear apically calcareous interfingering lamellae. Otherwise the lamellae are only slightly perforated. They are supported at intervals by little walls and pillars. These are arranged more or less in the form of parabolas which extend from the apex backward. They leave between them a labyrinth of passages which also extend from the apex (the axial tube) backward. The passages of one and the same interlamellar cavity are well connected with one another, but seldom with those of the neighboring spaces, since the lamellae seldom show a pore.

In all three genera one misses the meshy structure as well as the astrorhizae of the "true" Stromatoporoidea, aside from the fact that these fossils never have a treelike appearance or anything like it.

Again, the skeleton of the Labechidae is not at all stromatoporoid, having no network of meshes open on all sides, but rather a complex of circular, closed, flat vesicles, which, according to the genus, are broken through by pillars (*Labechia*), show reduced pillars on the convex side (*Rosenella*), or are free from pillars (*Beatricea*). Here is to be noted also, as an important negative characteristic, the absence of astrorhizae.

When, therefore, the families Labechidae and Idiostromidae are thus removed, the Stromatoporoidea no longer stand as a collective group of elements of unequal value, but the remaining "true" Stromatoporoidea represent a clearly limited order, for which the following definition may be given: The skeleton is built of seamlessly united, massive or porous calcareous fibers, which form a more or less regular network. In this can be recognized a more or less plainly layered arrangement of the tangential elements. Astrorhizae are always present.

From the examination of a greater mass of material it appears that in the skeletal structure of the Stromatoporoidea all transitional stages from regularly netted (reticulate) to markedly vermiform (vermiculate) are present. The division into a "hydractinoid" and a "milleporoid" group is incorrect, since it is founded upon a wrong supposition, for in none of the forms which were put into both groups are "zoöidal tubes" analogous to those of *Millepora* present. In fact, G. Steinmann in 1903 (*Milleporidium*, etc.) and W. Parks in 1909 (*Silurian Stromatoporoidea*, etc.), the former strongly, the latter at first doubtfully, questioned the so-called "zoöidal tubes."

A still sharper division into two groups lies in the fact that the relatively fine fibers of the family Actinostromidae are massive, while the somewhat thick fibers of the family Stromatoporidae show pores and little canals. On this ground a division of the Stromatoporoidae must rest.

This division principle: "Fibers massive"—"Fibers not massive" permits of an unquestionable division. Moreover, it is in harmony with the fact that in the massive-fibered group belong only entirely rectilinearly and altogether regularly built forms, while to the hollow-fibered group may be referred only those forms which are in some way irregularly vermiculate in their skeletal structures. The further division into genera rests in both groups on the degree of regularity of the skeletal mesh. It is, however, no longer quite so sharp, since in many forms it is not certain whether they have a greater or less degree of regularity and so are to be referred to this or that genus. The differentiation into species is at best dependent upon the number of lamellae and pillars per millimeter, while the development of the astrorhizae and the tubercles, on account of their variability, comes into consideration only secondarily, and in extreme cases can only lead to the making of varieties.

It is especially to be noted in the work of Parks, who has recently published various studies on American stromatoporids, that often in one and the same specimen the conditions, e.g., the number of pillars and lamellae, vary so much that one cannot be too cautious in the making of new species, if the specimens are to be identified.

In accordance with the principles above stated, the following classification may be formulated:

A. Family Actinostromidae Nicholson. Fibers massive.

Radial and tangential elements equally well developed and united into a linear network (rectilinear). (Surface therefore granular.)

- I. Pillars passing continuously through several lamellae: Genus *Actinostroma* Nicholson.
- II. Pillars only one lamella high:
  1. Lamellae quite flat: Genus *Clathrodictyon* Nicholson.
  2. Lamellae strongly vaulted: Subgenus *Stylodictyon* Nicholson and Murie.

B. Family Stromatoporidae Nicholson. Fibers not massive (porous or perforate).

- I. Radial and tangential elements equally strongly developed and plainly differentiated. Tangential section, however, in part vermiculate. (Surface therefore in great part granular, but in places vermiculate.)
  1. Pillars passing through: ?Genus *Hermatostroma* Nicholson.
  2. Pillars generally only one lamella high: Genus *Stromatoporella* Nicholson.
- II. Radial elements somewhat rectilinear and strongly prominent as compared with the much thinner tangentials. Tangential section vermiculate. (Surface vermiculate.) Genus *Parallelopora* Bargatzky.
- III. Radial and tangential elements equally strongly, very irregularly interlaced (vermiculate) and therefore no longer differentiated. Tangential and radial sections vermiculate. (Surface vermiculate.) Genus *Stromatopora* Goldfuss.

THE PHYSIOGRAPHY OF MEXICO[1]

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For one who approaches the study of Mexican physiography for the first time, it facilitates matters considerably to acquire in the very beginning a few fundamental concepts, particularly as regards the relations of the provinces of Mexico to those of the United States. We are likely to regard the Mexican provinces as ending abruptly on the north at the International Boundary, and at the south along an irregular political line separating Mexico from Central America. As a matter of fact, the Mexican physiographic provinces extend well into the United States, the natural northern boundary being in a general way the Pecos-Rio Grande, the escarpment of the Colorado Plateau, and the southern terminus of the Sierra Nevada Mountains. As thus bounded, Mexico, from a physiographic viewpoint, includes those provinces hitherto described for the United States under the names of Trans-Pecos Highlands, Arizona Highlands, and Colorado Desert.[2] The natural southern boundary is the isthmus of Tehuantepec. This excludes the states of Tabasco, Campeche, Yucatan, and Chiapas, but physiographically speaking, these political divisions belong to Central America rather than Mexico.[3]

All the topographic features included between these natural boundaries, with the exception of a narrow strip along the Gulf coast, may be traced back to a common feature which came into existence in early Tertiary time, and for which Hill has suggested the name "Cordilleran Peneplain."[4] This peneplain was made on the

[1] For complete bibliography see list of references compiled by me and published in *Mining Science*, LXX, Nos. 1745–47.

[2] N. M. Fenneman, "Physiographic Boundaries within the United States," *Ann. Ass. Am. Geog.*, IV, Pl. 1.

[3] E. Bose, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, XXXI, 15–16.

[4] R. T. Hill, "Growth and Decay of the Mexican Plateau," *Eng. and Min. Jour.*, LXXXV, 681–88.

closely folded Mesozoic sediments. The elevation of the peneplain made the great Mexican Plateau, which in its present condition may be described as a great tilted block, the up-tilted end overlooking the isthmus of Tehuantepec and the down-tilted end lying under the scarp of the Colorado Plateau and along the course of the Rio Grande.

On this plateau erosion and vulcanism have carved and molded a variety of topographic forms. The products of one or both of these factors characterize definite areas, and applying the definition that a physiographic province is an "area which is characterized throughout by similar or closely related surface features, and which is contrasted in these respects with neighboring areas,"[1] we find that the prominent topographic divisions of Mexico become its true physiographic provinces.

These provinces may be gathered for convenience in discussion into two groups: one, the northern, having a general north-south alignment, and the other, the southern, having a general east-west alignment (see accompanying map, Fig. 1). In order from east to west the members of the northern group are the Gulf Coastal Plain, the Anahuac Desert Plateau, the Sierra Madre Occidental, and the Sonoran Desert. Below these, in succession southward, come the Volcanic, the Sierra del Sur, and the Tehuantepecan provinces. Where province names are not self-explanatory, reasons for them will be given in the text to follow. In our discussion of the provinces we will begin with the Sierra Madre Occidental, for the reason that it is the oldest feature of Mexican topography and will aid in orienting us, so to speak, when we come to the discussion of younger features with more complex histories.

THE SIERRA MADRE OCCIDENTAL PROVINCE

Definition and boundaries.—The Sierra Madre has been defined as "a vast area of circumdenudation," "a higher island of summit survival,"[2] "a great plateau, fringed by mountains on the east, trenched by deep canyons in the center, and bordered by a wild and rugged complex of mountains on the west."[3] "It is not to be

[1] Fenneman, *op. cit.*, p. 87. [2] Hill, *Eng. and Min. Jour.*, LXXX, 633.

[3] W. H. Weed, *Trans. A.I.M.E.*, XXXII, 444.

regarded as a single chain or mountain mass, but rather a group of chains, generally of the same orientation, successively rising, one

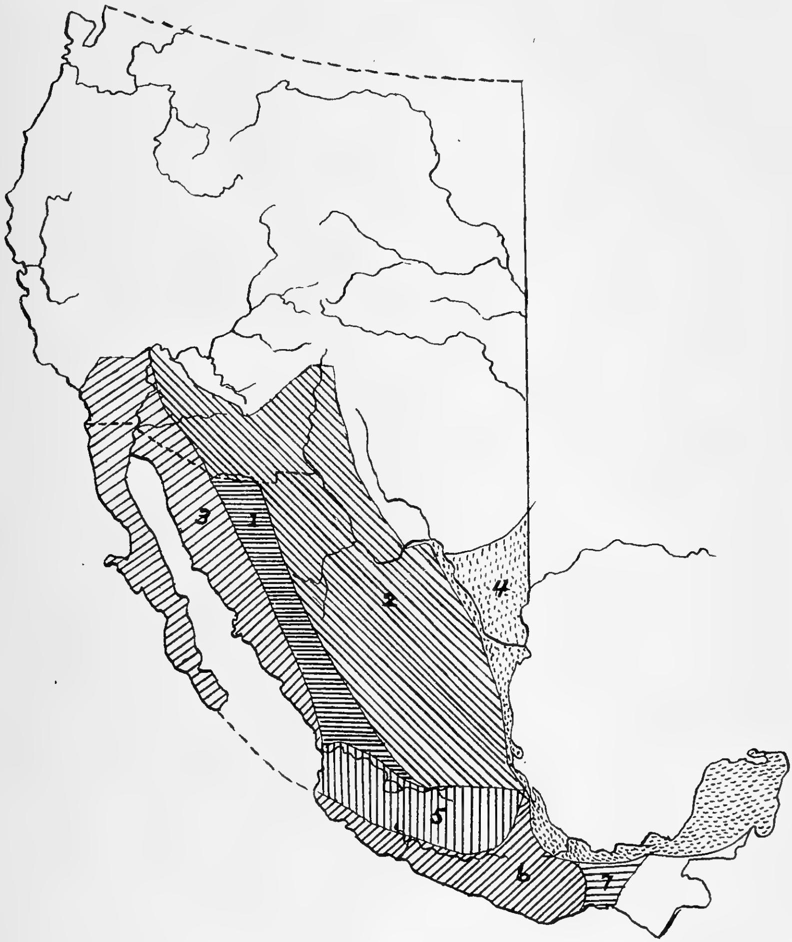

FIG. 1.—Physiographic Provinces of Mexico

1. Sierra Madre Occidental.
2. Anahuac Desert Plateau.
3. Sonoran Desert.
4. Gulf Coastal Plain.
5. Volcanic.
6. Sierra del Sur.
7. Tehuantepecan.

above the other, from west to east, separated by depressions of various widths and furrowed by streams of more or less importance."[1]

[1] E. Ordonez, *Inst. Geol., Mex.*, IV.

This province extends from near the International Boundary southward, roughly parallel to the Pacific coast, to the valleys of the Rio Grande de Santiago and the Rio Lerma. It has been suggested that the Chiricahua Range of Arizona may mark its former extent to the northward, and show the transition between it and the closely related province of the Colorado Plateau in the United States.[1] Throughout the greater part of its extent it will average 100 miles in width, but in the south it attains a width of 300 miles or more.

There are many Sierra Madres in Mexico; so many, in fact, as to be confusing to the casual reader of Mexican geography. The Sierra Madre Occidental, however, is the real "mother" Sierra, the progenitor of all the other Sierras in Mexico. If a section be drawn across Mexico from the Atlantic to the Pacific in almost any latitude, it will be found that every feature on the profile of that section, save a narrow strip of coastal plain, is related in some manner to this Sierra (see accompanying profile sketches, Fig. 2).

The northern boundary has been drawn at the International Boundary, where the Sierra Madre Occidental Mountains end rather abruptly and overlook the vast stretches of desert plateau to the northward.

The western boundary, from Naco, Arizona, to the mouth of the Rio Yaqui, follows the Rio Sonora and the Rio Moctezuma, which flow in structural valleys at the foot of the mountain scarp.[2] From Trinidad, Sonora, to the Rio Grande de Santiago, Tepic, this western line marks the highest escarpment overlooking the desert below, and is coincident with the state boundaries separating Chihuahua, Durango, and Zacatecas on the east from Sonora, Sinaloa, and Tepic on the west. There is no doubt that these boundaries between states are the result of natural selection, because the prominent topographic break makes an indisputable parting between political divisions. This line, which marks the present limit of the eastward retreat of the plateau, was determined by one of the prominent N. 45° W. fault lines which cut the plateau.[3]

[1] Hill, *Eng. and Min. Jour.*, LXXXIV, 631.

[2] See the Bartholomew map of Mexico, published by the National Geographic Society.

[3] J. D. Villarello, *Guides des excursions, 10th Inter. Cong. Geol. Mex., 1906*, No. 18.

The southern boundary of this province has been placed at the canyons of the Rio Grande de Santiago and the Rio Lerma; not arbitrarily, but because at this place there is a sharp change in the strike of the massive folded sediments.[1] North of this line the

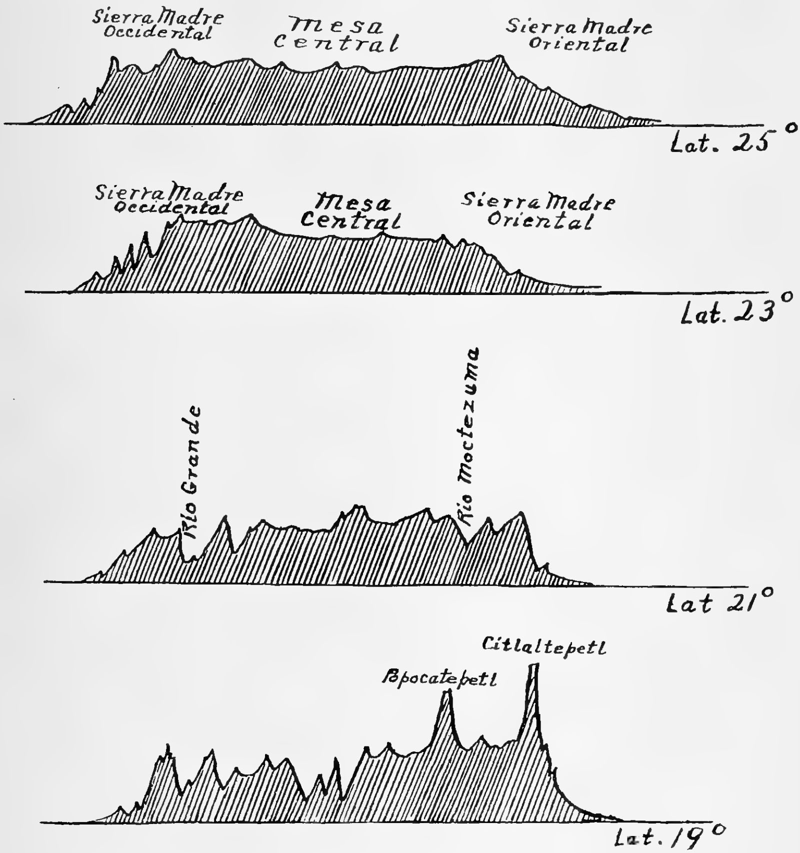

FIG. 2.—Profile of Mexican Plateau. (After J. G. Aguilera.)

structural trend is generally northwest–southeast, while south of it the trend is more nearly east-west. South of this line, also, erosional down-cutting in the plateau ceases to be the controlling factor in the making of the topography, and gives way to volcanic piling-up on it.

[1] Ordonez, *op. cit.*

The eastern boundary of this province begins at the International Boundary and runs in a general southerly direction through the states Chihuahua, Durango, Zacatecas, San Luis Potosi, and Queretaro to the Valle de Mexico. It is not a sharp line like the other boundaries of the province, but has been rather arbitrarily chosen throughout the greater part of its length, though not without certain criteria. It has been drawn to pass near such cities as La Junta, Parral, San Miguel, and Zacatecas, which are known to be situated at the eastern foot of the mountains. Between these cities the line has been drawn to pass through the points marking the sources of the small "suicidal" streams which rise near the border of the mountains and lose their small quantities of water by evaporation and percolation soon after reaching the desert below. The want of suitable topographic maps covering large areas makes a more accurate drawing of this line impossible. Its location cannot be far from correct, however, for it coincides with the line on the Willis geological map of North America, which separates the mountain country, where the volcanic cap rock is thick, from the desert to the east, where erosion has removed the extrusives and exposed the underlying Cretaceous sediments.

Topography.—In a general way the topography of this province may be described as "a succession of narrow and continuous northwest-southeast ridges, with foothills, separated by broad and continuous longitudinal valleys" which grow wider toward the coast.[1] The even skyline which one might expect to result from the uplift and dissection of a peneplain is not everywhere apparent, because of subsequent volcanic flows of uneven thickness; although viewed over broad areas there is a certain evenness of summits which is apparent in spite of the flows, which were not of the cone-building type, but more like those which resulted in the formation of our Columbia Plateau.

An east-west profile of the Sierra Madre in southern Chihuahua and Sonora shows an average elevation of about 7,000 feet on the east, rising to 10,500 feet at the Continental Divide, and dropping again to about 6,800 feet at the western scarp.[2] The term "Continental Divide" should not be understood too literally, for it is not

[1] J. G. Aguilera, *Inst. Geol. Mex.*, V. [2] Weed, *op. cit.*

between the Atlantic and Pacific, but between the Pacific and the interior basins of the Anahuac Desert province.[1] There is also a drop in elevation of a few thousand feet from south to north in conformity with the slope of the tilted plateau block which constitutes the Mexican country.

The Sierra Madre Occidental is generally regarded as a mountainous country, and experienced geographers write of its "ridges," but it is important to note that the roughness of its topography is due to down-cutting rather than upheaval or upbuilding; in other words, the slopes of the region are to be regarded as canyon walls rather than mountain flanks.

This province has no important drainage to the east save by the Rio Conchos and the Rio San Juan, both tributary to other streams. All of the other streams which rise in the mountains and flow eastward are of the "suicidal" or "lost"[2] type and disappear soon after reaching the desert below, or flow into undrained lagunas (lakes), where their water is gradually evaporated. The profound work of dissection and denudation which one sees in progress east of the mountains is not due to these streams, but to other processes which will be described later.

On the west, normal processes of erosion are under way, and numerous subsequent streams are working headward and pushing back the western scarp of the plateau at a rapid rate. In many places these have captured the streams occupying the longitudinal structural valleys, the latter entering the former at angles varying from 45° to 90°.[3] Some of these western streams, particularly the Aros, the Fuerte, and the Rio Grande de Santiago, have incised their canyons a mile below the top of the plateau, and emphasize the fact that the rugged character of the country is not due to upward departures from the general level, but to profound down-cutting in the plateau. The greatest depression is in the Grand Canyon of the Bolanos, a tributary of the Santiago. The depth of this canyon is accentuated by the fact that it lies at the foot of the maximum crest of the mountains—the Sierra de la Yesca.[4] Experienced travelers testify that the scenery to be found in these canyons

[1] E. O. Hovey, *Bull. Phil. Geog. Soc.*, No. 4, p. 247.

[2] Hill, *Eng. and Min. Jour.*, LXXXIV, 633.

[3] Aguilera, *op. cit.*

[4] Ordonez, *op. cit.*

rivals that of our own Grand Canyon, which was produced by the same causes and at the same time.

It is along the courses of these westward-flowing streams that the dentate character of the sierras is seen to the best advantage. Their longitudinal tributaries separate chains or mountain masses, the western slopes of which are marked by precipitous fault scarps. The eastern slopes of these masses being more gentle, the profile is clearly imitative of the teeth of a saw.[1]

Many of the longitudinal stream valleys, before being tapped by the westward streams, were intermontane basins. On the sides of these valleys are now to be found undeformed, stratified beds, which were for a long time unaccounted for. They are now regarded as loosely cemented débris which had been carried down the slopes and deposited in the basins, which, when filled with water, formed lagunas, and constituted "settling tanks," as Hill has termed them,[2] where the detritus was roughly classified according to size and deposited in layers. They are of course of a past, but quite recent, geologic age.

The general structure of this province may be described as a series of folds, varying from a close, even recumbent, type, to broad swells, passing out northward into monoclines, over the erosion-beveled edges of which are spread flow upon flow of eruptive lavas. Le Conte, twenty years ago,[3] proposed the theory that these Sierras were formed by intense folding movements in Early Tertiary time, followed by profound drops at the sides of faults parallel to the folds; that along these lines of less resistance, successive and prolonged volcanic eruptions took place, and that subsequent active erosion accentuated the escarped form which affects most of the slopes. Later studies pursued by prominent Mexican geologists have confirmed this theory.[4]

In the canyon of the Aros there have been counted as many as nineteen separate lava flows, one above the other, with intervening beds of tuff and local conglomerate derived from the disintegration

[1] Ordonez, *op. cit.* [2] Hill, *Trans. A.I.M.E.*, XXXII, 163.

[3] Le Conte, "The Origin of Mountain Ranges," *Jour. Geol.*, September-October, 1893.

[4] Ordonez and Aguilera, *Inst. Geol. Mex.*, IV.

of the preceding flows. Erosion has affected unequally these tuffs and the harder lavas (rhyolites and dacites), and in consequence there have been produced, on many of the slopes, several terraces or "shoulders."[1]

Physiographic history.—The history of the present Sierra Madre Occidental begins properly with the uplift which brought the Cretaceous sediments out of the sea. This uplift continued to a considerable altitude and was accompanied by profound deformation, which took the form of close folds and overthrusts passing into faults, the strike of the entire system being approximately north-south. This uplift, which was an event of early Tertiary time, inaugurated the first erosion cycle, which, when completed, had removed some thousands of feet of rock and resulted in the formation of the "Cordilleran Peneplain."[2]

Following this peneplanation, toward the close of the Miocene,[3] another uplift occurred, accompanied by widespread vulcanism. Numerous vents were opened over the province, from which flowed an enormous quantity of slightly viscous lava. Uplift continued; in fact, is still in progress. In the meantime, a second erosion cycle began, during which there has been removed at least two thousand feet of volcanic rock, and which has seen the larger westward-flowing streams incise their canyons a mile below the top of the plateau.[4]

Recent work on the Grand Canyon of the Colorado has indicated a third erosion cycle, intermediate between the two just described.[5] It is impossible to determine from the data at hand whether it included the entire Mexican Plateau. It is certain that in some places the early eruptives (andesites) as well as the intrusives (diorites and granites) were deeply eroded before the later eruptives (rhyolites and dacites) appeared. However, the evidence of this third cycle is obscure, even where displayed to the best advantage, whereas the evidence of the two cycles described above is perfectly clear to experienced physiographers.

[1] Hovey, *Bull. Am. Geog. Soc.*, XXXVII, 531.

[2] Hill, *Eng. and Min. Jour.*, LXXXV, 681.

[3] Ordonez, *op. cit.*

[4] Hill, *Science*, N.S., XXV, 710.

[5] L. F. Noble, *Am. Jour. Science*, XXIX, 374–80.

At some date subsequent to the completion of the first cycle extensive orogenic movements changed the whole structural trend from north-south to about N. 45° W.[1] The profound faulting which accompanied these movements blocked out the entire country into its present shape, determined most of the prominent structural features, and opened avenues for the intrusion of vast igneous bodies which have been responsible for the primary mineralization of the province.

THE ANAHUAC DESERT PLATEAU

Definition and boundaries.—Many names have been applied to this portion of the old Mexican Plateau, such as the Mesa Central, Chihuahua Desert, and Anahuac Plateau. Hill has suggested the name Anahuac and it will be used in this paper, for it seems eminently appropriate to fasten upon this decayed remnant of a former widespread feature the name of the aboriginal race which inhabited it, and which centuries ago went into decadence along with it. The terms "desert" and "plateau" are included, for they are descriptive of the province. Furthermore, these terms serve to correlate this province with those of the United States which Fenneman has included under the name of desert plateaus.[2]

The Anahuac Desert Plateau is a degraded area of scattered block mountains and intervening "bolson" desert. It extends from the plains of Texas and New Mexico and Arizona on the north,[3] southward through the Mexican states of Chihuahua, Coahuila, Nuevo Leon, Tamaulipas, San Luis Potosi, Queretaro, and Hildalgo to the Valle de Mexico and the base of Xinantecatl (Nevado de Toluca).[4] The portion lying north of the International Boundary is well known under the names of Trans-Pecos Highlands and Arizona Highlands.

The northern boundary line runs eastward from the great bend of the Colorado River, along the edge of the Colorado Plateau, through Silver City, New Mexico, then turns northeastward and passes the southern ends of the San Juan and Sangre de Cristo mountains.

[1] Hill, *Science*, N.S., XXV, 710. [2] Fenneman, *op. cit.*

[3] G. B. Richardson, *El Paso Folio*, *U.S. Geol. Survey*.

[4] Ordonez *et al.*, *Trans. A.I.M.E.*, XXXII, 259.

The eastern boundary follows the western slope of the Pecos valley to the southern edge of the Stockton Plateau.[1] Here it turns eastward along the Balcones scarp to the junction of the Pecos and Rio Grande. Here it turns again and continues in a southerly direction almost to Vera Cruz. In this part of its course it has been drawn on the 500-foot contour of the Bartholemew map, which is practically coincident with the western limit of sediments younger than Late Cretaceous as mapped by Willis. In the field, it should coincide with the line separating the undeformed sediments of the Gulf Coastal Plain from the folded rocks of the plateau.

The western boundary runs southward from the great bend of the Colorado River at the foot of the Grand Wash and Cottonwood Cliffs,[2] which represent the eastward-retreating scarp of the old plateau,[3] to the Gila River. From the Gila to Naco, Arizona, it follows the Rio San Pedro to the International Boundary. From this point southward the line has already been described in connection with the Sierra Madre Occidental province.

The southern boundary is drawn close to the edge of the volcanic area from Nevado de Toluca to Jalapa. It separates two easily distinguishable topographic divisions. North of it, denudation dominates the topography; south of it, great volcanic piles raise themselves above the general level. The Mexican National Railroad from Vera Cruz to Mexico City follows the same line for a considerable distance, and it is, I think, a safe assumption that the railroad survey took these topographic features into consideration.

Topography.—It is not possible to give a single descriptive statement of the topography of this province. Broadly speaking, it is a wide expanse of territory in which great islands of isolated mountain blocks rise above a vast sea of desert. This description may be applied with all faithfulness to the province through its entire north-south extent, but an important exception must be made with reference to the eastern and southern borders. In these places it is actually mountainous.

Beginning with the Sierra del Carmen and the Sierra del Burro, inconspicuous ranges of 5,000 feet altitude or less, just across the

[1] I. Bowman, *Forest Physiography*, Pl. I.

[2] *Ibid.* [3] Hill, *Eng. and Min. Jour.*, LXXII, 563.

Rio Grande from the Stockton Plateau, a chain rises above the desert level and increases gradually in height southward until it forms the Sierra Madre Oriental. These mountains increase in height southward until they attain truly magnificent proportions, with peaks reaching 10,000 feet or more in Hidalgo and Queretaro, where they meet eastward-extending spurs of the Sierra Madre Occidental and merge with them. The Gulf slope of these mountains is in many places a scarp dividing the plateau from the Gulf Plain. It is probable that this scarp marks the position of a great fault line having at some points a vertical displacement of at least 4,200 feet.[1] These mountains are not a continuous north-south barrier, like the western sierra, and the ramifications of the desert "extend through the passes of the limiting chains in many places and establish easy communication with the coastal lowlands."[2]

Travelers across the Trans-Pecos region of Texas and New Mexico are more or less familiar with the topographic forms which will be described as characteristic of the greater part of this province. Prominent among these are the north-south trending ridges, separated by broad plains—in part constructional and in part plains of degradation—many of the latter being of the basin type called "bolsons," from the Spanish word meaning "purse." A section across the Anahuac Desert Plateau in almost any latitude would show the same topographic features—"numerous isolated mountain ranges with intervening pocket valleys or wide expanse of undulating plain."[3] The general desert level has an altitude of from 2,000 to 4,000 feet, while the mountains generally rise above 5,000 feet, with an occasional peak ascending to 8,000 feet or more.

Other prominent features of the topography are the "lost" mountains, lagunas, medanos, and a peculiar formation known as "La Brisca."

Lost mountains are isolated mountain blocks standing in the desert, and so far removed from the main mass of mountains as to have no apparent connection with them. They are simply outliers (monadnocks) which have resisted denudation more effectively than the surrounding territory.

[1] F. L. Nason, *Econ. Geol.*, IV, 421.

[2] Aguilera, *Inst. Geol. Mex.*, VI.

[3] Hill, *Eng. and Min. Jour.*, LXXXV, 681.

Lagunas are shallow ephemeral lakes, mostly found in the lowest parts of the bolsons, and fed by streams whose sources are in the neighboring mountains and which flow only during time of storm—the "suicidal" streams previously discussed.

Medanos are sand hills or dunes, similar to those of our lake shores or the Great Basin. They consist of finely disintegrated particles, derived from the weathering of the plateau, which are constantly moved about, frequently in a general northeast direction, by the high winds.

In our discussion of the Sierra Madre Occidental province we mentioned a peculiar, stratified deposit of a past but recent geologic age which had been formed in intermontane basins. It must be remembered that the Anahuac Desert Plateau province formerly presented the same topography as is found in the Sierra Madre Occidental province at the present time, the latter by its definition being a survival of former widespread conditions. The dissection and weathering of the type of deposit mentioned results in a characteristic feature known in Mexico as "La Brisca." It is a superficial volcanic agglomerate consisting of rhyolitic tuff carrying subangular fragments of other igneous rocks and which weathers into striking forms due to inequalities of hardness—pinnacled cliffs, domes, pillars, etc.[1]

The Rio Panuco and the Rio Conchos, a tributary of the Rio Grande, drain the greater part of the province, although a considerable area known as the Bolson de Mapimi in Chihuahua and Coahuila is without exterior drainage. This great bolson is not a single basin, for within it are to be found mountains of considerable elevation; but its elevations and depressions are so disposed that none of the water falling in it (which is a negligible quantity) reaches the sea.[2]

The Rio Grande is an interesting river from a physiographic viewpoint. At one time it emptied its waters into a great laguna that lay southwest of the present site of El Paso. It appears then that a headward-working tributary of a stream which probably had the course of the present Pecos-Rio Grande tapped this

[1] Hovey, *Bull. Am. Geog. Soc.*, XXXVII, 539.

[2] Bose, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 19.

laguna and diverted its waters to the Gulf of Mexico. But the channel of the stream was far to the south and west of the present course of the Rio Grande, to which it was gradually crowded by encroaching volcanic flows.[1] It has never recovered itself, and in the vicinity of El Paso wanders about with an abandon that perplexes those who are charged with the duty of maintaining a definite line for the International Boundary.[2]

The desert plains of this province are of two types—degraded and constructional. The former are the result of denudation of greater plateau heights; the latter represent valleys or basins filled by detritus derived from the degradation of neighboring areas.

The mountains show several types of structure, though generally they are tilted fault blocks. Mountains in which an igneous core has been thrust up through the sedimentaries are not uncommon. Many are of the "mesa" type, the volcanic capping protecting the soft limestones beneath from erosion. A typical "lost" mountain is to be found in the Santa Eulalia, situated a few miles southeast of Chihuahua City. It is a mass of folded Comanchean limestone mantled by superficial eruptive material, tuffs, and cinders, and at present rises about 1,500 feet above the desert level. Scattered over the surrounding desert lie piles of débris derived from the denudation of the original mountain, which stood several thousand feet above its present height.

Physiographic history.—The history of this province coincides with that of the Sierra Madre Occidental until the beginning of the second erosion cycle. In brief, its known history begins with the withdrawal of the waters of the Gulf of Mexico and the emergence of the land mass at the end of the Cretaceous period. Then followed deformation along general north-south lines, with accompanying or subsequent elevation to a height sufficient to be susceptible of active erosion. This elevation, which probably occurred during the early Eocene,[3] ushered in the first erosion cycle, which ended with the base-leveling of the country to the condition of the Cordilleran Peneplain.

[1] Richardson, *El Paso Folio, U.S. Geol. Survey.*

[2] Mrs. A. S. Burleson, *Natl. Geog. Mag.*, XXIV, 381.

[3] Ordonez and Aguilera, *Inst. Geol. Mex.*, IV.

A little speculative interest is attached to the making of this first peneplain. In humid regions the processes of erosion tend ultimately to reduce the land surface to a base-level which is at or near sea-level; but in an arid region of basin-drainage type erosion cuts down hills and aggrades the basins, so that the plane of reference to which both hills and basins will be brought ultimately is not sea-level, but some higher indeterminate level.[1] Now if aridity characterized this early Tertiary base-leveling period in Mexico (a condition of which we are not certain), it is possible that the peneplain resulting from the erosion of the first cycle was not made at sea-level.

Following this peneplanation another uplift took place; in fact, is still in progress. This was accompanied in the beginning, probably Miocene time,[2] by orogenic movements which altered the entire structural trend to a general northwest-southeast direction.[3] There also occurred at this time widespread volcanic activity, both extrusive and intrusive.

In the second erosion cycle inaugurated by this uplift there were probably a number of stages, for there exist in many places old erosion surfaces made on both sedimentaries and volcanics, covered and filled by later volcanic flows. At the end of the volcanic period erosion became the dominant factor in determining the topography, and has remained so until the present time; and it is this epoch in the history of the province that holds the greatest interest from a physiographic viewpoint.

All of the features of the topography of this province which we have previously discussed are due to erosion agencies peculiar to an excessively arid region. In humid climates water in some form is the chief agent of erosion, but in this province nothing is more scarce than water, and the excessive denudation which has taken place must therefore be attributed to other agents. Chief among these is a large diurnal temperature variation. A midday temperature of 130° F. is not uncommon over a large part of the province, and a midnight temperature of 50° F. is usual throughout most of the year in the same places. This gives a maximum daily variation

[1] W. M. Davis, *Jour. Geol.*, XIII, 381.

[2] Ordonez, *op. cit.*

[3] Hill, *Science*, N.S., XXV, 710.

of 80° F., and it is safe to assume that the mean daily variation is not less than 50° F.

These sudden and excessive changes in temperature produce expansion and contraction stresses which even the hardest rocks are unable to withstand, and consequently they crack, splinter, and chip off. Then by gravity these particles are dragged down the slopes, comminuting each other as they go, until when they reach a certain minuteness of size they are seized by the strong, ever-blowing desert wind, which, like a great winnowing machine, fans them away. Much of this rock dust is carried out to sea, some of it perhaps is carried hundreds of miles to the northeast to add to the accumulation of loess on our Great Plains. Sheet floods following storms play an important part in erosion, but they are quite subordinate to the process just described. In the words of Hill, "the Mexican Plateau is being literally blown away."[1]

THE SONORAN DESERT PROVINCE

Definition and boundaries.—This province is the most degraded portion of the old Mexican Plateau. It is 1,700 miles long and lies between the Sierra Madre Occidental on the east and the Pacific Ocean on the west. It includes parts of Nevada, California, and Arizona in the United States, and the Mexican states of Baja California, Sonora, Sinaloa, and Tepic.

The northern boundary line runs from the edge of the Colorado Plateau near the great bend of the Colorado River westward to the southern terminus of the Sierra Nevada Mountains. It has been drawn to agree with the line marking the southern edge of the Great Basin as described by Fenneman[2] and Bowman[3] and requires no further justification.

The western boundary extends southward from the southern terminus of the Sierra Nevadas, between the Tehachapi Mountains of the Coast Ranges and a group of mountains which Ransome has referred to as the Sierra de Los Angeles, and reaches the coast between Los Angeles and San Diego.[4] From this point southward it coincides with the Pacific coast line to Cape San Lucas, and then

[1] Hill, *Science*, N.S., XXV, 710.

[2] *Op. cit.* [3] *Op. cit.* [4] J. S. Diller, *Science*, N.S., XLI, 1045.

cuts across the mouth of the Gulf of California to Cape Corrientes, where it closes with the southern boundary.[1]

The eastern boundary has been described in connection with the Sierra Madre Occidental and Anahuac Desert Plateau provinces.

The southern boundary is really a prolongation of the eastern boundary, which makes a turn to the southwest from the valley of the Rio Grande de Santiago to Cape Corrientes.

Topography.—Although there is a certain homogeneity of topography which distinguishes this province from its neighbors, there is, nevertheless, a minor diversity of features within its boundaries. The features which force themselves upon the attention of the student of physiography are as follows: (1) a great structural trough, occupied by the Gulf of California, the Salton Sink, and the Coachilla and Imperial valleys;[2] this trough, if not an actual southern extension of the same, is at least analogous to the great downwarp of the Pacific coast which is occupied in succession northward by the San Joaquin, Sacramento, and Willamette valleys and the Puget Sound basin; (2) a destructional coastal plain of varying width bordering the open ocean and the Gulf of California; (3) a foothill region bordering the western foot of the Sierra Madre Occidental and the Arizona Highlands, of which the mountains of the Peninsula of Lower California are a counterpart.[3]

The bottom of the structural trough is below sea-level from Riverside County, California, to Cape Corrientes, with the exception of the delta of the Colorado River, which lies slightly above sea-level and separates the submerged portion, known as the Gulf of California, from the Salton Sink and the Coachilla and Imperial valleys, which are at present land surfaces, though one point is 275 feet below sea-level.

The coastal plain is very narrow where it borders the open ocean and on the east side of the peninsula. On the mainland it assumes a wedge shape, and varies in width from zero in Tepic to 70 miles in the northern part of the province. It is nearly level, with few elevations above 200 feet, and "plainly the bottom of the Gulf of

[1] Ordonez and Aguilera, *Inst. Geol. Mex.*, IV and VI.

[2] Bowman, *op. cit.*, p. 235.

[3] C. Botsford, *Eng. and Min. Jour.*, LXXXIX, 223.

California until recently."[1] The fact that it has but recently emerged does not make it a constructional plain, for only a superficial bed of sediments covers the surface, denuded before the last submergence. Northward into Sonora, Arizona, and California this subdivision of the province grades quite imperceptibly into the lowlands of the Colorado Desert, where it loses its featureless coastal plain identity and is characterized by old valley floors with intermittent streams, old valleys filled with alluvium, and isolated mountains half-buried under alluvium, plains eroded by sheet floods descending from adjacent mountains, and true desert areas, of which the Mojave Desert is typical.[2]

The foothill region represents a less advanced stage of erosion of the edge of the old plateau. It is also wedge-shaped, its width varying from 20 miles in the south to 100 miles in the north. Its average altitude is less than 2,000 feet, though here and there peaks rise to 5,000 feet or more.[3] These are outliers, representing the former extent of the plateau, and are genetically analogous to the lost mountains of the Anahuac Desert Plateau province, previously discussed.

Northward these foothills grade into mountains of a somewhat different kind—the Basin Range or fault-block type. They still may be regarded as remnants derived from the old plateau but which have suffered recent faulting, as well as the erosion of two cycles.[4] The mountains of the peninsula are counterparts of the foothills of the mainland. According to Botsford the correlation of the two is perfect, as indicated by the "extent and characteristics of the Miocene rhyolytes and dacites on both sides of the gulf."[5] Northward it is probable that these peninsular mountains grade into the type of which the San Bernardino Mountains are characteristic, and not into the Coast Ranges, as they are generally mapped.[6]

The average altitude of these peninsular mountains is higher than the mainland foothills, on account of less active erosion due

[1] C. Botsford, *Eng. and Min. Jour.*, LXXXIX, 223.

[2] Bowman, *loc. cit.*, p. 237.

[3] Botsford, *loc. cit.*

[4] Bowman, *op. cit.*, p. 236.

[5] Botsford, *loc. cit.*

[6] Diller, *loc. cit.*, and Ordonez and Aguilera, *op. cit.*, p. 52.

to an almost entire absence of rainfall, and in places peaks rise almost to the level of the original peneplained surface of the old plateau; for instance, Santa Catalina 10,135 feet and Mount San Bernardino 10,630 feet.

In the northern part of the province there are numerous features that have many of the earmarks of glaciation—cirques, moraines, kettle holes, etc.[1] In the San Bernardino Mountains there is scarcely any doubt that these features are of glacial origin, the evidence presented by physical characteristics being supported by a boreal flora and fauna in the higher parts of the range; in Arizona and Sonora, however, there is some question concerning their glacial origin, and able geologists have held different opinions on this point. One holds that they are due exclusively to ice action;[2] another attributes them to volcanic brecciation and subsequent sheet flood erosion.[3] Inasmuch as either process would produce subangular fragments of varying size and would transport them to considerable distances from their point of origin, it is difficult to decide which is the more probable theory. Recent field work has not contributed much to the discussion.

The prominent drainage feature of this province is the Rio Colorado. It is of interest to physiographers for several reasons. Although it flows hundreds of miles through an arid country, without tributaries, and loses much of its original volume by evaporation, it delivers at its mouth a great volume of water, particularly from April to June. In this water is a larger average amount of suspended matter per unit volume than in that of any other North American stream, about twenty thousand parts per million, or enough to cover one hundred square miles of territory to a depth of one foot in a year. This accounts for its rapidly growing delta, and the cutting off of the Salton Sink and the Imperial and Coachilla valleys area.[4]

The lower course of this stream was consequent upon the surface of the great downwarp between the peninsula and the mainland.[5] In the bed which it found in this trough the river cut a canyon,

[1] Merrill, *Science*, N.S., XXIV, 117.

[2] *Ibid.*

[3] W J McGee, *Science*, N.S., XXIV, 178.

[4] Bowman, *op. cit.*, pp. 238–40.

[5] Botsford, *loc. cit.*

the mouth of which was on the coast somewhere between Cape San Lucas and Cape Corrientes.[1] This cutting may have been coincident with the elevation succeeding the downwarping or it may have occurred at some indefinitely later time. It is certain, however, that the depth of the gulf is not due alone to drowning by the sea, but largely to stream-bed corrasion incident to elevation. The maximum corrasion is estimated by Botsford to have been at least 6,000 feet.[2]

On the peninsula, but four small streams cut the coast line of more than two thousand miles. This is due to the fact that there is little or no precipitation. There are extensive areas on the peninsula where not a drop of rain has fallen in many years, which are characteristically desert in aspect and condition, even to the extent of supporting a fauna which apparently does not require water. In striking contrast to these conditions is the Sierra Pedro Martir, located in the northern part of the peninsula. This is a high plateau remnant, forested with conifers, and threaded here and there by small watercourses which flow through grassy and even marshy meadows.[3] Here cactus and yucca give way to conifers; and the horned toad and desert fox are replaced by mountain sheep and deer. In short, the region is the habitat of a fauna and flora akin to that found in the western mountains of the United States.

The reason for this change from desert conditions which exist on all sides is to be found in the height of the area, which causes it to receive considerable snowfall from December to April. The water from the melting snow lies close to the surface of the undrained plateau during a large part of the remainder of the year and gradually finds its way to springs scattered at lower altitudes. This condition dies out gradually down the gentle slope to the Pacific but ends abruptly at the scarp overlooking the gulf.

On the mainland, east of the gulf, there are numerous short streams which have their sources high up in the Sierra Madre Occidental, and receive considerable water during the rainy season. Many of these are dry during the greater part of the year, but are,

[1] Ordonez and Aguilera, *op. cit.*, p. 52.

[2] Botsford, *loc. cit.*

[3] North, *Am. Geog. Soc. Bull.*, XXXIX, 544.

nevertheless, active agents of erosion when carrying the excessive run-off which follows precipitation on the bare desert slopes. The Sonora, Yaqui, Fuerte, and Rio Grande de Santiago rise farther back in the mountains and have a continuous flow. The canyons which these latter streams have cut through the mountains and foothills are of profound depth, and present to the traveler a sublimely rugged scenery, not to be surpassed on the continent.

The structure of this province is quite complex on account of the extensive folding, faulting, and vulcanism to which it has been subjected. A cross-section would show folded sedimentaries, upon the beveled edges of which sheets of volcanic material are spread, and into which dikes, plugs, sills, laccoliths, and other igneous bodies have been intruded. The whole mass is broken by numerous faults, chiefly of the N. 45° W. system, though east-west faults are common and occasionally profound, one in the Cananea district having a vertical displacement of at least 1,000 feet.[1] The topographic effect of the predominating N. 45° W. faults is to be seen in the scarps of the western border of the Sierra Madre Occidental and of the eastern border of the peninsular mountains.

Physiographic history.—When this province emerged from the sea after receiving its thick deposit of Mesozoic sediments it was subjected to stresses, which resulted in close folding and in the making of the great synclinal trough previously described. Following this, in early Tertiary time, there came a period of erosion which beveled the edges of the folded strata and resulted in the making of the "Cordilleran Peneplain," previously described.

After the country had been base-leveled, vulcanism began to play an important rôle, and during the Miocene great masses of volcanic material were poured out from numerous vents, completely burying the sedimentaries. Coincident with this a second uplift occurred, giving the streams renewed energy and causing erosion to become the dominant process in the making of the topography. It was during this second uplift, which probably is still in progress, that the Colorado River cut its trench several thousand feet deep through the Pacific trough.[2] The remainder of the province was not seriously affected in the beginning by the erosion of this period,

[1] M. L. Lee, *Econ. Geol.*, VII, 324. [2] Botsford, *op. cit.*

because of its thick volcanic cap. During the early stages of this second cycle the synclinal trough was depressed, allowing the sea to encroach as far north as the Salton Sink, about 200 miles farther northwest than at present. At that time, "the mouth of the Colorado River was at Yuma, sixty miles from its present location, and was gradually building a delta that extended southwest toward the Cocopa Mountains. Deposition continued until the upbuilding of the delta had completely separated the head from the rest of the gulf, and converted the floor of the former into an inland sea."[1] At numerous times since, the Colorado has alternately emptied into the Gulf and into the lake or inland sea which it created.

The greater part of the degradation of the province has occurred during recent epochs of the period of second uplift. When once the volcanic capping is worn through, the softer sediments beneath erode with remarkable rapidity, and the larger westward-flowing streams have cut canyons of abysmal depths in them, in their short but steep courses to the sea. The smaller intermittent streams working headward into the plateau are attacking the softer rocks wherever exposed, and, with the sheet floods which follow the torrential downpours characteristic of the province, are doing a work the results of which are not so likely to attract attention as canyon-cutting, but which are infinitely more profound in the degradation of the plateau.

THE GULF COASTAL PLAIN PROVINCE

Definition and boundaries.—This province is a plain composed of recent and undeformed marine sediments. Being a southern extension of a similar feature in the United States it has no proper northern boundary, but is continuous through the Gulf states and up the Atlantic as far as Long Island.

Its western boundary has been described in connection with the Anahuac Desert Plateau province.

The eastern boundary, in common with that of the remainder of the coastal plain in the United States, may be taken as the border of the continental shelf, and is, of course, many miles east of the present coast line, which is but an incidental feature.

[1] Bowman, *op. cit.*, p. 239.

Inasmuch as both eastern and western boundaries of this province might be extended into Central America, it has no southern boundary as far as Mexico is concerned.

It is evident that the coastal plain is divisible into two parts, one submerged and the other a land surface. Of the former there is little to be said, save that its depth below sea-level is in most places very slight; the charts of the United States Coast and Geodetic Survey show but 30 fathoms at a distance of 125 miles out from the mouth of the Rio Grande.

The landward portion has its greatest width along the International Boundary, where it attains a width of about 225 miles. South of Brownsville the province narrows suddenly and continues to grow narrower until at Tampico it has practically no development at all. This condition continues with more or less variation as far as Vera Cruz. South of this point there is a gradual widening which increases with distance until, in the peninsula of Yucatan, the plain has a maximum width of over 300 miles.

Topography.—The most prominent topographic features of this province lie close to the coast line—a multitude of spits, bars, coastal islands, lagoons, and salt marshes. The greater part of the surface above tide is a featureless flat, which terminates rather abruptly at the foothills of the Sierra Madre Oriental. It is not possible to draw a straight line of any considerable length between the coastal-plain type of topography and that of the mountains. Indeed, it is common to find jutting headlands of the Sierras and reduced areas of intrusive rocks almost down to the water's edge,[1] and on the other hand to find recent marine sediments in the coves 40 or 50 miles inland. This condition has already been explained and is mentioned again only to justify the generalization of the boundary line.

No large or important streams cross the province south of the Rio Grande. The paucity of streams and the number of lakes are noteworthy features of the peninsula of Yucatan. This condition is closely related to the lithology of the bedrock. This consists of thick beds of limestone and shale of Cretaceous age. Where the coastal plain is narrow, as in the vicinity of Tampico, these deposits

[1] V. R. Garfias, *Jour. Geol.*, XX, 666.

are deeply covered by marine sands supplied by the débris washed down from the eastern edge of the plateau, but on the peninsula, where the plain is very wide and the greater part of it at a considerable distance from the mountains, the limestones are close to the surface. These limestones are of a particularly soluble character, and on account of the low, flat, or undulating surface, the heavy rains of the region soak into the ground and percolate through them, developing great caverns (*cenotes*). Where the cavern roofs have fallen in the natural channels of circulation are stopped, and water fills the depression; forming shallow ponds (*akalches*).[1] In other places the waters continue to circulate downward until they strike a stratum of impervious shale, along which they move in underground channels to the sea, or upon which they form subterranean lakes. These form the only permanent natural sources of water on the peninsula, and as a result they are of considerable economic value.

Physiographic history.—As in other sections of the Atlantic Coastal Plain, the later history of this province may be summed up as a series of submergences and emergences. At times, perhaps several times, the present land portion has been under water. At other times the present submerged portion has been above the sea, even to the edge of the continental shelf. The tendency at this time is toward a submergence of the present land surface portion.[2]

THE VOLCANIC PROVINCE

Definition and boundaries.—This province embraces a high mountainous strip of country in which the axes of folding are aligned east-west, and in which the departures from the general level are upward instead of downward, as elsewhere over the plateau. The province extends across Mexico in an east-west direction from Cape Corrientes to Jalapa. Early geographers called it the "Còrdillera de Anahuac,"[3] but the term has fallen into disuse because it is now recognized that it is as much an integral part of the great Mexican Plateau as the Sierra Madre Occidental.[4]

[1] Huntington, *Bull. Am. Geog. Soc.*, XLIV, 801; V. R. Garfias, *Inst. Geol. Mex.*, III, 18.

[2] C. Sapper, *Inst. Geol. Mex.*, III.

[3] Virlet de Aoust, *Bull. Soc. Geol. de France*, 2d Ser. XXIII, 14–15, 1866.

[4] Aguilera, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 7, p. 3.

The northern, western, and eastern boundaries have already been described in connection with other provinces. The southern boundary line extends in a general way from Cape Corrientes along the courses of the Rio Armeria, the Rio Tepalcatepec, the Rio Balsas, the Rio Mexicala, and the Rio Atoyac, all of which skirt the southern edge of the recent volcanic flows, to the vicinity of Esperanza, and then around the volcano of Orizaba and the Cofre de Perote to Jalapa. The change in topography when one crosses the boundaries of this province are sharp and definite, and if not always comprehended in a single view, at least become apparent within a few miles.

Topography.—Viewed from any commanding eminence, this province presents a wildly rugged topography—"a variegated sea of rolling, timber-covered, constructional, volcanic hills, mesas, peaks, and monticules, alternating with basin valleys and plains."[1] The great altitude of the major portion of the province (8,000 feet and upward) is not due alone to the higher altitude of the plateau itself, although it is 5,000 feet above El Paso, but to the vast quantities of volcanic material which have been ejected from numerous vents and piled upon it.

This volcanic material consists not only of lava, but also of tuffs and pumice, in some places *in situ* and in others as old lacustrine deposits. The material from which these lacustrine deposits were made was derived by erosion from the surrounding volcanic heights and carried into the lakes, raising their waters until they overflowed into neighboring streams, and finally filling the lakes completely. As many of these Pliocene and Pleistocene lake beds were of considerable areal extent, their deposits have effaced much of the pre-existing volcanic topography.[2]

It is probable that the plain upon which the higher peaks rest was formed simultaneously with them. According to Ordonez the more fluid portions of the magma were ejected from the vents by violent explosions and raised into such prominent andesitic cones as Popocatapetl and Ixtaccihuatl, while the denser basalts flowed from connecting fissures to form the "badland" plains surrounding them.[3]

[1] Hill, *Eng. and Min. Jour.*, LXXIX, 410.

[2] Ordonez, *Guides des excursions*, *10th Inter. Geol. Cong. Mex.*, *1906*, No. 8 and plate.

[3] Ordonez, *ibid.*, No. 1, p. 4.

Figures are totally inadequate to express the amount of this extrusive material. Even using the largest familiar units of volume they would run into orders which no mind is capable of comprehending. There are a half-dozen or more peaks rising from 5,000 to 10,000 feet above the plateau, and these are but stubs of former peaks which have been reduced by erosion.[1] A few of these are worthy of particular mention.

Orizaba, the "shining star" or "Citlaltepetl" of the Aztecs, is a majestic cone which rises from the eastern edge of the plateau to a height of 18,240 feet above the sea, and is visible 80 miles out from the coast.[2] Popocatepetl, the "smoking mountain," is built upon the plateau just south of Mexico City. It rises 17,520 feet above the sea and has a crater half a mile in depth and of the same diameter, from which steam and sulphur gases escape continually, proclaiming it not extinct, but dormant. Ixtaccihuatl, "the woman in white," raises its cone just east of Popocatepetl and to a height of 15,082 feet; and Toluca, called in the Aztec tongue Xinantecatl, and supposed to mean the "nude man," is situated just west of Popocatepetl and rises to a height of 13,000 feet.[3] The Cofre de Perote, or "Nahucampatepetl," to the north of Orizaba, rises to a height of 13,411 feet. Volcano Jorullo in Michoacan belongs to the third era of eruption, which will be discussed under the head of physiographic history, and although not situated on the plateau is a sort of "outlier" of this province. It rises from an amphitheater almost 3,000 feet below the level of the plateau.[4] Colima, on the western edge of the plateau, shows an altitude of 12,664 feet, while numerous other cones, somewhat lower, though scarcely less imposing, dot the plateau in many places. Most of the cones are of the "strato-volcanic" type and show plainly the several flows of which they were built.[5]

The volcanoes of Colima, Popocatapetl, and Orizaba are unique in that they consist of twin peaks, one with a crater and the other

[1] Hill, *Eng. and Min. Jour.*, LXXXV, 681–88.

[2] Melgareo, *Natl. Geog. Mag.*, XXI, 741.

[3] Melgareo, *loc. cit.*

[4] Ordonez, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 9.

[5] Hovey, *Science*, N.S., XXV, 764; T. Flores, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 9, p. 14.

without. The names used herewith are applied to the peaks with craters. Their accompanying craterless cones are known respectively as Nevado, Ixtaccihuatl, and Cofre de Perote. From a distance, Nevado appears to have a crater, but this is in reality but a furrow, produced jointly by the sinking of the lava crust and later erosion. The few geologists that have studied the phenomena have apparently avoided giving an explanation of the genesis of the craterless peak, and the single reference available does no more than cite the analogy between these and a type described by Stübel in Ecuador.[1]

Numerous basins, formed in constructional depressions in the volcanic surface, are scattered over the province. These abound in the environs of the city of Mexico. The city itself is situated in the so-called Valle de Mexico, which is an inclosed basin 50 miles long by 35 miles wide. This basin contains six shallow lakes and a considerable area of marshes. This marsh area is all the more unique and interesting when it is considered that it lies at an altitude a mile and a half above sea-level. The drainage of this basin, which is of the first order of necessity for sanitary living during the rainy season, was an engineering problem which defied successful solution for three centuries. Finally, in 1900, there was consummated a successful plan involving a seven-mile tunnel under the Xalpam Mountain, and an aqueduct over the Guadalupe River, by which the sewage and storm water of the city of Mexico is drained from the basin and emptied into a stream which carries it to the Gulf of Mexico.[2] Many of the basins are filled with water, forming lakes of considerable size, namely, Chapala, Quitzeo, and Patzcuaro, all in the state of Michoacan.

Among other interesting topographic features are the cinder cones and their crater lakes of the Valle de Santiago, and the pit craters of the state of Pueblo. The former are low cones of ash and breccia, eleven in number, the craters of which vary in diameter from 1,500 feet to one mile. The bottoms of some of these craters contain shallow lakes of clear, fresh water (*xalalpascos*). This

[1] P. Waitz, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 13, pp. 10–21.

[2] S. F. Emmons, *Science*, N.S., XVII, 309.

water is not derived directly from rainfall, but from a subterranean sheet flowing under the porous volcanic soil. The slopes of the craters, both interior and exterior, are frequently covered with green, cultivated fields.[1] These craters are generally regarded as having been produced by explosions caused by steam generated when superficial water came in contact with heated rocks below.[2] The basis of this opinion is the fact that the stratified basaltic flows and beds of tuff forming the plain in which these craters are discovered have not been disturbed profoundly, the eruptions appearing to have been strictly local.[3]

The pit craters of Pueblo are apparently similar features. These occupy the centers of cones which rise with very gentle slopes to slight elevations. They are from 3,000 feet to a mile in diameter, and average 150 feet in depth. On the floors of the craters are lakes of fresh water, and their walls show plainly the stratified volcanic beds of which the plain on which they stand is composed. In places are to be observed breccia-filled stream channels, buried under the eruptives which built the cones and formed the craters.[4] Their genesis is no doubt similar to that of the cinder cones described above, though no less an able geologist than Ordonez states that they seem unduly large for the explosive force which is generally regarded as having produced them.[5] Both types of phenomena are relatively recent features of the topography, and probably belong to the second period of vulcanism, to be discussed later.

The important drainage systems of this province are those of the Rio Grande de Santiago, the Rio Lerma, and the Rio Balsas of the Pacific slope, and the Rio Papaloapam with its tributaries and a few small streams of the Atlantic slope. The Rio Lerma is really the upper course of the Rio Grande de Santiago, which is divided about midway in its course by Lake Chapala. The two streams and the lake together form a watercourse about 800 miles in length, the largest in Mexico, if we omit the Rio Grande del Norte, having a drainage basin of about 60,000 square miles. In

[1] Ordonez, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 14.

[2] Hovey, *Bull. Am. Geog. Soc.*, XXXVIII, 730.

[3] Ordonez, *loc. cit.*

[4] W. M. Davis, *Science*, N.S., XXVI, 226.

[5] Ordonez, *Inst. Geol., Mex., Los Xalalpasgos del Estado de Pueblo.*

places its gradient is very steep. Near Guadalajara there is a beautiful falls with a sheer drop of 100 feet, and above La Juntas the stream descends 1,800 feet, over a series of cascades, in a distance of 15 miles.[1]

The structure of this province is difficult to determine, owing to the concealment of all early formations by the more recent extrusives. Where it has been possible to obtain data, however, it has been interpreted as follows: bedrock of massive Cretaceous limestones and shales, folded along east-west axes, badly faulted, cut by granitic intrusives, and covered by a great cap of lava and tuff.

This is the first province to be discussed where the structural trend is east-west. Ordonez thinks that the number and disposition of the volcanic craters along the Rio Grande de Santiago suggests the idea of its marking the line of an important fracture, corresponding to a place of dislocation in the general elevation of the plateau, and where it has brusquely interrupted its direction (northwest-southeast) and effected a movement in a different direction (east-west).

Physiographic history.—The early history of this province is similar to that of the rest of the plateau, as far, at least, as the making of the Cordilleran peneplain and the second uplift; beyond that it is obscure. We may infer, however, that the second erosion cycle had proceeded to the extent of cutting rather deep valleys in the sedimentaries before the first eruptions occurred. The first flows filled these valleys, leaving hills of sedimentaries standing out above them. Erosion continued, and in time these hills were reduced to valleys, and the lava-protected valleys became hills and mountains. Over the greater part of the province later vulcanism completely effaced all traces of these earlier events, and built the great volcanic plain and the peaks which now characterize the province, and it is only around its borders that this part of its history may be determined.[2]

It appears that there have been two periods of vulcanism in this province: the first in the Miocene and affecting all Mexico;

[1] H. A. Horsfall, *Eng. and Min. Jour.*, LXXXVIII, 665.

[2] Hill, *Eng. and Min. Jour.*, LXXIX, 410.

the second beginning in the Pliocene and continuing to the present time and limited to this province.[1] This second period appears to have been divided into three well-defined epochs: first, that which produced the high peaks and cones; secondly, that which produced the pit craters; thirdly, that which is manifested in the hot springs and geysers of the present time. Between the first and second epochs there was a time of lesser activity during which were produced the minor cones which have since been reduced to slight eminences.[2]

An exception is found in Colima, which according to the classifaction given would belong to the first epoch of the second period. This volcano has erupted at intervals during the life of the present generation. The eruptive material has not consisted of lava, but of glassy fragments of various sizes. It has been assumed that the eruptive forces at work during this latter epoch of activity have not been sufficient to overcome the altitude of more than 12,000 feet, and that therefore the lava rises to a much lower level in the crater and only the hot scoriae are ejected over the sides.[3]

As we have indicated, the second erosion cycle in this province was interrupted by widespread and long-continued vulcanism. Since the cessation of volcanic activity, erosion has again become the dominant factor in making the topography of the province. Shall we call this a continuation of the second cycle or the beginning of the third? Inasmuch as the topographic effects of the second erosion cycle were largely obliterated, and as early youth is manifested over a large part of the province, I believe we are justified in stating that a third cycle is beginning, and although it is by no means certain that the titanic forces which built up this area are exhausted, erosion seems to have the better of vulcanism in the contention for supremacy.[4]

THE SIERRA DEL SUR PROVINCE

Definition and boundaries.—This is the southernmost division of the old Mexican Plateau and is in all essential respects, save

[1] T. Flores, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 9.

[2] Ordonez and Aguilera, *op. cit.*, p. 80.

[3] J. M. Arreola, *Jour. Geol.*, XI, 749.

[4] Ordonez and Aguilera, *op. cit.*, p. 80.

the direction of its folds, a counterpart of the northern provinces, from which it has been cut off by the volcanic flows of the province, previously described. It would no doubt fall under the discussion of the Sierra Madre Occidental province were it possible to connect with that. The volcanic area, however, has completely isolated it, and it therefore requires separate treatment. It is an area of odd shape, aligned roughly with the folds, and lies between the volcanic area on the north and the Pacific Ocean on the south.

The northern boundary has been described, and for the greater part of its length is a natural dividing line separating two regions of widely different types of topography. The Pacific Ocean forms a natural southern and western limit and the remainder of the boundary line is drawn at the foot of the escarpment, where the edge of the plateau rises above the lowlands of the Isthmus of Tehuantepec. (Compare the accompanying sketch map, Fig. 1, with the Bartholomew topographic map previously referred to.)

Topography.—In the general literature of Mexican geology and geography this area is frequently described as though it were a part of the volcanic area. Such description is erroneous, however, for here again the characteristic feature of the topography is plateau dissection. It duplicates the erosional features of the northern provinces and is unaffected by the extrusions which characterize the Volcanic province.[1]

The interior is a labyrinth of mountain ranges trending in diverse directions, with here and there an occasional peak, more resistant than its neighbors or by its configuration less exposed to erosion agencies, rising to a height comparable to that of some of the volcanic cones.

On the Pacific side, head-working streams are rapidly degrading the plateau, leaving its front a tattered edge, with long headlands jutting out between the stream courses. The Rio Balsas, which in its upper course is known as the Rio Mexcala, is one of the most important streams in Southern Mexico, and drains a large portion of the interior of both this and the Volcanic province. The Rio Tehuantepec of the isthmian slope is remarkably straight in its lower course, and without tributaries there. In the upper course,

[1] William Niven, *Eng. and Min. Jour.*, XC, 672.

however, it is developing a typical dendritic system of drainage, and is rapidly dissecting the plateau in Oaxaca. The stream was probably originally consequent upon a fault rift in the steep slope of the plateau edge flanking the isthmus, but has since lengthened its course and developed a drainage basin by processes characteristic of subsequent streams.[1]

The structure on the whole is similar to that described for the northern provinces, namely, folded, faulted sedimentaries, overlain with superficial volcanic material, and intruded by various igneous bodies; but the trend of the folds here is generally east-west. Over the greater part of the province the Miocene volcanic cap has been removed, laying bare the metamorphosed sediments beneath. In addition to having the sedimentaries clearly exposed, we know the character of the actual basement rock—a condition which may only be surmised over the rest of Mexico. The basement rock in this province is Archean crystallines, which may be observed in the deepest canyons not far above sea-level and upward to positions on mountain flanks 6,000 feet above tide.

Physiographic history.—In the other Mexican provinces we were obliged to begin the history at the first post-Cretaceous cycle. Here, although we have Archean rocks determining the topography in places, history must again begin with the Mesozoic era, for the Paleozoic record is a blank. We have Mesozoic sediments resting unconformably on Archean crystallines. How many erosion cycles, or what length of time was necessary completely to remove all traces of Paleozoic rocks and carve deeply into the crystallines, is indeterminable. There is little evidence to warrant the belief that the Mexican Plateau was an island during the Paleozoic era, and consequently without marine sediments. Moreover, there are Paleozoic rocks exposed in small patches in Sonora, and again in Chiapas and Central America[2] and I believe we may safely infer that they once covered the entire plateau and were removed. After the uplift of the plateau following the deposition of the Mesozoic sediments, the history of this province becomes coincident with that of the northern provinces.

[1] Bose, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 31, p. 21.

[2] Hill, *Eng. and Min. Jour.*, LXXXIV, 63.

THE TEHUANTEPECAN PROVINCE

Definition and boundaries.—This province comprises an area of very old, low-lying rocks occupying the Isthmus of Tehuantepec. If we were to draw province boundaries on a basis of topography alone we should be obliged to include most of this area in the Gulf Coastal Plain province, for there is scarcely any difference in topography. But considering also structure and history, we are compelled to make this a separate province, with boundaries as indicated on the accompanying sketch.

It is bounded north and south respectively by the Gulf of Mexico and the Pacific Ocean. The greater part of the western boundary is the scarp of the plateau, which rises 8,000 feet above the isthmus,[1] while to the east the heights of Chiapas rise to an almost equal altitude.[2] Between these two highland areas lies the isthmus, like a great block dropped out of an arch.

Topography.—The isthmus is an area of low, rounded hills, with two regional slopes, the longer toward the north and the shorter toward the south, the two slopes meeting to form a divide at Tarifa Chivela. Both slopes are very gentle, and the maximum altitude at the divide is less than 800 feet.[3]

The drainage follows the regional slopes, regardless of structure, the Rio Coatzalcoalcos and its tributaries draining northward, and the Rio Geronimo, southward.

Physiographic history.—The oldest rocks exposed in this province are the Archean crystallines, in the vicinity of Tehuantepec. Farther up the slope at Chivela are metamorphosed sediments of probable Paleozoic age, and still higher, unaltered Middle Cretaceous and Upper Miocene. Down the Atlantic slope, Pliocene deposits grade into the Recent sediments of the coastal plain.

It may be a permissible figure to speak of the isthmus as a block dropped out of an arch, but as a matter of fact it will require us to postulate more profound changes than the mere dropping of a fault block to account for the peculiar structure of the isthmus.

[1] Hill, *Trans. A.I.M.E.*, XXXII, 163.

[2] Bose, *Guides des excursions, 10th Inter. Geol. Cong. Mex., 1906*, No. 31.

[3] Bose, *op. cit.*, profile sketch.

The low mountain chain running through Tarifa Chivèla is probably a spur of the Mexican Mountains—a southward extension of the Sierra Madre Occidental perhaps—that came into existence with the Cretaceous-Eocene uplift; the plicated and metamorphosed sediments are to us as a mutilated page torn from an important but now missing chapter in our historical account of Mexican physiography; and the low swells and undulations of the Atlantic slope are the result of the uplift and deformation that "constructed the bridge between the two American continents."[1]

Summing these events up in chronological order we may say that upon the fundamental Archean complex were deposited a series of Paleozoic rocks of unknown thickness and areal extent. These were so profoundly deformed as to become highly metamorphosed. Following the deformation came a period of erosion which probably continued until the Middle Cretaceous submergence. In other words, the pre-Mesozoic history of this province probably was coincident with that of the Mexican Plateau, of which the isthmus was no doubt an integral part. At the time of the uplift referred to a great structural movement took place which cut this province off from the remainder of the plateau, the place of rupture being still visible in the great scarp in Oaxaca. The dropping of the block on the east of this fault line brought about the inundation of what is known as the isthmus. The character and distribution of the Tertiary deposits would indicate that the submergence thus produced was not to great depths. In late Tertiary and early Quaternary time an orogenic movement took place which produced a second series of folds, and raised the isthmus above the sea. This movement is to be regarded as an event peculiar to Central America, at all events to that part of the country south of Oaxaca. The Mexican Plateau was not affected.

[1] Bose, *op. cit.*, p. 26.

REVIEWS

The Mississippian Brachiopoda of the Mississippi Valley Basin. By STUART WELLER. Monograph I, State Geological Survey of Illinois, June 10, 1914. Pp. 508, pls. 83, figs. 36.

In the introduction a brief description and classification of the Mississippian formations as shown along the Mississippi River and in adjacent regions is given. The formations recognized and described are as follows:

V. Chester group.
- Clore formation.
- Palestine formation.
- Menard formation.
- Okaw formation.
- Ruma formation.
- Paint Creek formation.
- Yankeetown formation.
- Renault formation.
- Brewersville formation.

IV. Ste. Genevieve limestone.

III. Merrimac group.
- St. Louis limestone.
- Salem limestone.

II. Osage group.
- Warsaw formation.
- Keokuk limestone.
- Burlington limestone.

I. Kinderhook group.
- Containing many formations more or less local in their geographical distribution.

Weller has submitted these Mississippian brachiopods to a rigorous, critical study and revision. The method of study by working out the internal anatomy had already been outlined in his paper on the "Internal Characters of some Mississippian Rhynchonelliform Shells.[1]

Since the literature on these fossils has long been in an unsatisfactory and incomplete condition, the revision and redescription of the known forms with the added new species and genera will be welcomed by all students of the fossils of the Mississippian rocks.

[1] *Bull. Geol. Soc. Amer.*, XXI (1910), 497-516.

"The present work is a start toward the publication of a series of monographs which it is hoped may eventually cover all the groups of organisms whose fossil remains are preserved in these formations." The scope of the present work is practically that of the Mississippian rocks of Illinois, Missouri, and Iowa, the typical Mississippian section.

All the genera and all the species are described and abundantly illustrated. More than that, all the old descriptions of species have been rewritten, "so that the usage of terms is uniform throughout."

There are 62 genera and 297 species described. Of this number 4 genera and 80 species are new to science. The limits of the genera and species are closely drawn throughout. However, they are no more closely drawn than is necessary to give a clear understanding of the anatomical relationships and to give proper stratigraphic value to a species. This does not necessarily imply that all the genera are limited to a few species, since there are 44 species of the genus *Spirifer* recognized as valid and described from the Mississippian rocks of the Mississippi Valley basin. The list of species described as new is given herewith, together with the critical characters of the new genera: *Lingula louisianensis*, *Leptaena convexa*, *Schuchertella fernglenensis*, *Schellwienella crenulocostata*, *S. chouteauensis*, *S. planumbonum*, *S. alternata*, *S. burlingtonensis*, *Streptorhynchus tenuicostatum*, *Chonetes missouriensis*, *C. chesterensis*, *Productella sublaevis*, *Productus mesicostalis*, *P. crawfordsvillensis*.

The genus *Echinoconchus* was erected for those species of *Productus* with "more or less sharply differentiated concentric bands which commonly grow broader in passing from the beak to the outer margins, each band bearing numerous, crowded, fine, appressed imbricating spines, either subequal or unequal in size, which are produced from elongate, node-like bases." *Productus punctatus* is the genotype. It so happened that a work entitled *The British Carboniferous Producti*, the first part, by Ivor Thomas, was issued on June 6, four days prior to the issue of Weller's monograph. In this memoir,[1] treating of the first part of the genus, apparently the same group of shells are gathered under the genus *Pustula*. If they are the same, this term, having priority, will be used instead of Weller's term given above. The genus corresponds with Waagen's section IV, *Fimbriati*, in a general way, as published in the *Salt Range Fossils, Brachiopoda*, p. 671. The species referred by Weller to the genus are: *P. alternatus*, *P. genevievensis* n.sp., *P. biseriatus*, *P. morbilianus*.

[1] *Memoirs Geological Survey, London*, I, Parts 2, 4, June 6, 1914.

Continuing with the new species: *Rhipidomella jerseyensis, R. tenuicostata, Schizophoria chouteauensis, S. Sedaliensis, S. poststriatula, Camerotoechia subglobosa, Allorhynchus acutiplicatum, Rhychotreta elongatum, R. missouriensis, Tetracamera missouriensis, Rhynchophora? rowleyi, R.? perryensis, Centronella louisianensis.*

Under the Terebratulidae a new genus, *Centronelloidea,* is erected. "In its external form this genus is like *Centronella,* but its brachidium is essentially like *Dielasma,* although the development of the crutal lamellae in the rostral portion of the brachial valve is entirely different from that genus." *T. rowleyi* is the only known species.

Cranaena globosum, C. sulcata, Dielasma chouteauensis, D. osceolensis, D. sinuata, D. inflata, D. illinoisensis, D. arkansanum, D. subspatulatum, Girtyella cedarensis, G. intermedia, Dielasmella calhounensis, Atrypa infrequens, Spiriferina saleminsis, Delthyris similis, Spirifer shepardi, S. platynotus, S. biplicoides, S. legrandensis, S. crawfordsvillensis, S. washingtonensis, S. pellaensis, S. breckenridgensis, S. marshallensis, S. floydensis, S. indianensis, S. maplensis, S. subrotundatus n. nom., S. gregeri, S. rowleyi, S. montgomeryensis, S. calvini, Brachythyris burlingtonensis, B. gurleyi, B. altonensis, Cyrtina inexpectans, Syringothyris bushbergerensis, S. newarkensis, S. platypleurus, S. solodirostris.

The genus *Pseudosyrinx* is erected "to include a group of spiriferoid shells with high cardinal area, punctate shell structure, and distinct delthyrial plate which differs from that in *Syringothyris* in the entire absence of a syrinx upon its inner surface." Genotype, *P. missouriensis.* Other species are: *P. keokuk* and *P. gigas, Spiriferina latior.*

The genus *Acanthospira* differs from *Spiriferina* in the possession of a non-punctate shell and the absence of a median septum in the pedicle valve. It differs from *Spirifer* in the possession of fine spines. The genotype and only species known is *A. rowleyi.* The remaining new species described are: *Martinia sulcata, Ambocoelia unionensis, Reticularia salemensis, Eumetria acutirostrata, Nucleospira rowleyi, Cleiothyridina glenparkensis, C. lenticularis, C. scitula, C. laevis, C. pentagona, and C. globosa.*

There is no table showing the range of these species through the rocks of the Mississippian formations. This table would be of great assistance to stratigraphic geologists and paleontologists as well. Indeed the reviewer was tempted to prepare one and insert it in the review, since many of the species have a very limited range. However, it will probably accompany a study of the Mississippian formations at a later date when it will be more appropriate. J. W. B.

"Features of Karakoram Glaciers Connected with Pressure, Especially of Affluents." By WILLIAM H. WORKMAN. *Zeitschrift für Gletscherkunde*, Bd. 8, 1913. Pp. 40, pl. 1.

Great relief, numerous large, high snow-fields, and a series of long, branching valleys reaching down from the uplands furnish the conditions in the Karakoram Mountains for a ramifying system of glaciers that exhibits phenomena lacking in most valley glaciers. The phenomena are chiefly connected with pressure, particularly that developed by affluent glaciers where they press down on their mains. The tremendous force of the tributary glacier, directed essentially at right angles to the direction of movement of the main glacier, forces the latter aside, but the affluent is shortly bent downward and moves parallel to the other glacier. The two glaciers crowd upon one another and are individually somewhat squeezed together, but they remain perfectly distinct, in some instances to a distance of 50 or 60 km. below the point of junction. Of particular interest is the union of the Siachen Glacier (4.4 km. wide, 40 km. long above this junction) and Tarim Shehr (3 km. wide, 25 km. long) which meet at an angle of about 140°. With much structural disturbance and a partial displacement of the main glacier, Tarim Shehr turns through 140° around a small promontory before it moves parallel to the main. Where the valleys are constricted the glaciers are notably narrowed, and the white ice tongues may completely disappear; but the glaciers do not spread to fill the wide parts of the valley.

Where the pressure of affluents on the main glacier is very great, the ice surface, especially along moraine-covered belts, is thrown up into rather irregular-shaped hillocks. Below the juncture of the two ice masses the hillocks become more pronounced, they are covered with piles of discrete débris, and become more or less united in a band parallel to the direction of ice movement; they are then termed "hillock moraines." Individual hillocks vary from 10 m. to 70 m. (exceptionally 150 m.) in height above the rest of the glacier. The moraine shows no evidence of having been pushed up from below or formed simply by differential melting. Transverse to the direction of pressure, white ice exhibits a series of long parallel ridges. Seracs have developed where there is a steepening of the gradient of the glacier beds, where the ice of Tarim Shehr impinges upon a plowlike promontory, and where constriction of the valley causes longitudinal crevassing. It is concluded that differential melting is an important agent in increasing the height of moraine-covered belts down the glacier. Vertical bands parallel to the direction of movement of the ice are to be noted in all the glaciers;

some vertical sections show extensive folding, faulting, and foliation of the ice strata.

It is concluded that pressure has had a very important rôle in determining variations in the course of the glaciers, surface forms on the glaciers, especially hillock moraines, stratification, and local deformation of the ice, and in the erosion accomplished.

R. C. M.

The Squantum Tillite. By ROBERT W. SAYLES. Bull. of the Museum of Comparative Zoölogy, Harvard College, Vol. LVI, No. 2, Geological series, Vol. X, 1914. Pp. 141–75, pls. 12.

The origin of the Roxbury conglomerate has always been a matter of doubt. It has been held by a number of geologists to be of glacial origin, while yet others have favored its marine derivation.

Robert W. Sayles in the present paper describes a bed of what appears to be tillite in the Roxbury series of Boston and vicinity. The Squantum tillite has a probable thickness of 600 feet and consists of sand, angular, subangular, and rounded pebbles and bowlders, and irregular fragments of slate. The size of the fragmental material varies from that of a sand grain to large, angular blocks, one bowlder having been found which has a length of 6 feet and a width of 1 foot. Practically all of the material is less than a foot in diameter, with the greater proportion less than 6 inches. All of these fragments are firmly cemented in a matrix of argillite. There are also intercalated beds of slate and conglomerate.

The criteria necessary for the recognition of tillite are enumerated and their application has been made to seventeen outcrops of this apparently glacial material. Mr. Sayles presents strong evidence in favor of the glacial origin of the Squantum tillite. The illustrated bowlders and pebbles have a subangular outline and also show fairly distinct striae. A striated bedrock has not been found, but this may be due to the nature of the underlying rocks, which are slates and sandstones.

In one locality the contact with the tillite and underlying sandstone was very ragged, the suggestion being made that the sand deposit, before having been firmly cemented, had been disrupted by violent movements of the ice.

The supposition is made that the movement of the glacier was from the southeast, and that as the advance took place into the Boston basin, the recently deposited beds of sand and clay were torn up and the fragments mingled with the débris of the glacier. The intercalated beds of slate, which become more numerous toward the top of the tillite, are indicated as representing successive lengthening of the periods of the ice retreat, the slate present above the tillite representing the final retreat of the ice, followed by subsidence and deposition.

The age of the Squantum tillite is given as Permo-Carboniferous, with a probability that because of the widespread Permian glaciation it may be Permian.

C. B. A.

"Die Gletscher des Sarekgebirges und ihre Untersuchung." By AXEL HAMBERG. *Sveriges geologiska undersökning*, Ser. Ca., I, 4:0, No. 5. Pp. 26 (4mo), pls. 4.

The Sarekgebirge are the largest range in Sweden and contain more than 100 glaciers. Increase of snowfall toward the west, lower temperature in the north, and elevation above the sea determines the location of the larger and greater number of glaciers in the high, northwest part of the range. Winds are very strong, so topography has a very important influence in the locations of snow-fields. At high altitudes, however, the work of hoarfrost (*Rauhfrost*) to some extent counterbalances the effect of the wind. Two types of glaciers are distinguished: (1) valley glaciers, mostly in young cirquelike valleys at the edge of the upland, ranging in length from a few hundred meters to 5 or 6 km.; and (2) plateau glaciers which form on the broadly undulating flat tops of some of the mountains. The latter are not like the convex surface *Inlandeistypus* of Norway. Cliff glaciers are present, also, in very subordinant number.

Experiments were made to determine the yearly snow accumulation at various points on some of the larger ice-fields. This was done by means of marked standards and showed:

At 1,200 m. elevation	0 accumulation = snow line
1,340 m. elevation	1.29 m. accumulation per year
1,440 m. elevation	2.16 m. accumulation per year
1,500 m. elevation	2.43 m. accumulation per year

Observations on the rate of melting at the surface of the glaciers were undertaken by means of bored holes, the bottoms of which were specially marked. This showed a very rapid decrease of melting with increased distance from the lower edge of the ice.

Dist. from glacier end (m.)	150	350	1,000	2,000
Elev. above sea (m.)	970	1,000	1,100	1,200
Melting in 1 year (cm.)	330	244	90	4

Measurements on a number of the larger glaciers of the rate of movement were made. These showed the differential movement in various parts of the individual glaciers and indicated a much greater speed of movement in the summer. Not any variation of importance has been observed in the position of the lower end of the larger glaciers in recent years.

R. C. M.

"Die Geomorphologie und Quartärgeologie des Sarekgebirges." By AXEL HAMBERG. *Geol. fören. förhandl.*, Bd. 32, Heft. 4, April, 1910. Pp. 25, map 1.

The Sarekgebirge (north Sweden) are made up of the following rocks:

4. Amphibolite (1,000–1,200 m.)
3. Syenite (350 m.)
2. Silurian beds (150 m.)
1. Basement complex

The topography shows a striking dependence on the structural relations and resistance of the rocks. As an example is cited the development of numerous falls where the easily eroded Silurian shales have been weathered from beneath the resistant syenite. The mountain massifs are mostly flat-topped, possibly indicating remnants of an old erosion surface. Large deep valleys have been cut in the amphibolite but not far into the syenite. This is doubtless due to the superior resistance of the latter, not to any interruption of a former drainage cycle.

The Sarekgebirge were almost certainly a center of ice dispersion in the early Pleistocene. The presence of erratics from some distance to the southeast indicates that the center of ice movement later changed in this direction. In the retreat of the ice there was apparently a time when the ice from the southeast was no longer able to move up the slope of the mountains, and lakes were formed between the valley walls and the edge of the ice. Shore-line phenomena, especially where the valley walls are less steep, mark the levels of these lakes, but because the outlet over the ice was continually and gradually lowered, the level of the lakes was inconstant, and instead of a few sharply defined beaches there are a large number of indistinct shore lines. Ice blocks left at certain places in the valleys seem to have determined in part the courses of certain glacial streams which are independent of the present topography of the valleys.

Glaciers are now the most important erosive agents in the Sarekgebirge. Because of the altitude, frost, ice, and daily temperature range have developed extensive rock-fields, or on steep slopes, large talus piles. Deltas have, in a number of places, been built in the lakes by the heavily mud-laden streams from the glaciers. As an indication of the immense amount of post-glacial filling may be cited the extinction of one or more considerable lakes by this process.

R. C. M.

A Geologic Reconnaissance of a Part of the Rampart Quadrangle, Alaska. By HENRY M. EAKIN. Bull. U.S. Geol. Surv. No. 535, 1913. Pp. 38.

This report takes into account the Rampart and Hot Springs district which include most of the triangular area between the Yukon and Tanana rivers west of longitude 150°, and a strip of territory on the north side of the Yukon that extends nearly to longitude 154°. The base of the geologic column is formed by a series of metamorphic rocks which consists of probable Silurian and Devonian limestones and schists, late Paleozoic greenstones (that contain some sedimentary beds), early Mesozoic slates, sandstones, and conglomerates, Cretaceous and older slates, quartzites, and schists. All of these beds are closely folded. The metamorphic series is overlain locally by Eocene beds which represent part of the notable fluviatile deposition of Eocene time, "evidence of which is widespread in Alaska." The strata are considerably folded and faulted. A good part of the region is mantled by Quaternary silt, sand, and gravel deposits. The silt is probably of glacial origin. The igneous rocks consist of probable late Paleozoic rhyolite flows, tuffs, and flow breccias, probably late Paleozoic basic flows, tuffs, diabase, glassy lavas, and tuffs, late Mesozoic or early Tertiary monzonite sills and batholiths with numerous dikes. Erosion occurred in post-early Mesozoic, post-Lower Cretaceous, post-Upper Cretaceous, and in post-Tertiary times. Placer gold is the only mineral of economic importance. The gold and silver production of the Rampart district is decreasing while that of the Hot Springs district is rapidly increasing. The largest output of the latter district was in 1911. The placer gold has been derived from quartz veins in the old metamorphic rocks, from carbonaceous beds, and from hematite deposits in the neighborhood of monzonite. The placers are of two types—those of present stream and those of terrace gravels. Pebbles of cassiterite occur with the gold in the Sullivan Creek placers but are not worked to any extent.

V. O. T.

"Untersuchung über Gletscherstruktur und Gletscherbewegung." By HANS PHILLIP. *Geologische Rundschau*, Bd. 5, Heft 3, März, 1914. Pp. 6.

The author has just completed observations on the arctic glaciers of Spitzbergen and the valley glaciers of the Alps and states he finds "banding a specific property of all ice-masses moving of themselves." Opportunity to observe the structure of these bands on the vertical faces at end and sides of a number of glaciers indicates a conformability of the bands to the shape of the valley containing the glacier; they are hence "trough-shaped." The bands are not formed by pressure analogous to that which forms slaty cleavage in rocks, for they are alternately of blue, compact ice and white, air-filled ice. Neither are they the original bedding of the snow-field for in certain instances this is seen in conjunction with the longitudinal banding. The bands are separated by deep cracks (*Rissen*) about 2 cm. wide and traceable for as much as 100 m. The cracks are from one-half to two meters apart and, like the bands, are trough-shaped. Careful measurement has shown a differential movement of the bands separated by the cracks. On the average this differential movement was 20 cm. in six weeks, with the greatest movement a short distance below the surface.

The writer concludes that the trough-shaped cracks between the bands indicate a differential movement of the bands. The movement along the cracks produces the white, air-filled bands by crushing the ice fragments. This conception of glacier movement is to be distinguished from the notion of movement by means of gliding planes (*Gleitfläche*) within the ice crystals.

R. C. M.

Corries, with Special Reference to Those of the Campsie Fells. By J. W. GREGORY. Trans. Geol. Soc. Glasgow, XV, Pt. I, 1912–13. Pp. 15, plates 2, figs. 4.

"Corries" (Scottish equivalent for "cirque," "Kar") are rounded amphitheater-shaped depressions with steep, smooth walls and flat floors. They have been explained (1) by glacial plucking at the head of small local glaciers during the last stage in the glaciation of a district, (2) by the action of a series of confluent waterfalls, each of which undercuts the rocks at its foot and leads to the erosion of a vertical cliff, and (3) by the alternate action of frost and thawing which disrupts the walls of the valley, while the floor is essentially protected from erosion by a covering of snow and ice. The typical corries of Balglass, north of Glasgow, are described, and their origin attributed partly to the preglacial erosion of confluent water-falls, partly to the disruption of the wall rocks during glaciation by the agency of frost and ice.

R. C. M.

"Kurze Übersicht der Gletscher Schwedens." By Axel Hamberg. *Sveriges geologiska undersökning*, Ser. Ca., I, 4:0, No. 5. Pp. 8; 1 large topographic map showing glaciers.

The glaciers of Sweden are found in the high mountain area that extends along the international boundary between Sweden and Norway and in the northern part of Sweden, chiefly in the provinces of Jämtland and Lappland. The most southerly glacier is found in latitude 62° 55′ N. The glaciers of the north may be divided into an east and a west zone, the latter including the larger and greater number of glaciers. This distribution has climatic significance. There is a larger snowfall north and west because of the lower temperature and larger precipitation from the winds from the Atlantic. It is noted that the snow line is quite rapidly lowered to the north.

At lat. 63° N. elevation of snow line = 1,355 m.
At lat. 66° N. elevation of snow line = 1,245 m.
At lat. 68°.5 N. elevation of snow line = 885 m.

Valley glaciers and plateau glaciers are distinguished; cliff glaciers are subordinate. A catalogue of the various glacier districts and the more important individual glaciers is given.

R. C. M.

"Nochmals zur Frage der Glazialbildungen in der Rhön. Erwiderung auf die Ausführung von A. Penck und Ed Brückner." By Hans Phillip. *Zeitschrift für Gletscherkunde*, Bd. 8, 1914. Pp. 4.

Philipp takes exception to statements made by Penck and Brückner relative to his report on cirques (*Kars*) of the Rhone Valley.

R. C. M.

VOLUME XXIV NUMBER 2

THE JOURNAL OF GEOLOGY

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FEBRUARY-MARCH 1916

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VOLUME XXIV NUMBER 2

THE

JOURNAL OF GEOLOGY

FEBRUARY-MARCH 1916

THE ACADIAN TRIASSIC

SIDNEY POWERS
Troy, New York

PART II

Gerrish Mountain.—Gerrish Mountain consists of a basalt flow capping Triassic sandstones (Figs. 20, 22). The sandstones on the west side of the mountain are horizontal, those on the east side dip northward at angles of 15° or less.

Opposite Moose Island is a cross-section of the basalt flow (Fig. 22), showing sandstone faulted against agglomerate on the west, with the agglomerate overlain by sandstone in one exposure; a columnar basalt dike east of the agglomerate, and probably separated from it by a fault; and red sandstone, east of the dike, overlain by a 3-foot bed of ash, above which is columnar basalt. The dike is 50 feet thick. It extends northward for some distance, but it is cut off on the south by a fault between the mainland and Moose Island. In either the dike, or the basalt flow, magnetite has been mined near Lower Economy.

The final exposure of Triassic basalt on the east, which may originally have been connected with that at Gerrish Mountain, is at Portapique Mountain, 12 miles distant, and north of Birch Hill (see Fig. 23).

Gerrish Mountain–Truro.—The broad lowland underlain by Triassic strata east of Gerrish Mountain is interrupted by a long strip of Carboniferous conglomerates and shales forming a high, rugged topography from Lower to Upper Economy, as shown in Figs. 19 and 24, rising 250 feet, or more, from the lowland on the south. The relation of the Triassic to the older rocks, as seen along the shore, is a fault west of Carr Brook, and an unconformity near Lower Economy (Fig. 25).

At the fault, the Triassic consists of very calcareous sandstones, containing conglomerate lenses and cross-bedding. Calcite has been introduced into the sandstone, forming dark-red concretions.

The unconformity near Lower Economy shows a basal conglomerate composed of subangular pebbles 1 to 3 inches in length, resting on upturned and leveled Carboniferous red shale. The shale within a foot of the contact is weathered into a clay, but this

FIG. 22.—The shore section along Gerrish Mountain, as seen from the eastern end of Moose Island. The Triassic sandstone, at the left, is faulted against a mass of agglomerate overlain by a capping of sandstone. The agglomerate is probably faulted against the dike of diabase, which has fed the basalt flow which caps the cliffs on the right. At the base of this flow is a bed of green ash, and beneath this is normal Triassic sandstone, with some shale.

weathering is of recent date. The basal Triassic conglomerate pebbles consist of slate, schist, quartz, and igneous rocks from the Cobequid Mountains. Above the basal conglomerate, which is 25 feet thick, are interbedded sandstones and conglomerates as seen in Fig. 26. It is 1,200 feet stratigraphically between the basal unconformity and the Gerrish Mountain basalt flow.

From Economy to Truro, Minas Basin is fronted by a comparatively low land underlain by practically horizontal Triassic sandstones, above which, in places, are Pleistocene gravels.

The northern contact is of importance because there is a question whether there is a fault or an unconformity. The exposures are confined to the steam valleys, and are quite unsatisfactory. It may be briefly stated that the relation is probably a fault as far as Chiganois River, with another fault from there to North River,

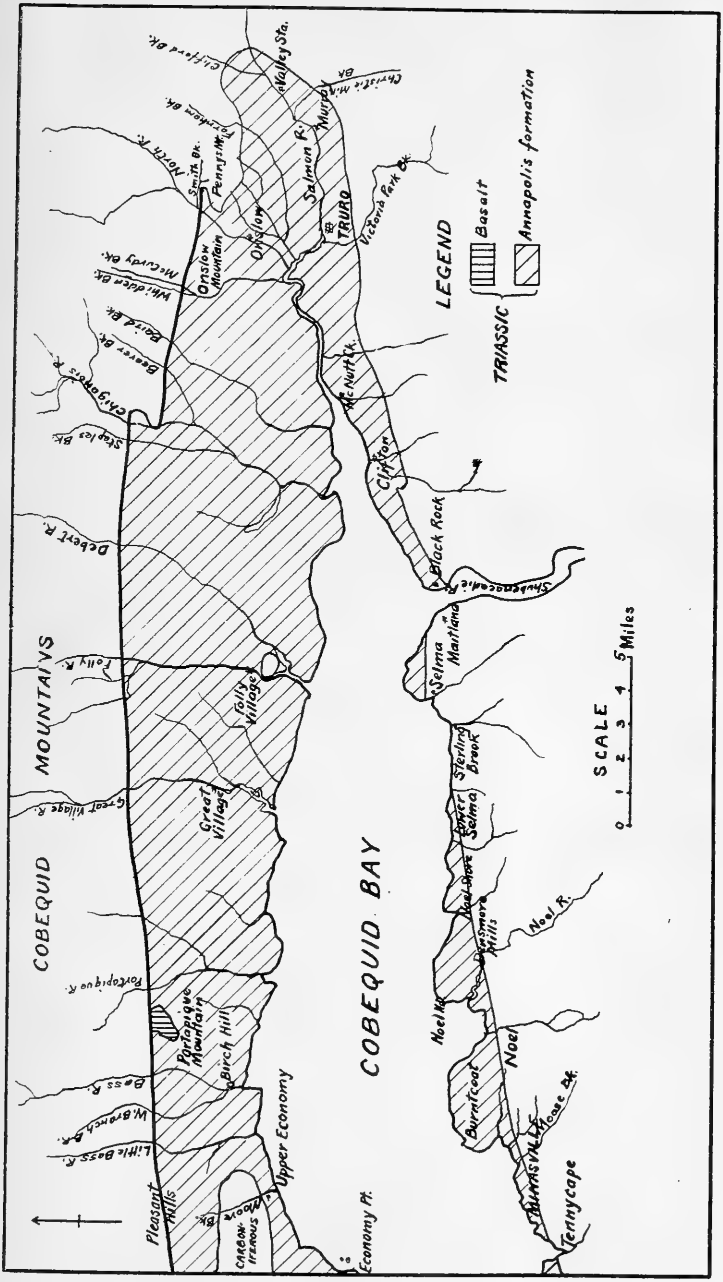

FIG. 23.—Map of the head of Minas Basin

as shown in Fig. 23. The evidences which favor this conclusion are the apparently dragged dips of the Triassic in several cases; and the lack of pebbles of adjoining older rocks in the Triassic conglomerates near by, and the actual fault seen in Harrington River on the west.[1]

At Birch Hill and at Folly Village, older rocks project through the Triassic strata according to Fletcher, who mapped both

FIG. 24.—The base of the Triassic at Minasville, showing the basal sandstones and conglomerates resting on horizontally trunkated Carboniferous shales. The character of the erosion surface indicates a peneplain, and the composition of the basal conglomerate indicates a lack of residual soil on this surface at the beginning of Triassic sedimentation.

localities with exaggeration of their size. There are reasons for questioning the existence of older rock at Birch Hill, but the copper prospect where these rocks are supposed to occur was not visited in the reconnoissance.

[1] Certain of the localities are described by H. Fletcher, *Geol. Surv. Canada, Ann. Rept.*, V (1892), 142–43 P.

At Folly Village, Mississippian fossiliferous limestone and gypsum, belonging to the Windsor group, appear on the northwest side of Debert River. The Triassic sandstones are very calcareous, and resemble the Windsor limestones, as both are red in color. It appears that the limestone is overlain conformably by the gypsum, and that these Mississippian strata are overlain disconformably by the Triassic red sandstones. With this view, the Mississippian is confined to a small area on the northwestern side of Debert River where fossils are readily found.[1]

Truro–Wolfville.—The end of the arm of Triassic in Minas Basin lies near Truro, and the relation of these to the older rocks

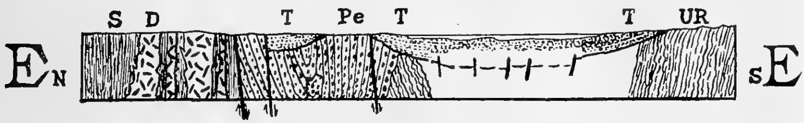

Fig. 25.—Section EE. Structure section through Minas Basin near Bass River, to show the unconformity of the Triassic on an island of Permian strata, Parrsboro formation, just north of the Basin. *SD*, Cobequid group; *UR*, Union-Riversdale series (Pennsylvanian); *Pe*, Permian. The major Cobequid fault is shown at the south of the Cobequid group. The closely folded syncline of the Parrsboro formation is in part overlain by Triassic sediments (*T*), which appear to be down-faulted on the north.

is an unconformity, as shown in Fig. 23. This unconformity is well exposed in Salmon River and in Victoria Park Brook (where there is also a fault). The underlying Carboniferous strata always show a beveled surface. This unconformity continues along the south shore of Minas Basin, and may be seen at Minasville, on the sides of Moose Brook (Fig. 24), at Tennycape, and at Walton. Over this area the Triassic sandstones show nothing unusual, except for calcitization north of Maitland.

West of Cheverie, the first exposure of Newark rocks is at Oak Island, north of Avonport (Fig. 3). On the east side of this island, quartz-pebble conglomerate and sandstone are exposed, overlain by stratified Pleistocene gravels, 6 feet thick, above which is Wisconsin till.

[1] This view differs from that of J. W. Dawson, *Acadian Geology*, 3d ed., 1878, p. 99.

North of Oak Island is Boot Island, which is separated from the mainland, called Long Island, by a narrow channel, formed within the last two centuries. North of this channel is a buried forest, exposed at low tide. North of Boot Island, and on the north side of Long Island, are exposures of red sandstones with occasional thin shales in which Dr. H. M. Ami reports the presence of *Estheria ovata*.[1]

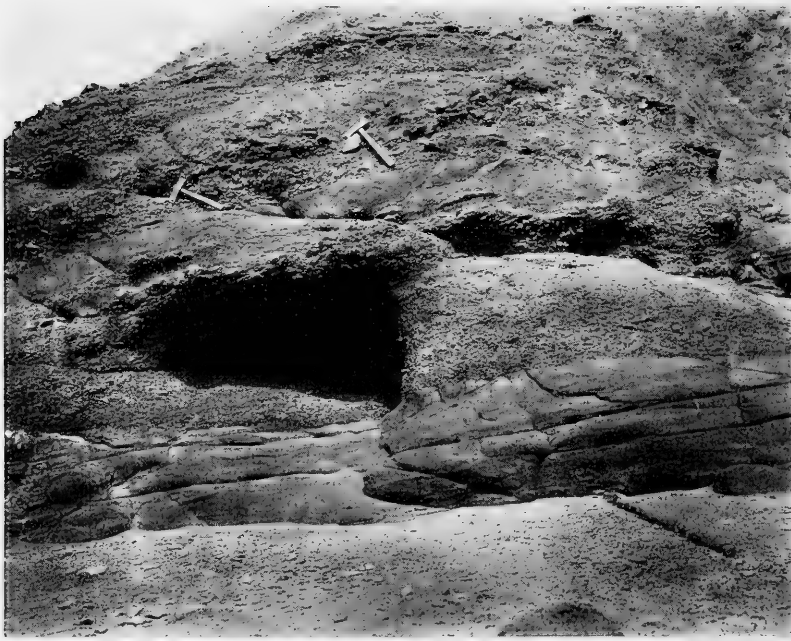

FIG. 26.—Details of the Triassic sandstone and conglomerate 30 feet above the base of the Annapolis formation, one mile east of Lower Economy.

At Wolfville the basal Triassic unconformity is exposed in a small brook west of the buildings of Acadia College, resting horizontally on upturned and beveled slates of the Meguma series.[2] The basal unconformity is again exposed at Kentville, just below the mill on Black River.[3]

[1] Verbal communication.

[2] The writer is indebted to Professor Ernest Haycock of Wolfville for pointing out this locality.

[3] J. W. Dawson, *op. cit.*, p. 92; L. W. Bailey, "Geology of Southwestern Nova Scotia," *Geol. Surv. Canada, Ann. Rept.*, IX (1898), 128 M.

Wolfville–Scots Bay.—The Wolfville sandstone outcrops on the exposed points between Wolfville and Pereau River, the most continuous exposure being near Kingsport. The sandstone contains occasional conglomerate beds and red shales. The proportion of shale to sandstone gradually increases toward Blomidon. The shale in this locality is largely a red clay, with occasional green bands, persisting horizontally throughout the exposure. The general dip of the strata is 5°–10° northward. Small faults are numerous.

About midway between Kingsport and Pereau River, Haycock found fragments of well-consolidated fossiliferous red shale in till, overlying the Triassic.[1] The fossils are *Estheria ovata*. Dipping under North Mountain are poorly consolidated Blomidon shales, with the characteristic thin green beds at distances of 10–20 feet.

The Blomidon shale continues around the hook of North Mountain beyond Cape Blomidon, but not as far as Amethyst Cove. At the latter locality, basalt cliffs, partly columnar, rise abruptly from the sea to a height of 300 to 400 feet. These cliffs are kept vertical by frost action on the vertical joint planes parallel to the shore.

Two basalt flows are visible at Amethyst Cove, dipping gently northward, with undulating folds. The collecting place for amethysts is in a greatly veined area about 100 feet below the top of the lower flow.

Scots Bay–Bennetts Bay.—In the region around Scots Bay there are two points of especial interest: first, the origin of the curve in North Mountain at this point, and, secondly, the presence of the Scots Bay formation overlying the North Mountain basalt along the southeast side of the Bay. Furthermore, the structural evidence furnishes a clue to the former thickness of the younger formation.

The curve in North Mountain is formed in a syncline pitching down to the west, and in the nose of this syncline Scots Bay has been eroded (see Figs. 27, 28). The basalt flows of North Mountain dip toward the Bay on all sides at angles of 3°–5°. The topographic

[1] E. Haycock, "Fossils in the Boulder-Clay of Kings County, Nova Scotia," *Trans. N.S. Inst. Sci.*, X (1901), 376–78.

slope follows the dip slope closely, beveling it slightly. At the water's edge there is no sea-cliff, but merely a sheet of basalt (where exposed) sloping upward from the shore. Farther southwest along North Mountain there are low sea-cliffs, but the general dip-slope persists to the end of Brier Island. The crest of North

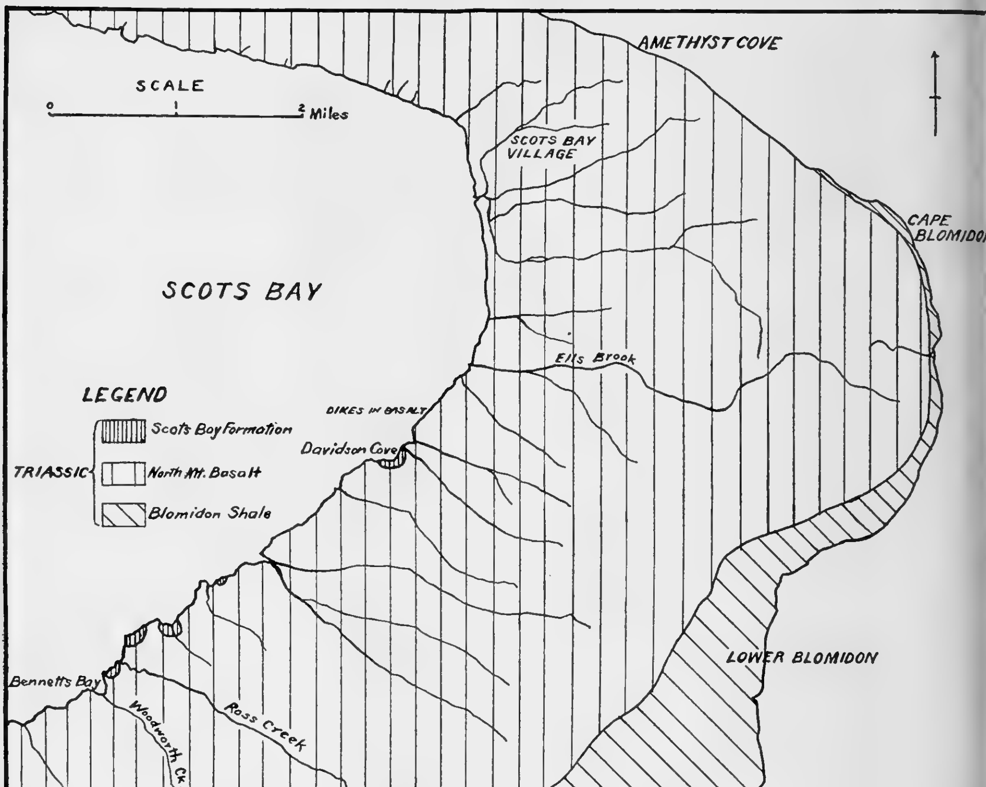

FIG. 27.—Map of the Scots Bay–Cape Blomidon region

Mountain is a mile or two southeast of the Bay of Fundy shore. It is a uniformly rolling surface which bevels the tilted basalt flows and forms a remnant of the Summit peneplain.

Around Scots Bay the top of the uppermost basalt flow is marked by a green amygdaloidal layer in which the amygdules are one-half to three-quarters of an inch long. This amygdaloid outcrops on the shore from Bennetts Cove to Ells Brook (Fig. 27). From this point to the north shore of the Bay there are no outcrops. Along the north shore toward Cape Sharp, the amygdaloid has been eroded, exposing the solid basalt beneath. In places this basalt is columnar, and in other places it contains balls, a foot or more in length, composed of dense basalt surrounded by amygdaloidal rims. The balls are not sufficiently abundant for the basalt to be called a pillow lava.

The younger, sedimentary formation, named for its occurrence on the south side of Scots Bay, the Scots Bay formation, has a thickness of 25 feet. It was discovered by Ells in 1876, and described by him[1] and later by Haycock.[2] It consists of white, very calcareous sandstone, quite distinct in color from any other Triassic sandstone of Acadia, with some interbedded shale and normal sandstone.

The Scots Bay formation outcrops in five small synclines between Scots Bay and Bennetts Bay (formerly called Woodworth Bay). These small remnants rest conformably on the basalt, contrary to the opinion of Haycock, and are preserved in small synclines in the basalt. They extend southeast only a few hundred feet, as the topographic slope of the

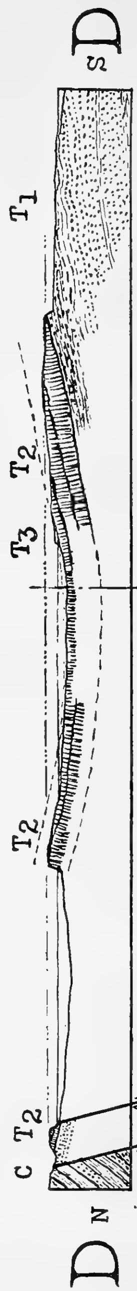

Fig. 28.—Section DD. Geologic cross-section through Cape Sharp on the north; Cape Split, Scots Bay, and Cape Blomidon, on the south. *C*, Carboniferous; T_1, Triassic, Annapolis formation; T_2, North Mountain basalt; T_3, Scots Bay formation. The vertical scale from Cape Split southward is exaggerated to show the overlying Scots Bay formation which is only 25 feet thick. The level of the Summit peneplain is shown by the line with three dots and a dash, the top of the flows of North Mountain by the finely dashed line. The area between these two lines must have been filled with the Scots Bay formation at the time the Summit peneplain was developed.

[1] R. W. Ells, "Notes on Recent Sedimentary Formation on the Bay of Fundy Coast," *Trans. N.S. Inst. Sci.*, VIII (1894), 416–19.

[2] Ernest Haycock, "Records of Post-Triassic Changes in Kings County, Nova Scotia," *ibid.*, X (1900), 287–302.

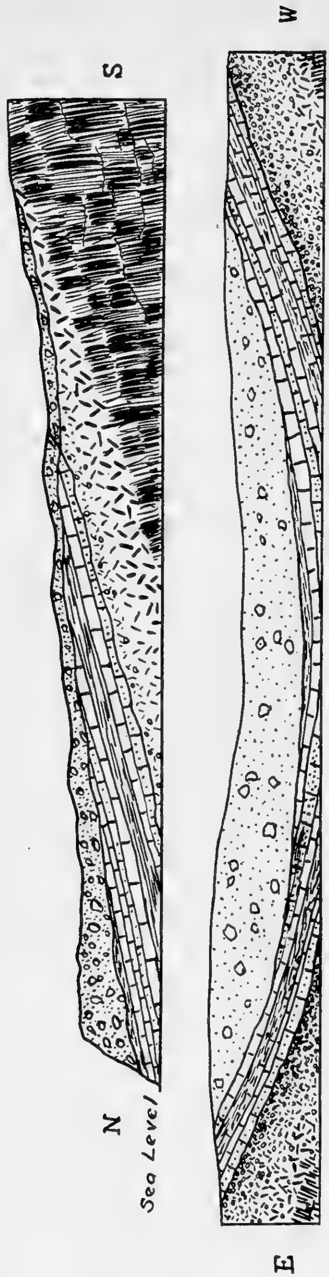

FIG. 29.—Structure sections of a syncline of the Scots Bay formation, lying conformably over the top of the North Mountain basalt. Above the Scots Bay formation is till, filling the pre-Wisconsin valley. The top of the upper flow is very amygdaloidal. The basal beds of sandstone have been replaced by chert.

mountain cuts across them and the flows at a low angle. These synclines are shown in Fig. 27.

The Scots Bay formation consists of calcareous white or gray sandstone, frequently replaced by chert, and greenish sandstone or shale. The exposures are nowhere over 15 feet in thickness (Fig. 29) and are remnants of a formation which once filled the syncline of Scots Bay up to the level of the Summit peneplain, as shown in Fig. 28. The white sandstone, or chert, rests directly on the amygdaloid at the top of the basalt flows, and veins of chert run downward from the sandstone into the amygdaloid. The beds in any one syncline do not match exactly with those in any other, but this condition is to be expected in basal beds of which only a few feet are shown, on the irregular top of a lava flow.

Fossils have been found in the calcareous sandstones by Haycock. They consist of faint green markings, probably plant remains; worm burrows; fish scales, bones, coprolites, and other fragments of fish. The coprolites are from 1 to $1\frac{1}{2}$ inches in length, an inch wide, and half an inch thick. In 1913, Haycock found a portion of the head of a fish which has been identified by Mr. L.M. Lambe as the Triassic genus, *Semionotus fultus* (Agassiz).

Digby Gut.—Between Kentville and Digby Gut there are few outcrops of the Annapolis formation and no cross-sections of the North Mountain basalt. The best cross-section of the latter is at

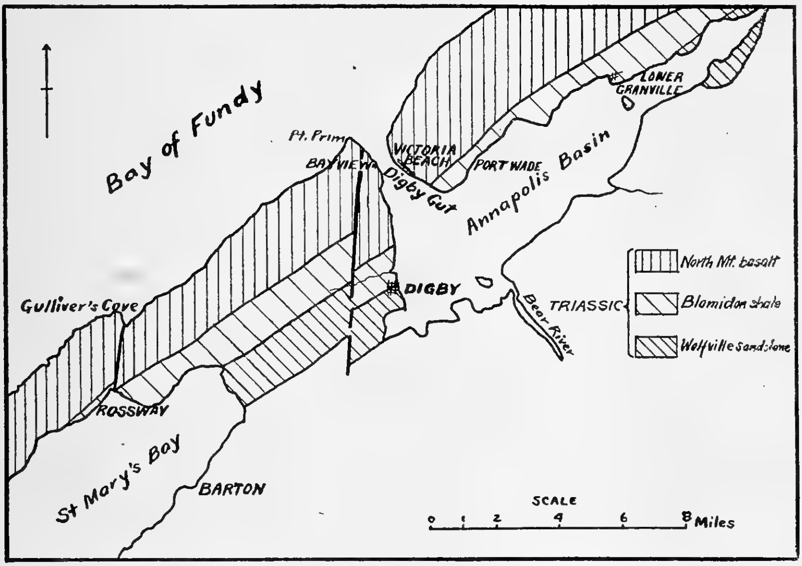

FIG. 30.—Map of the Digby-Rossway region

Victoria Beach, on the east side of Digby Gut (Fig. 30). The exposures on the west side of the Gut are disturbed by faulting.

The section of North Mountain basalt, except the lower flow, which appears at the side of Digby Gut, commences on the Bay of Fundy shore, where 7 flows may be seen (see Fig. 31), each having a thickness ranging from 2 to 45 feet. All the flows dip toward the Bay of Fundy at a low angle, as seen in Fig. 32, but this uniform slope is in places interrupted by minor folds. The presence of a low syncline and the lack of exposures make the exact thickness of the lower flow uncertain, but it is probably about 600 feet.

Faults occur at right angles to the axis of North Mountain, at Digby Gut and at Bay View (Fig. 33). The physiographic evidence of these faults is seen in the offset of the North Mountain basalt, and in the valleys along the fault-lines.

On the shore of Annapolis Basin near Port Wade, and at Digby, there are exposures of slightly cemented sand, containing blocks

FIG. 31.—Five lava flows of North Mountain at Digby Gut, as seen north of Victoria Beach, on the northeast side of the Gut. The upper flow is the third from the top of the series as exposed.

of basalt, which were considered by Bailey to be of Triassic age, and to underlie the basalt flows of North Mountain.[1]

These beds are of post-Wisconsin age, because of (1) the lack of consolidation, except very locally; (2) the yellow color, like ordinary stream gravels (unlike any Triassic deposit except the

[1] L. W. Bailey, "Triassic (?) Rocks of Digby Basin," *Trans. N.S. Inst. Sci.*, IX (1898), 356–60; also "Geology of Southwestern Nova Scotia," *Geol. Surv. Canada*, IX (1898), 126 M.

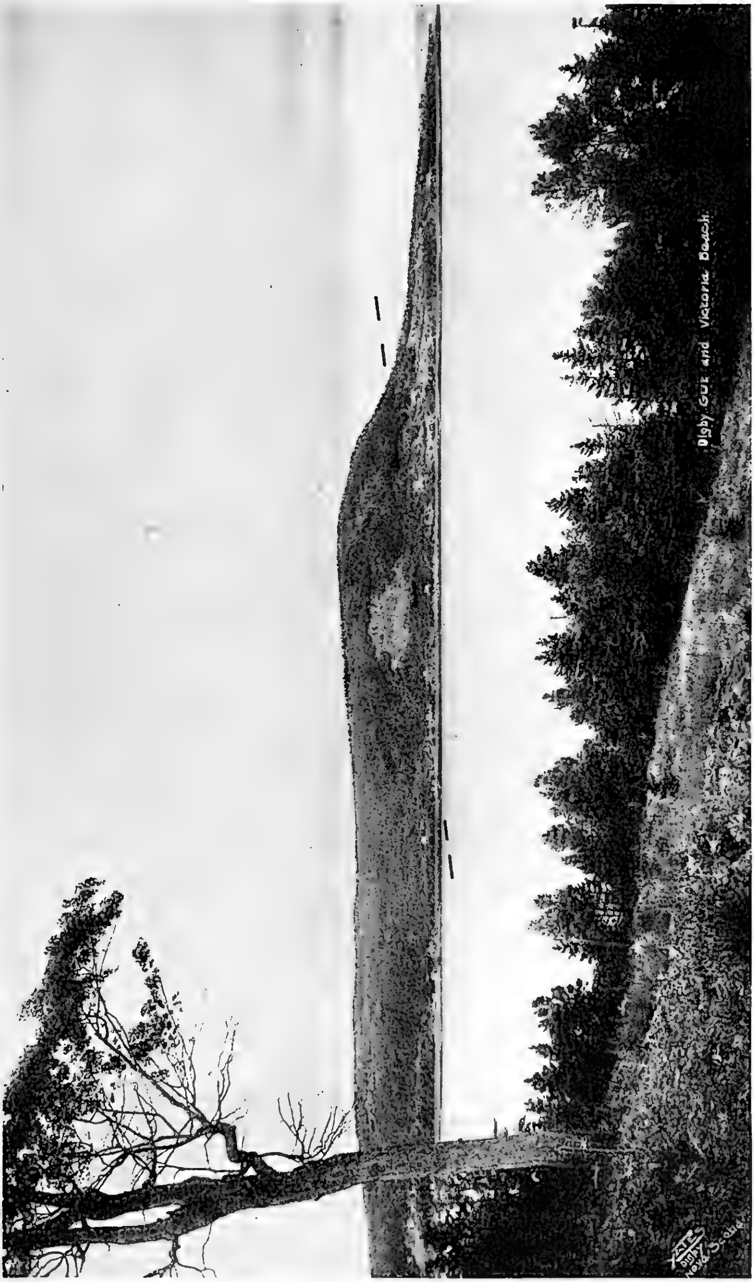

Fig. 32.—The section through North Mountain on the northeast side of Digby Gut. The village of Victoria Beach is seen on the opposite shore. North Mountain consists of basalt flows dipping to the north at approximately the angle seen in the dip-slope at the extreme left. The base of the flows is just beneath the landslide on the mountain near the center of the picture (as shown by dashes). Below and to the right of this landslide is red shale which has been weathered back to produce the escarpment on the south side of North Mountain.

Quaco conglomerate); (3) the lithological character and the lack of green laminae; (4) the delta character of the deposit at Digby; (5) the basalt fragments decreasing in number with increasing distance from the talus of North Mountain basalt; (6) the horizontality of the stratification (the red and green Triassic shales near Victoria Beach dip northward at an angle of 3°).

Rossway–Brier Island.—At Rossway on St. Mary's Bay (Fig. 30), there are excellent exposures of red shale, with occasional green beds and red sandstone beds, comprising the Blomidon shale. Rossway and Gulliver's Cove are connected by a valley which marks a north-south fault similar to that at Bay View. The displacement of the fault may be seen at Gulliver's Cove, in columnar basalt. No thin flows are shown here, or along Digby Neck to Brier Island.

The Blomidon shales at Rossway have a thickness of about 500 feet. They dip northward at angles up to 10°. No other shales in the Acadian Triassic are as well consolidated. Ripple marks, current undulations, cross-bedding, and rarely mud cracks are seen in the shales.

On the shore of Digby Neck, west of Rossway, the shales are exposed for a mile, dipping under the basalt. Half a mile west of the first exposure are Pleistocene clays containing black lignite and basalt fragments. This clay may have been deposited in the post-Wisconsin submergence.

Digby Neck, Long and Brier islands show in common a depression in the center of the ridge, parallel to the strike of the lava flows. This depression marks the amygdaloid at the top of the lower flow, as portions of but two flows are shown above the sea. No sedimentary rocks are shown on the St. Mary's Bay side west of the exposure near Rossway.[1]

Cross-faults are shown between Digby Neck and Long Island, and between Long Island and Brier Island. Another fault probably occurs between Brier Island and the submerged ledge on the

[1] A. Gesner described red sandstone exposed off Brier Island at low tide, but he probably mistook either the red seaweed or a hematite stain over basalt for sandstone (*Remarks on the Geology and Mineralogy of Nova Scotia*, Halifax, 1836).

FIG. 33.—Digby Gut and Digby from the foot of South Mountain. The top of North Mountain, in the distance, marks the Summit peneplain. The arrow on the left points to the notch which marks the Bay View fault. The arrow on the right points to Digby Gut, which was probably formed on a similar fault-line. The block between the arrows stands relatively nearer Digby than the remainder of North Mountain on the left, because the downthrow of the cross-faults is on the southwest.

west. Beyond this ledge there is no evidence of the existence of any Triassic rocks.

AGE

The age of the Newark group must be determined by a comparison of its fauna and flora with that of Europe where the Triassic system is well developed. As forms common to both countries are not abundant, there are slight differences of opinion as to the exact correlation. Table I gives a correlation scheme which is modified from one given by Eastman.[1]

Trias	Great Britain	Germany	Eastern U.S.
	Rhaetic	Rhaetic	
Upper	Keuper marl Keuper marl (Upper Keuper sandstone)	Upper } Keuper Middle } Keuper Lower } Keuper	Newark group
Middle	Lower Keuper sandstone	Lettenkohle Upper } Muschelkalk Middle } Muschelkalk Lower } Muschelkalk	
Lower	Upper variegated sandstone Pebble beds Bunter sandstone	Buntersandstein	

On the evidence of the fish fauna Eastman[2] concludes that the Newark is to be correlated with middle and upper divisions of the Alpine Trias (the Upper Muschelkalk–Middle Keuper of the German section). The plants indicate a similar age, and several forms have been cited as the equivalent of the Lettenkohle forms of Germany.

In the Acadian area the fossils which have been found are: plant remains at Split Rock (Gardner's Creek), Quaco, and Martin Head, New Brunswick; fish remains in the Scots Bay formation at Scots Bay; and impressions of the shells of bivalved crustaceans in drift material from the Blomidon shale, found near Kingsport.

[1] C. R. Eastman, "Triassic Fishes of Connecticut," *Conn. Geol. and Nat. Hist. Surv., Bull. 18*, 1911, p. 26.

[2] *Ibid.*, p. 29.

The plant remains were described by Dawson[1] from poorly preserved material as *Dadoxylon Edvardianum.* They consist of silicified plant-stems and of lignite, showing pith-casts. At Gardner's Creek and at Vaughan Creek (Quaco), the material is largely silicified, and appears to have been transported some distance. At Martin Head, lignite is exposed in several horizons and is quite abundant. Silicification has not replaced the plant tissues to such an extent as in the other localities.

The Martin Head locality is the only one where material is available for study. Miss Holden has recently examined the lignite, and found two species of plants.[2] The form which was assigned by Dawson to the genus *Dadoxylon* has been found to be identical with *Voltzia coburgensis* Schaur., from the Lettenkohle and Lower Keuper of Germany. The other form is *Equisetum rogersii*, Schimper, which has been described by Fontaine from the Virginia Triassic.[3]

The correlation of these forms is also considered by Miss Holden. The *Voltzia* is apparently the same as the form described by Newberry as *Palissya* from the New Jersey area,[4] and as the form *Cheirolepis* from New Jersey and Virginia. The *Equisetum rogersii* is probably identical with *E. columnaris*, described by Bronn, from the Lettenkohle.

Fragmentary fish remains have been found by Haycock[5] at Scots Bay in the calcareous sandstones overlying the basalt. Recently further collections have been made by Professor Haycock and the material has been identified by Mr. L. M. Lambe, of the Geological Survey of Canada, as probably *Semionotus fultus* (Agassiz), a form common to the other Newark areas.

[1] J. W. Dawson, *Acadian Geology*, 3d ed., 1878, p. 108; also, *Notes and Addenda*, p. 99.

[2] Ruth Holden, "Fossil Plants from Eastern Canada," *Annals of Botany*, XXVII (1913), 248–54.

[3] W. M. Fontaine, *U.S. Geol. Surv., Mono. 6*, 1883.

[4] J. S. Newberry, *U.S. Geol. Surv., Mono. 14*, 1888.

[5] E. Haycock, "Records of Post-Triassic Changes in Kings County, Nova Scotia," *Trans. N.S. Inst. Sci.*, X (1900), 287–302.

In fragments of shale found in the drift near Kentville, by Haycock, are impressions of *Estheria* of two slightly different types, both of which must be provisionally called *E. ovata*. The shale fragments were evidently derived from the Blomidon shale, and they are very similar to some of the hard barren shale exposed at Rossway.

The paleontological and paleobotanical evidence proves that the Acadian area is a part of the Newark system, and further shows a pronounced similarity between the Newark and the Lettenkohle of Germany.

[*To be continued*]

NOTES ON RIPPLE MARKS

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In a paper on ripple marks, recently published in the *Journal of Geology*, by Dr. E. M. Kindle, the opinion is expressed that the size of ripple marks may bear some relation to the depth of the water in which they were formed. Entertaining the same idea, I have on various occasions taken notes on the size of ripple marks. That most ripple marks vary in size with depth of the water seems to me hardly to admit of a doubt. Ripple marks from 3 to 4 inches in width appear to be most common. They are often to be seen in thoroughly sorted beach sands of all ages, from the Cambrian up to the Pleistocene.

In the Lower Comanchean, in Pecos County, in Texas, I have found some ripple marks of very small size, the smallest I have seen, with one exception. These were noted at several points in some thin-bedded layers of sandstone of fine texture. These sandy layers are interbedded with clays and limestones. A piece of this ripple-bedded rock is shown in Fig. 1, in natural size. Twelve ripples measure together 3 inches across, making an average of one-fourth inch for each ripple, from crest to crest. The depth of the troughs measures about one twenty-fifth of an inch. These ripple marks are symmetrical. A rough mechanical analysis of the sand in this rock is as follows:

Diameter of Grains in Millimeters	Percentages by Weight
1/8 –1/16	80
1/16–1/32	20

Two years ago I found ripple marks of the same size, or possibly slightly smaller, forming in some fine sandy silt in the Rio Grande, in Webb County. The silt had been washed up on some large blocks of sandstone, which were strewn in the channel of the river. It lay in shallow depressions on these rocks, and the water covered the ripple marks from a half to one inch deep. The wind stirred the surface of the water gently into small waves, and the ripple marks in the sand were seen to be building, under the influence of these waves.

Fig. 2 shows some ripple marks in a fine silty sand of the marine Jurassic, near Minnekahta, South Dakota. They measure $1\frac{1}{3}$ inches from crest to crest and have an average depth of fifteen-hundredths

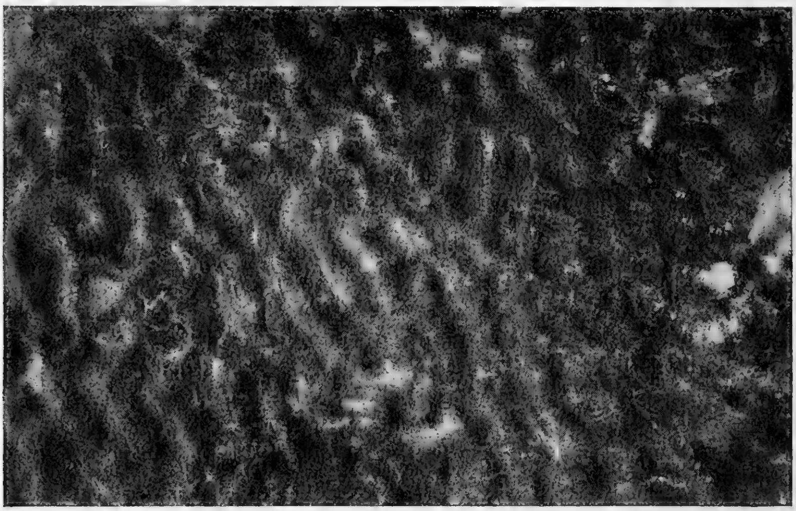

FIG. 1.—Ripple marks in Comanchean sandstone, from Pecos County, Texas. Natural size.

of an inch. These ripple marks are unsymmetrical, their longer slopes bearing the average ratio of 152 to 100, to the shorter slopes. A mechanical analysis of the sand in this rock was found to be, roughly, as follows:

Diameter of Grains in Millimeters	Percentages by Weight
1/2 –1/4	Trace
1/4 –1/8	55
1/8 –1/16	30
1/16–1/32	15

Some large-sized ripple marks occur in the Ordovician dolomites at Utica, in Illinois. In the old entries where cement rock long ago was mined for the Utica Cement Works, some ripples have been disclosed that measure from 4 to 5 feet across from crest to crest. This is in a somewhat thin-bedded dolomite, which contains some sand. Evidently this limestone was not a shallow-water deposit. The ripple-bedded layers lie some 100 feet below the base of the St. Peter sandstone.

The widest ripple marks that have come under my observation are in a crinoidal limestone in the lower part of the Burlington,

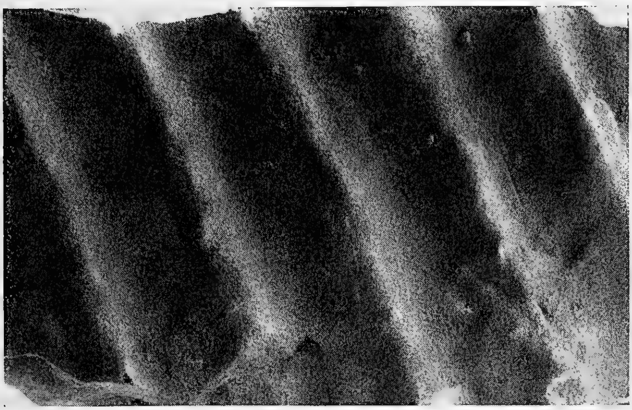

FIG. 2.—Ripple marks on Jurassic sandstone, near Minnekahta, South Dakota. One-half natural size.

in the southeast part of Louisa County, in Iowa. These ripples measure nearly 6 feet from crest to crest, and are at least 6 inches deep. The presence of crinoidal remains in this rock, which contains some shaly material, indicates, if not proves, deep-water conditions. How deep?

Higher up in the geological column I have seen some quite large ripple marks in the Comanchean, in Texas, in a horizon near the Kiamitia clay. About 17 miles west-southwest from Kerrville such ripple marks occur in the bed of Guadalupe River (see Fig. 3). They measure about 14 inches across and are about $1\frac{1}{2}$ inches deep. They are slightly unsymmetrical. The rock in this case is a mixture of calcareous and shaly material, which contains variable quantities of fine sand, so that some layers might more properly be called sandstone. The same horizon is exposed in the bottom of Bosque River, at Clifton, 155 miles northeast from the locality just mentioned, and again some 6 miles north of Clifton in the same beds in the same stream. Some layers of limestone here show ripple marks that measure 4 feet across, near Clifton (see Fig. 4), and from 2 to 3 feet across at the northernmost locality (Fig. 5). The lime-

FIG. 3.—Ripple marks in thin-bedded sandy limestone in the bottom of Guadalupe River, about 17 miles southwest of Kerrville, Texas.

stone layers here are compact and quite pure in composition, but are interbedded with marly shales.

Perhaps it may be permitted to submit some general remarks anent the phenomena of ripple marks. They shall be brief. Ripple marks must be due to rhythmic variations in currents in the medium of sedimentation. They are in this respect kin to wavelike etchings, known to be caused by rhythmic movements of corrading currents. Perfectly symmetric ripple marks are probably the result of to-and-fro movements of equal extent in both directions, when these movements are such that the velocity of the motion happens to be sufficiently strong to move material of the coarseness present where the rhythmic motion prevails.

On the bottom of any billowy water, sufficiently shallow for the size of the waves, there must be a to-and-fro motion for each passing wave. For waves of the same size, the deeper the water the more slow and the more limited will this motion be. Hence the less will

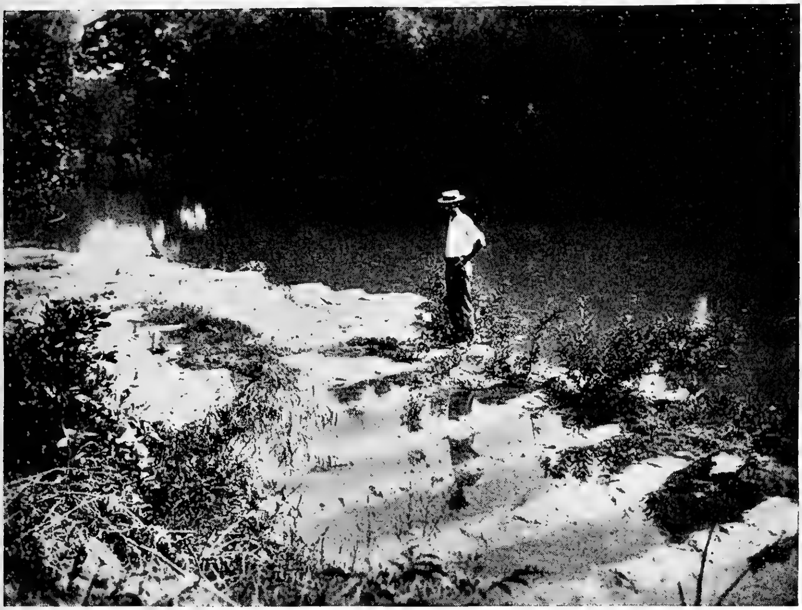

FIG. 4.—Ripple marks in Comanchean limestone in the right bank of Bosque River, near Clifton, Texas.

be the diameter of the particles it will be able to stir. There must be a certain depth where the motion will be just speedy enough to stir particles of silt. Where the bottom lies at this depth, and where it is covered with silt, ripple marks will form. Should not their width be determined by the extent of the to-and-fro movement in each direction? This decreases downward according to a known law.

It is evident that the velocity of each to-and-fro movement on the bottom of an agitated body of water begins with zero, rises to a momentary maximum, and falls again to zero. For particles of different sizes, there must be different times of duration of speeds attaining and exceeding the respective limits effective for their transportation. This time, and hence the latitude of this effective translatory motion, will increase with the fineness of the stirred sediment. With waves of one and the same size, and with the

FIG. 5.—Ripple marks in Comanchean limestone in the bed of Bosque River, about 6 miles north of Clifton, Texas.

same depth of water, the width of ripple marks should be greater in fine sediments than in coarse. The currents producing them will carry fine elements farther than coarse. With waves of the same size ripple-mark building in sand should then also take place in somewhat more shallow water than ripple-mark building in silt.

Some ripple marks must be produced by a wavelike or rhythmic motion which results from a reaction by the transported material on translatory bottom currents in water and in the air. No surface billows in the atmosphere can have anything to do with ripple marks in dune sands. Do dune-sand ripple marks vary in size with wind velocity and coarseness of the sand? They do not vary very much. May ripple marks be formed by a like reaction with bottom currents in deep water? If so, their variation in size may also be small. Such ripple marks, like those in sand dunes, should always be unsymmetrical. Their sizes are probably independent of depth of the water.

PYROPHYLLITIZATION, PINITIZATION, AND SILICIFICATION OF ROCKS AROUND CONCEPTION BAY, NEWFOUNDLAND

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INTRODUCTION

This paper embodies the results of a study of the regional and local alterations which have affected a series of volcanic rocks lying around the borders of the head of Conception Bay, on the Avalon Peninsula of Newfoundland. The field work was accomplished by the writer as a member of the Princeton Geological Expedition in Newfoundland during the summers of 1913 and 1914, in connection with a general study of the pre-Cambrian rocks of this region. The writer is indebted to the Geology Department of Princeton University for facilities for studying these rocks in the field and laboratory; to Dr. C. H. Smyth for supervision in the preparation of the report; to Professor G. Van Ingen for the photographs with which this paper is illustrated and for his interest in the work. The numbers used in this report refer to specimens deposited in the museum of Princeton University.

LOCATION

Regional alterations, such as silicification and chloritization, have affected the volcanic series wherever they outcrop, either in the area here under consideration (Fig. 1), or at other points to the north, such as Clarenville on Trinity Bay or Goose Arm on Bonavista Bay. The local alterations, comprising pyrophyllitization and pinitization, have affected the volcanics only in limited areas; the former being exhibited in a long narrow strip of rocks south of Manuels and the latter in outcrops to the north of the monzonite stock at Woodfords and in minute amounts associated with the pyrophyllite rocks at Manuels.

STRUCTURE

The volcanic series forms the lowest member of the Algonkian rocks in this region and has been mapped as Huronian by Howley (1907). The volcanics at the head of Conception Bay outcrop on

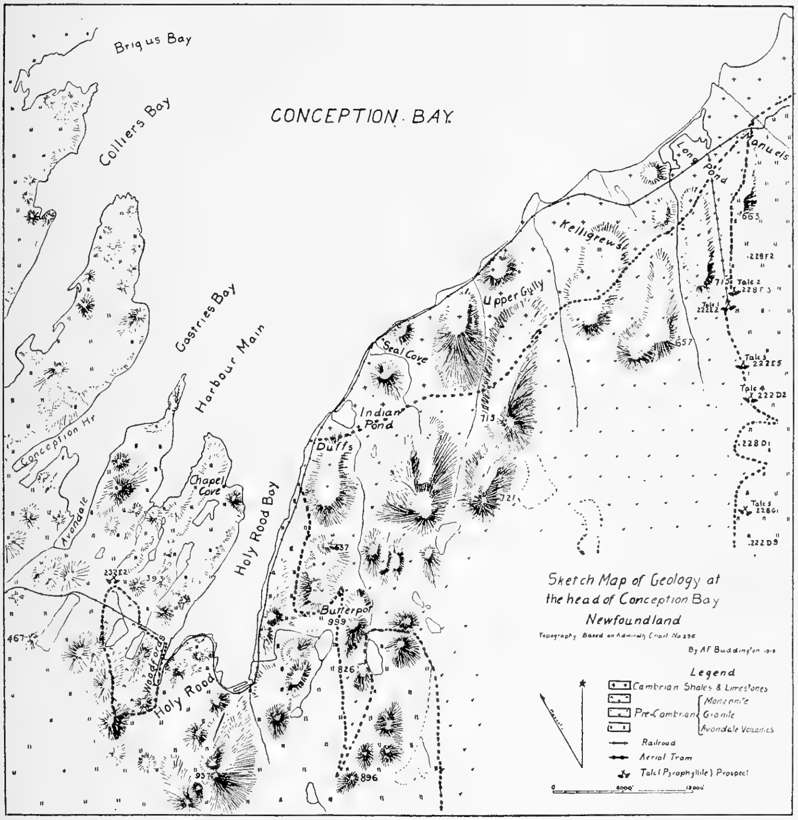


FIG. 1.

the core of a major anticline, the eastern limb of which has been intruded by a huge batholith of granite. On the west side of Holyrood Bay they are also intruded by a stock of monzonite. The rocks are in addition excessively disturbed by profound and intensive faulting, and usually dip steeply.

There is a strong probability that the line of contact between the granite and volcanics at Manuels marks the approximate locus of a fault zone. For at talc prospects 3, 4, and 5 the volcanics are faulted against either granite or green slate beds, and at prospect 3 the granite adjacent to the fault plane is silicified and pyritized and the rhyolite is silicified and carries traces of pyrophyllite. The pyrophyllite veins in turn are offset by small cross-faults.

CHARACTER OF VOLCANIC SERIES

The volcanics comprise a thick series of rhyolite and basalt flows with corresponding interbedded breccias, crystal tuffs, and tuffs, and a minor amount of waterworn material. The evidence with respect to their origin all points to their having accumulated under subaerial conditions.

TOPOGRAPHY

The topography developed on the volcanics at Manuels is that of a long, narrow, more or less barren plateau about 600 feet above sea-level. The volcanics at the head of Conception Bay are carved into a series of rugged isolated hills or ridges with differential elevations of from 200 to 1,000 feet. Glaciation during the Pleistocene period had a marked effect on the superficial features of the country, and many of the outcrops were scraped and polished by this agency.

WALL ROCKS OF THE PYROPHYLLITE VEINS

The pyrophyllite is confined almost exclusively to the rhyolite flows. Occasionally, however, pockets are found in the rhyolite breccias and conglomerates, but none at all occurs in any of the other rocks. The rhyolite flows exhibit three characteristic structures: flow or banded, spherulitic, and elliptical or lenticular. The spherulites may range in size from micro-spherulites visible only with the high powers of the microscope to huge spheroids as big as a man's head or even larger. They are usually more or less replaced by quartz of chalcedony. The elliptical structure has been called such because of its appearance on the weathered surface of the rock, where it shows as an assemblage of rude ellipses, or as lenses surrounded by a more or less schistose material which may be pyrophyllitized (Fig. 2). The ellipses vary from several inches to a foot in the direction of their longest axis. At talc prospect 5 a rhyolite showing this structure also contains scattered spherulites. This structure is characteristic of the white rhyolites of this area and may owe its origin to primary flowage phenomena, or to secondary dynamic forces, or probably to the former accentuated by the latter.

DESCRIPTION OF PYROPHYLLITE

The pyrophyllite veins are of such an extent that they attracted attention as a source of talc; many prospects were opened in the

Fig. 2.—Lenticular structure in rhyolite. The material surrounding the more massive portions is partially pyrophyllitized.

deposits and a 2½-mile aerial tram was built to the nearest mine. But, owing probably to the difficulty in separating the pyrophyllite from the admixed quartzose nodules, all work has been abandoned since 1904.

The pyrophyllite where it replaces rhyolite flows, as it does almost exclusively, is a soft cryptocrystalline, light greenish-yellow rock with a waxy luster and a good cleavage parallel to the schistosity. In one case where it replaces the matrix of a volcanic conglomerate it is a light brown and in another where it replaces the matrix of a volcanic breccia it is cream colored.

The pyrophyllite may occur either as single well-defined veins, or as a series of veins, pockets, and lenticels, which together constitute what may be called a pyrophyllitic zone.

The former character is illustrated at talc prospect 5, where the pyrophyllite forms a vein about 500 feet long and varying from 6 to 15 feet in width in a white, densely spherulitic rhyolite. Near the one end of the vein which is exposed the pyrophyllite is full of nodules and stringers of the rhyolite, but becomes almost clear pyrophyllite in its central portion.

The latter character (pyrophyllitic zone) may be illustrated by the character of the pyrophyllite deposits at talc prospects 1 and 2. The country rock of the pyrophyllitic zones may be so altered as to constitute a quartz-pyrophyllite schist consisting of microcrystalline quartz and pyrophyllite, as at talc prospect 1, or it may be partially pyrophyllitized, as at talc prospect 2, or relatively unaltered as at talc prospect 4.

At talc prospect 1 large masses of pyrophyllite occur in pockets from 1 to 15 feet in diameter containing more or less country rock, or as thin sheets incasing lenses of quartz-pyrophyllite rock oriented parallel to the cleavage. It frequently occurs as an interlacing network of films veneering lenses of the quartz-pyrophyllite rock or as lenticels replacing the matrix between adjacent quartzose nodules. The pyrophyllite (222 *E* 2 *f* *x*) usually serves simply as a matrix for these nodules varying from a fraction of an inch to several feet in diameter, and even hand specimens are infrequent which do not contain one or more of them. Ramifying stringers of country rock may wander aimlessly through the pyrophyllite (Fig. 3) and veins of pyrophyllite reticulate in the country rock. It is quite possible that the nodular structure originated through the total replacement by pyrophyllite of the sheared zones between lenses of a rhyolite like that shown in Fig. 2, and the alteration of the lenses themselves to a quartz-pyrophyllite rock. On the west side of the talc mine here small pockets of cream-colored pyrophyllite, weathering green or yellow, are found replacing the matrix of a very coarse rhyolite breccia.

At talc prospect 2 there is a pyrophyllite zone about 30 feet wide in which pyrophyllite constitutes from a small percentage to one-half of the rock. Paralleling this zone at a distance of about 20 feet is a pyrophyllite vein 18 feet in width with a 3-foot stringer and many spheroids of altered rhyolite wall rock in its central portion. The spheroids vary from an inch to a foot in diameter, but average about 4 inches. A lenticular or elliptical structure (Fig. 2) characterizes the rhyolite adjacent to the vein and the schistose matrix of the lenses or ellipsoids is partially pyrophyllitized. A few hundred feet north of here a light brownish pyrophyllite is

FIG. 3.—View of portion of pyrophyllite vein, showing intermingling of pyrophyllite and country rock. *p*=pyrophyllite; *q*=quartz-pyrophyllite.

found replacing portions of the matrix of a white rhyolite conglomerate.

DESCRIPTION OF PINITE

At Manuels the pinite is a relatively rare constituent and is interesting only from the viewpoint of its origin. It is best exhibited at talc prospect 5 and at a point marked 228 *D* 1 on the map. Fig. 4 is a photograph taken at this latter locality and represents the matrix of a spherulitic rhyolite (228 *D* 1 *h*) replaced by dark-colored pinite. The spherulites here average about 1 inch in diameter and are so intermingled with smaller ones as to make up almost the entire bulk of the rock. The pinitized groundmass possesses a waxy luster, dark dirty-green in color, and is quite soft. The parting of the pinite is in general parallel to the cleavage of the rhyolite, although in detail it is a series of curving shell-like scales, owing to its parting following the circumference of the more resistant spherulites. An analysis of this matrix is given in this

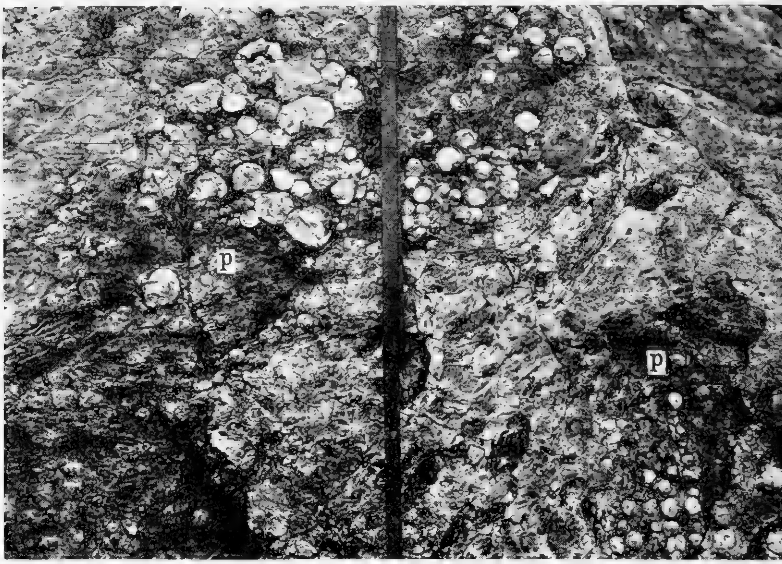


FIG. 4.—Pinite (*p*), replacing portions of the matrix of a spherulitic rhyolite

Journal on p. 137 (No. 7). Very rarely pinite is found along the original contraction cracks of the spherulites or at the heart of a spherulite. Patches, lenticels, and minute veins of pinite are found throughout the rhyolite flows and agglomerates, often replacing the matrix of spherulitic zones (228 *G* 1 *k*) or certain flow lines (222 *E* 2 *x*).

In the valley of Harbour Main Brook, among a series of rhyolite flows and tuffs, tuff beds up to 75 feet thick have been partially altered to pinite, and spherulitic rhyolite flows up to 30 feet thick are streaked and banded with pinite. These rocks have been prospected to depths of 15 and 20 feet, probably under the misapprehension that they carried pyrophyllite. A chemical analysis of the pinitized groundmass of the spherulitic rhyolite is given on p. 137 (No. 8).

CHEMICAL ANALYSES

Chemical analyses of eight typical rocks showing the various types and some of the stages of the alterations and replacements which have affected the volcanics are here given. These analyses were recalculated to correspond approximately to the mineral composition of the rocks. Small amounts of water of absorption, iron oxides except in No. 7, excess alumina, etc., have been lumped together as such under "other constituents." This involves of course a slight but inappreciable error in the proportions of the other minerals. It is probable that some sericite is also present in rocks Nos. 3 and 4, but owing to the difficulty of distinguishing sericite from pyrophyllite under the microscope, and because of the fact that the decrease in potash with an increase in water

TABLE I

SHOWING CHARACTER OF ALTERATIONS OF RHYOLITE

	1	2	3	4	5	6	7	8
SiO_2	76.24	80.60	74.51	72.10	65.04	88.09	54.47	61.07
Al_2O_3	13.94	11.27	17.12	21.51	29.49	9.53	27.14	22.99
Fe_2O_3	0.89	0.89	1.28	0.54	0.28	0.20	2.58	1.56
FeO	0.13	0.08	0.08	n.d.	n.d.	n.d.	0.47	0.42
MgO	0.27	0.31	0.04	0.04	0.04	0.05	2.44	0.65
CaO	1.07	0.66	0.13	0.49	0.10	0.58	0.81	1.63
Na_2O	2.55	1.16	0.48	0.42	0.33	n.d.	0.68	0.63
K_2O	4.95	4.68	3.68	2.21	0.33	n.d.	8.01	7.58
H_2O+	0.15	0.49	2.44	3.09	4.84	1.68	3.44	2.93
H_2O-	0.03	0.11	0.09	0.23	0.03	0.04	0.27	0.23
MnO	Trace	Trace	Trace	n.d.	n.d.	n.d.	0.09	0.17
	100.22	100.25	99.85	100.63	100.48	100.17	100.40	99.86
Sp. G.	2.64	2.64	2.73	2.77	2.83	2.70	2.82	2.70

1. Unaltered dark-gray flow rhyolite (228 *D* 1 *c*).
2. Silicified drab spherulitic rhyolite (228 *F* 2).
3. Pyrophyllitized rhyolite. Matrix of lenses; talc prospect 2 (228 *F* 3).
4. Pyrophyllitized rhyolite. Matrix of spherulite; talc prospect 1 (222 *E* 2 *j*).
5. Pyrophyllite. Light greenish-yellow waxy pyrophyllite from talc prospect 1 (222 *E* 2 *f*).
6. Quartz-pyrophyllite schist. Nodule in pyrophyllite (5); talc prospect 1 (222 *E* 2 *g*).
7. Pinite; dark dirty-green waxy, matrix of spherulitic rhyolite. Manuels (228 *D* 1 *h*).
8. Pinite schist. Matrix of spherulitic rhyolite, Harbour Main (232 *E* 2 *b*).

indicates that the replacing mineral is pyrophyllite, it has been calculated as that alone. Owing also to the liability of error involved in assigning the elements of the pinitic rocks to the correct minerals in the right proportions, only a rough estimate of their mineral composition is given. The iron oxides and magnesia of No. 7 must be present as an integral part of the white mica molecule, as no other mineral except quartz can be distinguished in thin section.

TABLE II

RECALCULATED ANALYSES

	Quartz	Orthoclase	Albite	Anorthite	Pyrophyllite	Other Constituents	White Mica
1......	39.6	29.4	21.4	5.2	....	4.4	....
2......	53.7	27.8	9.9	3.1	....	5.5	....
3......	28.3	21.7	4.2	0.6	43.6	1.6	....
4......	18.7	13.3	3.6	2.5	61.1	0.8	....
5......	1.3	....	....	....	91.8	1.6	5.3
6......	65.7	....	....	....	33.4	0.9	....
7......	Present	....	....	....	....	....	About 75 per cent
8......	Present	Present	Present	....	....	....	About 60 per cent

PETROGRAPHY

No. 1 (228 *D* 1 *c*). This specimen was taken near the top of a 50-foot banded reddish-gray felsite flow. In thin section the texture varies from microfelsitic to very minutely microcrystalline and the flow lines are marked by hematite dust. The flow lines are sharply curved and crenulated and several are replaced by quartz, especially in the loops of the curves, so that the rock analyzed as representing the composition of the original rhyolite only approximates such an unaltered condition.

No. 2 (228 *F* 2). This rock is a drab to fawn-colored microspherulitic rhyolite with secondary iron oxide in veinlets and specks. In thin section the groundmass is a finely microcrystalline aggregate of quartz and orthoclase, with fan-shaped microspherulitic areas. Secondary quartz is present as grains and lenses, as well as replacing portions of the spherulitic aggregates. A minute amount of sericite and quartz occurs along fractures.

No. 3 (228 *F* 3). This specimen, a pyrophyllitized rhyolite, was taken from the slightly sheared matrix surrounding lenses of white rhyolite (Fig. 2) adjacent to pyrophyllite veins at talc prospect 2. In thin section the rock shows as a microcrystalline aggregate of granular quartz and feldspar and of scales and fibers of pyrophyllite in about equal amounts.

FIG. 5.—Perlitic structure preserved in pyrophyllitized rhyolite. Ordinary light, ×60.

No. 4 (222 *E* 2 *j*). This is the matrix, a pyrophyllitized rhyolite, in which a 6-inch spherulite was found essentially unaltered. In thin section the rock consists of an aggregate of very minute microscopic scales of pyrophyllite, complete except for a remarkably well-preserved perlitic structure, outlined by microcrystalline quartz with probably some orthoclase (Fig. 5). The rock is in a much more advanced stage of alteration to pyrophyllite than the preceding specimen.

No. 5 (222 *E* 2 *f*). Light greenish-yellow pyrophyllite with a fair cleavage. In thin section the rock is seen to be composed of a homogeneous felt of exceeding minute microscopic scales and fibers of pyrophyllite, with a strong tendency toward a very good alignment parallel to the cleavage in a section at right angles to it and with long, parallel, fibrous shreds in a section approximately parallel to the cleavage.

No. 6 (222 *E* 2 *g*). A white quartzose nodule or lense of quartz-pyrophyllite schist about 1 foot in diameter taken from a pyrophyllite vein at talc prospect 1. In thin section the rock presents what might be called a micro-blotchy groundmass composed of aggregates of either microcrystalline quartz or of scales of pyrophyllite. Some fibers of pyrophyllite also occur interstitially in the quartz areas.

No. 7 (228 *D* 1 *h*). This is the dark grayish-olive, waxy-lustered matrix of the spherulitic rhyolite illustrated in Fig. 4. In thin section the rock is seen to consist of an aggregate of extremely fine shreds and scales of white mica with lines of partially replaced microcrystalline quartz which are probably replacements of certain of the original rhyolite flow lines not yet entirely replaced by the white mica.

No. 8 (232 *E* 2 *b*). Grayish-olive pinite schist with small unaltered spherulites or spherulites partially replaced by quartz. In thin section the material appears as a perlitic microcrystalline groundmass of quartz and orthoclase partially replaced by sericite. The perlitic cracks are outlined by threads of sericite fibers, as illustrated in Fig. 6, and they often form the boundaries of serocitized areas which present the appearance of eyes, sometimes with a reticulating network of sericite veins connecting two adjacent eyes. Within the sericitic material, isolated microspherulites, clusters of microspherulites, and long axiolites are often preserved intact. A few phenocrysts of orthoclase are present and are remarkably fresh, although occasionally flecked with sericite. The secondary material consists of an aggregate of microscopic sericite scales and fibers associated with grains and areas of secondary quartz. Minerals originating through decomposition at the surface are completely absent except for a trace of iron oxides in the groundmass and a slight cloudiness in the feldspars, probably due to kaolin.

PRELIMINARY SILICIFICATION

The first process of alteration which operated on the Avondale Volcanics was that of regional silicification. On these preliminary silicified rocks a local series of alterations, those of pyrophyllitization, pinitization, and further local silicification, were superimposed.

FIG. 6.—Perlitic structure preserved in pinitized rhyolite. Ordinary light, ×35. *m*=microspherulites; *p*=pinite.

This is evidenced by the following data: (1) few later quartz veins are found traversing the pinite, quartz schists, or pyrophyllite; (2) fragments of breccia in the volcanic breccias often exhibit quartz veins which stop abruptly at the contact with the matrix, and (3) under the microscope aggregates of sericite scales are found replacing granular quartz which had previously replaced the heart of a spherulite, and these sericite scales finger into and inclose unreplaced fragments of quartz, proving definitely their later origin.

The spherulitic rhyolites are the rocks which exhibit most clearly the manner in which the silicification has taken place. The silica here is present for the greater part as a milky-white chalcedonic quartz, but vitreous, granular, and white vein-like quartz as well as quartz crystals are common. The chalcedony usually forms the outer borders of the concentric crescent-shaped areas, and of the hearts of the replaced zones of the spherulites, while the inner portion may be recrystallized to form comb structure through the interlocking of quartz crystals, or little geodes with terminated crystals projecting into a small cavity, or granular vitreous quartz. When only one form of the silica is present it is very generally of a chalcedonic nature. It is interesting to note that while at Manuels it is the spherulites of the rhyolites which are most generally replaced, at Clarenville it was the groundmass which was replaced instead of the spherulites, because of the perlitic structure of the former offering the most favorable surfaces for attack. The banded rhyolites are often lined or streaked with quartz veins parallel to the planes of flow, which in some cases are a result of replacement and in others of vein filling. In thin section, lenses, lines, and granules of secondary quartz are found to be a common characteristic of the slightly silicified banded flows. Fig. 7 illustrates the preservation of the perlitic structure in the quartz which is replacing the groundmass of a spherulitic rhyolite from Clarenville. The perlitic cracks are outlined by sericite.

That the silicification of the rhyolites has been due to secondary metasomatic processes and is not a primary phenomenon is indicated by (1) the interruption of fluxion lines by the replacing quartz, (2) by the presence of unsupported fragments of unreplaced rhyolite in the quartz areas, and (3) by the preservation in the quartz of original structures of the rhyolite, such as the perlitic structure.

The first stage then in the alteration of these volcanics has consisted in the silicification under relatively static conditions by hot siliceous waters of rhyolite flows which may be represented as having had a similar chemical composition to the present relatively unaltered gray felsites. Analysis No. 1 may be taken as the composition of the original rock from which the silicified rhyolite represented by analysis No. 2 has been derived.

Chemically this has resulted in a decrease in the percentages of potash, soda, lime, and alumina, an increase in the percentage of silica, and a relative decrease in the percentage of sodium with respect to potassium. The process operated through the replacement of the feldspars by quartz and a relatively more rapid

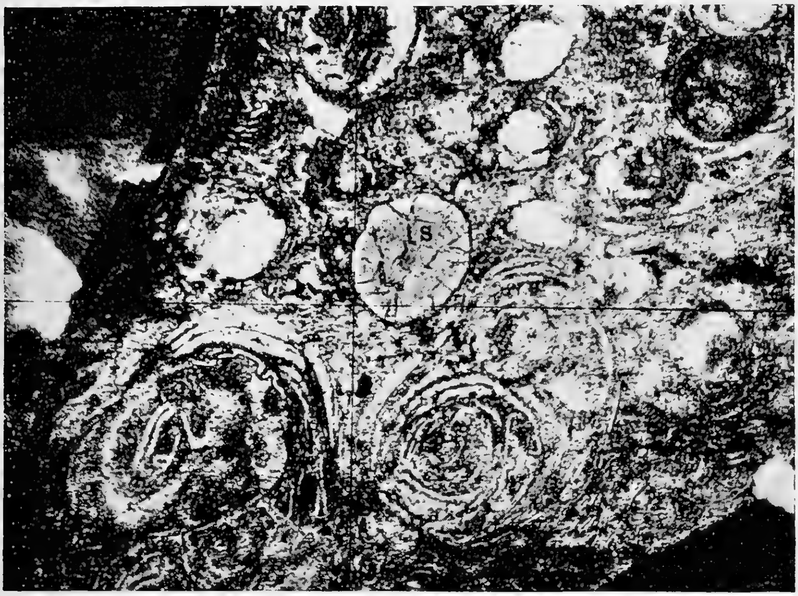


FIG. 7.—Perlitic structure preserved in quartz replacing the groundmass of a spherulitic rhyolite. Ordinary light, ×35. *s* = spherulite.

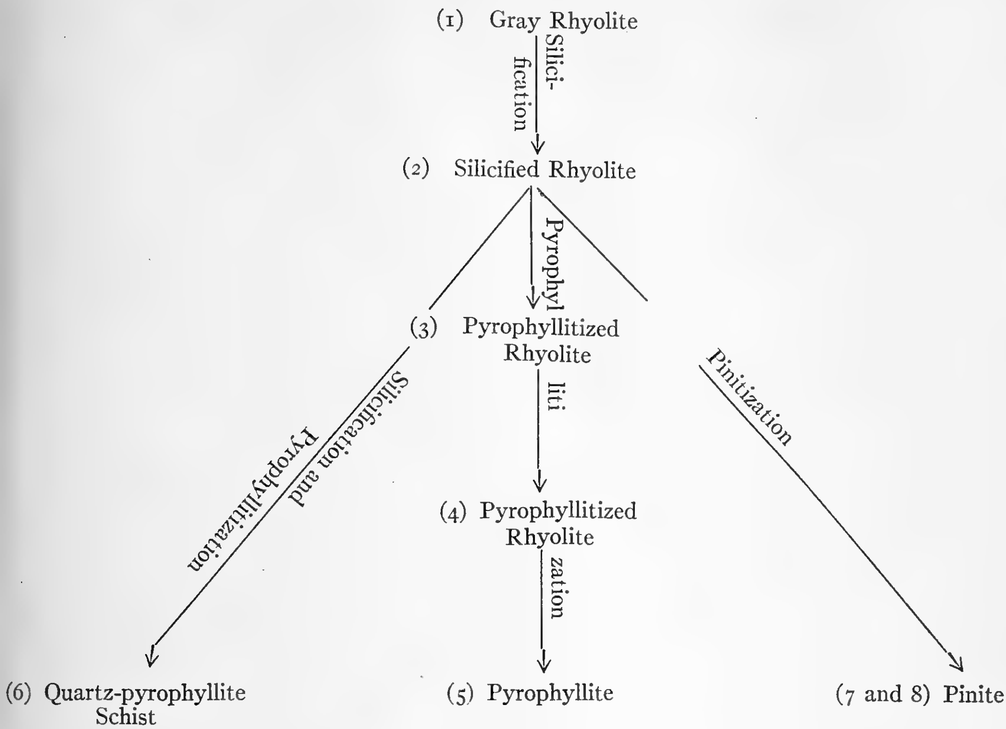
replacement of the soda feldspars than of the potash feldspars. The solutions which effected this alteration doubtless belonged to the same general period of volcanic activity as the extrusion of the lavas themselves.

PYROPHYLLITIZATION, PINITIZATION, AND SILICIFICATION

As has been remarked before, a later series of local alteration processes has been superimposed on the already widespread slightly silicified volcanics. The origins of the pyrophyllite, the pinite, and the quartz-pyrophyllite or quartz schists are so intimately interwoven that all may be treated together.

The proof that these rocks have originated through replacement is based on the following data: (1) the preservation of the structures of the primary rock in the secondary rock, (2) the presence of unattached and unsupported portions of the country rock within the replacement products, (3) the introduction of large quantities of some elements and the solution of others without any notable change in volume or porosity, (4) gradational contacts, and (5) the massive homogeneity of all the rocks, and especially of the pyrophyllite, which does not show the foliated crystalline structure so characteristic of pyrophyllite veins which fill preexisting fractures. To quote examples which belong to the first category, we find the following structures preserved in pyrophyllitized rhyolite: (1) flow structure, (2) spherulites, (3) pebbles of a partially replaced conglomerate, and (4) perlitic structure (Fig. 5); these in the quartz-pyrophyllite rocks: (1) spherulites and (2) breccia structure; the following in pyrophyllite: (1) fragments of volcanic breccias, (2) pebbles of conglomerates, and (3) spherulites; while in the pinite and pinite schists we have preserved spherulites, traces of flow structure, axiolites, microspherulites, and perlitic structure (Fig. 6). Additional evidence of replacement is found in the inclusions and stringers of country rock within the pyrophyllite veins and the intimate manner in which the two are often intermixed. Not only this most convincing field evidence but chemical considerations prove almost conclusively that these rocks must have originated through replacement of rhyolite or rhyolitic volcanics.

From a study of the foregoing field and chemical evidence, conclusions have been drawn as to the genetic relationships of the eight different rocks described under "Chemical Analyses" and "Petrography," and as to the succession of processes which produced them. This relationship is graphically represented by the following diagram, in which the numbers refer to the chemical analyses given under "Chemical Analyses," which may be taken as typifying the composition of the respective rocks:



TEMPERATURE OF FORMATION OF PYROPHYLLITE

Clapp (1914, 120) assumes that alunite and pyrophyllite are probably developed only under moderate conditions of pressure and temperature such as exist near the surface. Although this is a common mode of origin for both alunite and pyrophyllite, it is certainly not the only set of conditions under which the latter forms.

For instance, pyrophyllite is noted by Dana (1909) as a mineral often forming the base of schists and gneisses, and by Lacroix (1895) as a mineral of the crystalline schists and Paleozoic metamorphics.

Artificially, K. von Chrustchoff (1894) obtained what he believed to be pyrophyllite by heating gelatinous silica, gelatinous alumina, and gelatinous zirconium hydrate in a platinum tube at increasing temperature for six days. The product obtained was a zirconia-bearing pyrophyllite. Its specific gravity was 2.87 and it appeared in thin hexagonal plates, which he states are not true hexagonal plates unless there be optical anomalies.

SiO_2	Al_2O_3	ZrO_2	H_2O	Total
53.65	23.76	14.54	7.86	99.81

Le Chatelier (1887) determined the points at which pyrophyllite loses its water by noting the points at which the temperature remained constant with absorption of heat and found two such points, the first at 700° and the second at 850°.

From the foregoing data it is evident that pyrophyllite is a mineral which may form under conditions varying from the high temperatures of dynamic metamorphism to the near-surface temperatures and pressures of solfataric agencies.

TEMPERATURE OF FORMATION OF PINITE

Pinite, if considered as an impure sericite, as suggested by Clarke (1911), has a varied range of conditions under which it may form. Clarke states, however, that "the alteration [to sericite] is most conspicuous in regions where dynamic metamorphism has been most intense, high temperature, the chemical activity of water and mechanical stress all working together to bring it about."

A green micaceous mineral described as mariposite by Silliman, and whose composition, shown by two analyses, as suggested by Hillebrand (1895), resembles pinite, is characteristic of the mother lode in Tuolumne and Mariposa counties, California.

Crosby (1880) describes pinite as a product of surface decomposition of petrosilex and felsites in the vicinity of Boston, Massachusetts. Bell (1887) found it at Ballater Pass interspersed through granitic rocks and along their joint planes, and ascribes its origin to the decomposition or alteration of orthoclase feldspar, an intermediate stage in its conversion into kaolin.

Cole (1886) describes pinite occurring as an alteration product of spherulitic rhyolites, in conjunction with silicified spherulites. He suggests that thermal waters are responsible for the origin of both the pinite and quartz.

From these references it is evident either that there is a difference of opinion as to the conditions under which pinite forms, or that it is stable under widely variant temperatures and pressures. It is probable, however, that it demands higher temperatures and pressures than exist at the surface as conditions for its most favorable development, and such is doubtless the case with respect to the pinite of Conception Bay.

ALTERNATIVE DEVELOPMENT OF PINITE OR PYROPHYLLITE

Since sericite or pinite is the usual product of hydrothermal alteration it is pertinent to inquire if any reason can be found why in certain cases pyrophyllite should be the product formed. A possible equation (1) representing the formation of sericite from orthoclase is quoted from Clarke (1911), and a similar possible equation (2) representing the formation of pyrophyllite from orthoclase is given below:

$$(1)\quad 6\ KAlSi_3O_8 + 2H_2O \leftrightharpoons \underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}} + 2K_2SiO_3 + 10SiO_2$$

$$(2)\quad 6\ KAlSi_3O_8 + 3H_2O \leftrightharpoons \underset{\text{(pyrophyllite)}}{6HAlSi_2O_6} + 3K_2SiO + 3SiO_2$$

From these equations three factors are suggested as the possible elements influencing the alternative development of sericite and pyrophyllite: (1) the effectiveness of hydrolysis, (2) the mass action of the excess silica in solution, and (3) the mass-action effect of excess potash in solution. The dominance of the first two factors would be conducive to the formation of pyrophyllite, and the dominance of the third factor would be favorable to the production of sericite. This may be illustrated more graphically, without however implying anything as to the actual mode of operation, by writing the equation for the formation of pyrophyllite from sericite as a balanced reaction:

$$\underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}} + 6SiO_2 + H_2O \leftrightharpoons \underset{\text{(pyrophyllite)}}{6HAlSi_2O_6} + K_2SiO_3$$

If now the quantity of silica is present in the solution in large enough excess and the effectiveness of hydrolysis is relatively stronger, the reaction will produce pyrophyllite:

$$\underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}}+6SiO_2+H_2O \rightarrow \underset{\text{(pyrophyllite)}}{6HAlSi_2O_6}+K_2SiO_3$$

while if K_2SiO_3 or potash in some other form is present in large enough quantity the alternative reaction will take place and sericite will be produced:

$$\underset{\text{(pyrophyllite)}}{6HAlSi_2O_6}+K_2SiO_3 \rightarrow \underset{\text{(sericite)}}{2KH_2Al_3Si_3O_{12}}+6SiO_2+H_2O$$

CHEMICAL PHENOMENA CONNECTED WITH ORIGIN OF PYROPHYLLITE

From a comparison of the analysis (No. 2) of the silicified rhyolite with that of the pyrophyllite (No. 5), it will be seen that the change in composition has been such as might have been brought about essentially through three processes: (1) the introduction of alumina, (2) the replacement of the alkalies by hydroxyl, and (3) the solution of silica. The analyses 2, 3, 4, and 5, recalculated into their mineral composition, show a direct transition from the country rock (the silicified rhyolite) into pyrophyllite through a decrease in the quantity of quartz, feldspars, and impurities and a simultaneous increase in the content of pyrophyllite. In order that the original rock may be so altered as to give the mineral analyses shown by the transitional rocks, it is necessary that metasomatic replacement of both the quartz and the feldspars should have proceeded synchronously and at a much faster rate with respect to the quartz than with respect to the feldspars. This process would involve the introduction of large amounts of alumina, the gradual replacement of the alkalies by hydroxyl at a more rapid rate in the case of the soda than of the potash, and the solution of portions of both the silica existing in combination with other elements in the rock and that present as free quartz.

The heterogeneous, blotchy character of the quartz-pyrophyllite rock when seen in thin section suggests that the rock may have been in the condition of a more or less homogeneous glass when acted upon by the silicifying and pyrophyllitizing solutions, in view of the fact that its chemical composition and mineral arrangement would involve the simultaneous replacement of the feldspars of a crystalline rock by silica and pyrophyllite, and of its quartz by pyrophyllite.

ORIGIN OF PINITE AT MANUELS

From a further study of the chemical analyses, it becomes evident that while the silicified rhyolites, pyrophyllitized rhyolites, and pyrophyllite have all decreased in their content of iron, magnesium, potassium, and soda, the pinite analysis (7) shows a decided increase in the first three of these elements. During the formation of pyrophyllite vast quantities of potash must have been liberated and carried in solution in the circulating waters. Is it not possible that away from the main channels these waters deposited their load as pinitic replacements of the rhyolite under the control of lower temperatures and pressures and the mass-action effects of the excess potash in solution? It seems reasonable to suppose that the pinite here was an essentially contemporaneous formation with the quartz-pyrophyllite schists and pyrophyllite, receiving some of the magnesia, potash, and iron released by the formation of the pyrophyllite, as the quartz schists have received some of the silica originating at the same time.

ORIGIN OF THE PINITE SCHIST AT HARBOUR MAIN

The chemical analysis of the pinite schist recalculated for sericite gives the rock a mineral composition of about $\frac{3}{5}$ sericite and $\frac{2}{5}$ quartz, feldspar, and other constituents. Examination of thin sections shows that this result has been brought about through the replacement of both the feldspar and quartz by sericite. If we consider the rock previous to pinitization to have had the composition of the silicified rhyolite (No. 2), then the process cited involves the substitution of potash for soda in the feldspars, the addition of potash and alumina, and the subtraction of silica and soda.

There is considerable evidence that this rock was not formed at the surface. There are no secondary products of decomposition, such as kaolin or limonite, associated with the pinite. It occurs in quantity only in certain zones and extends to a considerable depth, as exposed in a prospect pit for talc, south of Harbour Main.

Where it occurs as patches or specks it bears no apparent relation to the surface. Furthermore, the pinitic material has undergone dynamic metamorphism and is sheared and cleaved, while chemically its origin involves the introduction of alumina and potash through replacement.

GENERAL OBSERVATIONS

It is quite probable that the foregoing processes operated under conditions of some dynamic movement, as their characteristic development is along shear zones, and their products assume a lenticular structure which is as characteristic of the minuter structures of the rocks as of the veins themselves. Moreover, the rocks themselves have been sheared and possess a more or less prevalent cleavage, conditioned by the growth of their constituent minerals in more or less parallel arrangement.

It is probable that the factors determining which of these three rocks—pyrophyllite, pinite, and quartz-pyrophyllite—shall form are to be found in the temperature, pressure, and chemical content of the solutions themselves, in the relative effectiveness of hydrolysis, and in the mass-action effects of the compounds in solution.

The concentration of the potash in the pinite, and the silica in the quartz-pyrophyllite rocks may be accounted for on the theory of a redistribution of the elements, but the tremendous contributions of alumina represented by the pyrophyllite, and to a minor extent by the pinite, must be accounted for otherwise. The close connection between the pyrophyllite deposits and the granite-Avondale Volcanics contact south of Manuels and between the pinitized rhyolites and the Woodfords monzonite stock is hence of significance. It may be that there is no genetic connection between these minerals and the intrusives, and that their formation was entirely dependent on the locus of fault zones in those localities. But there are numerous other profound fault and shear zones in this area with no exceptional alterations.

Hence it seems probable that when faulting took place between the volcanics and the intrusive granite or monzonite, the still hot magmatic waters were released and found their way upward along these fault zones, either contributing the alumina directly, or perhaps indirectly through mingling with already aluminous solutions. Such solutions, if present, would be those which had accomplished the silicification of the volcanics with their attendant solution of alumina under static conditions and hence before the period of orogenic movement, which folded the volcanics and witnessed the intrusion of the plutonic batholith and stock. The evidence bearing on the exact dates of the periods of faulting and folding, however, is not conclusive.

COMPARISONS WITH OTHER DEPOSITS

Comparisons with other deposits show that, according to the descriptions, the pyrophyllite deposits of the Pambula goldfield, New South Wales, and of Chatham and Moore counties, North Carolina, are essentially similar to those in Newfoundland, and it is here suggested that possibly they have had a similar origin.

Clapp (1914) described quartz-pyrophyllite rocks from Kyuquot Sound, Vancouver Island, which may be taken as a type of pyrophyllite deposits developed by solfataric agencies under conditions of temperature and pressure existing near the surface; while those of Newfoundland are a type originating under intermediate conditions of temperature and pressure.

In the first case the pyrophyllite rocks are associated with alunite and in the latter case with pinite. In the Kyuquot deposits the original quartz of the replaced dacite has not suffered any loss except in one doubtful case, while the distinctive feature of the Newfoundland rocks has been the replacement of quartz in rhyolites by pyrophyllite.

The two deposits are similar in that, in both cases, the rocks are associated with intrusive batholiths, the one with a feldspathic quartz diorite and the other with granite. Both are metasomatic replacements of acid volcanics, while in the zone of alteration there seems to have been some transfer of material, and soda, lime, magnesia, and iron oxides have been lost in each case.

CONCLUSION

From the foregoing evidence the conclusion may be drawn that: the pyrophyllite, pinite, and quartz-pyrophyllite schists of the

Avondale Volcanics owe their formation to metasomatic replacement and alteration of previously silicified rhyolites or rhyolitic volcanics by thermal waters, under conditions of dynamic stress and intermediate temperatures and pressures, operating along channels primarily determined by fault or shear zones. Chemically, the salient features of these alterations have been the introduction of alumina, the more or less complete substitution of the hydroxyl element in place of the alkalies, and the solution of soda. The solutions instrumental in causing these alterations may have been to a greater or less extent juvenile waters emanating from the intrusive granite batholith and monzonite stock at some period subsequent to the time of their injection.

May, 1915

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THE ORIGIN OF RED BEDS

A STUDY OF THE CONDITIONS OF ORIGIN OF THE PERMO-CARBONIFEROUS AND TRIASSIC RED BEDS OF THE WESTERN UNITED STATES[1]

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PART I

[1] A revision of a thesis presented in partial fulfilment of the requirements for the degree of Master of Arts at the University of Wisconsin, in June, 1914.

PART II

PART I

PREFACE

Certain general facts concerning the origin of the western Red Beds have been known for some time and have become incorporated into current textbooks. There has been, however, much difference of opinion in the interpretation of some features of this remarkable group of sediments, especially as to the significance of the color itself. This paper is devoted to an investigation of the causes and history of the coloring matter, which, more than all other features put together, distinguishes the Red Beds from other sedimentary series.

The investigation on which this paper is based has been chiefly a study of the literature to which reference is made in the footnotes, together with all available published descriptions of the western Red Beds, and much miscellaneous literature dealing with related subjects. The writer's first-hand acquaintance with the Red Beds has been gained from two summers of field work in Wyoming and Idaho (under the direction of Eliot Blackwelder, of the United

States Geological Survey), and from laboratory study of thin sections. For valuable suggestions and criticism and for review of the manuscript the writer is indebted to Messrs. Eliot Blackwelder, A. N. Winchell, W. J. Mead, and F. T. Thwaites, of the University of Wisconsin; to Messrs. W. H. Emmons, C. R. Stauffer, F. F. Grout, C. J. Posey, and A. W. Johnston, of the University of Minnesota; and to Dr. R. D. Salisbury, of the University of Chicago.

SUMMARY DESCRIPTION OF THE FEATURES CONSIDERED

List of formations.—Clastic sedimentary strata of reddish color outcrop or constitute the uppermost part of the bedrock over about 4 per cent of the area of the United States and exist beneath a cover of younger sediments under an additional area probably twice as large. Much the greatest volume of such strata is included in the single group of rocks which forms the subject of the present study: namely, those Red Beds which outcrop in many areas from Kansas and Texas to Arizona and Montana (Fig. 1). The formations included in this group are related closely in age, ranging from Pennsylvanian to Triassic, or possibly Jurassic, and are probably for the most part physically continuous. They comprise the Cimarron series of Kansas and Oklahoma, and the Wichita, Clear Fork, Double Mountain, Greer, Quartermaster, and Dockum beds of Texas; the Wyoming, Fountain, and Maroon formations of central Colorado; the Cutler and Dolores of southwestern Colorado; the Aubrey, Shinarump, Vermilion Cliff, and Moencopie of the Colorado Plateau, with the Saliferous and Zuni of the Zuni Plateau in New Mexico; the Spearfish, Opeche, and Chugwater of Wyoming and southern Montana; and the Ankareh and Nugget of southeastern Idaho and northeastern Utah.

Similar Red Beds constitute a large part of the sediments of the Newark series (Triassic) of the Appalachian Piedmont region—typified by the Stockton and Brunswick formations of New Jersey.[1] They make up also, among others, much of the Catskill formation (Devonian) of eastern New York and Pennsylvania; the Medina and Clinton (Silurian) of New York; the Vernon shale (Silurian, a

[1] See H. B. Kümmel, *Ann. Rept. of the State Geologist of New Jersey*, 1896.

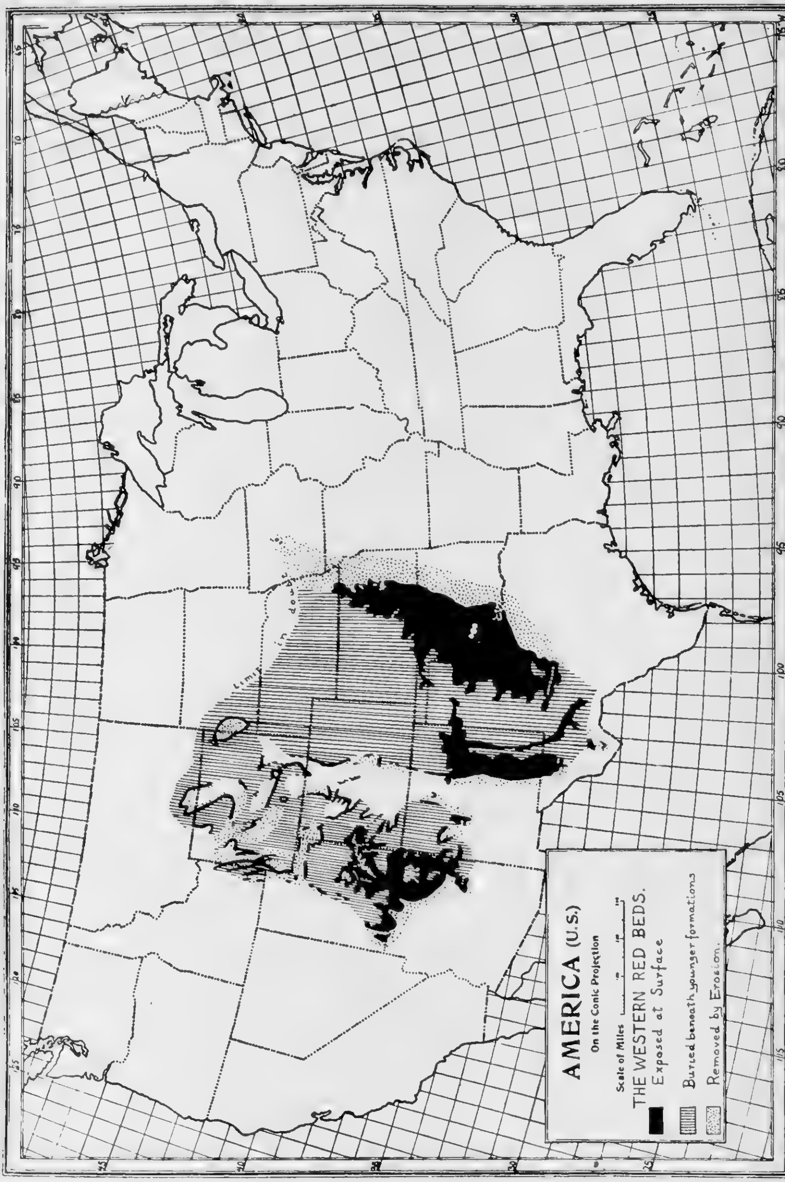

FIG. 1.—Map showing distribution of the western Red Beds

member of the Salina beds), the Bedford shale (Mississippian), and the Dunkard series (Permian) of Ohio; the Lake Superior sandstone (probably Algonkian) of northern Michigan, Wisconsin, and eastern Minnesota; and the Belt series (Algonkian) of Montana and British Columbia. Occasional reference will be made in this paper to these formations, and to Red Beds in other countries as well; but this discussion applies especially to the western group, with which the writer is most familiar.

Colors of gypsum and limestone.—The beds of gypsum occurring in many areas of Red Beds strata are described everywhere as remarkably pure and white, except where stained by a red coating washed down from overlying clastic sediments. The same is true of a majority of the limestones and dolomites occurring in the red series, most of which are gray or drab or bluish on fresh fracture. Even the famous Redwall limestone (2,500 feet thick) underlying the Aubrey Red Beds of the Grand Canyon section is gray on fresh fracture;[1] its surface color is due to concentration of iron oxide by weathering, to wash from above, or to both of these causes. Exceptions are found in limestone or dolomite bands in the lower Chugwater in Wyoming,[2] and in the Minnekahta limestone[3] of the Hartville quadrangle, which are characteristically purplish or rosy gray; and locally in certain limestones in northern Oklahoma, where they are in transition to sandstone.[4] These limestones are in most localities nearly or quite barren of fossils.

Color in clastic strata.—Another and perhaps a yet more significant fact is the variation of hue among the clastic strata. Interbedding of greenish, gray, or buff beds with red sediments is found in a majority of Red Beds sections; notably in the Saliferous of the Colorado and Zuni plateaus, in the Dockum group of Texas, and in

[1] G. K. Gilbert, "Geology of Portions of Nevada, Utah, California, and Arizona," *U.S. Geog. Surveys W. of the 100th Meridian*, III (1875), 177–78.

[2] Eliot Blackwelder and C. W. Tomlinson, "Field Notes on Work in Western Wyoming, 1910 and 1911," unpublished; property of the United States Geological Survey.

[3] W. S. T. Smith, Hartville Folio (No. 91), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1903.

[4] J. W. Beede, "The Neva Limestone in Northern Oklahoma," *Okla. Geol. Survey Bull. No. 21*, 1914, p. 24.

the Red Beds of the San Juan region and of the Anthracite, Crested Butte, and Tenmile quadrangles of Colorado. Alternation of paler with darker and with brighter shades of red is remarked in almost every occurrence of Red Beds. In all these instances it is significant that the color boundaries tend to follow bedding planes,

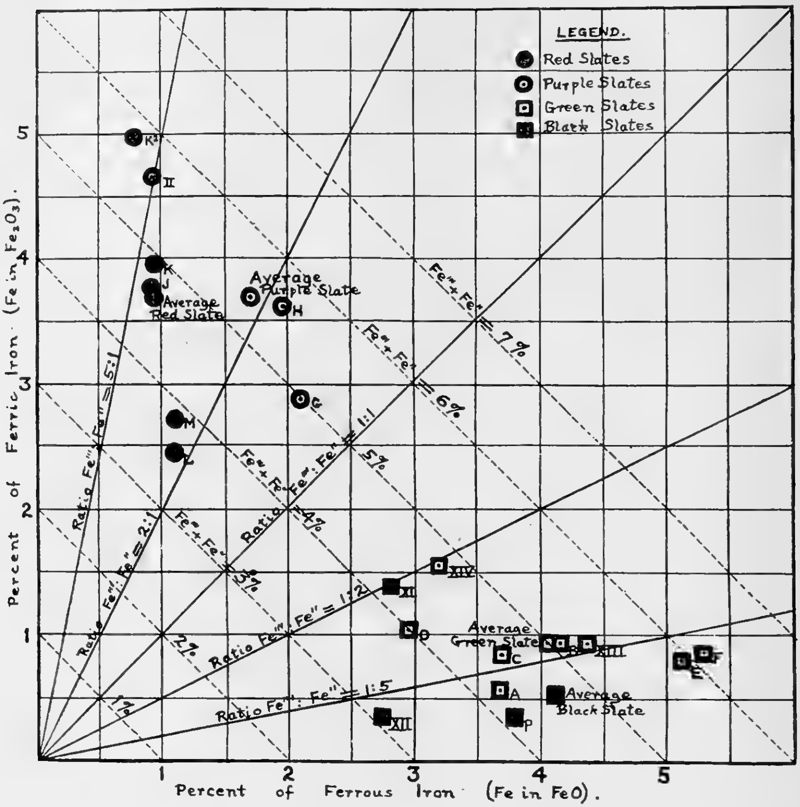

FIG. 2.—Diagram to illustrate the relation between color and the proportion of ferric to ferrous iron in ferruginous slates. Analyses (from Dale) are lettered to correspond with text.

and usually accompany changes in coarseness of grain. Many of the color boundaries are distinct, even planes, but they may be rendered irregular by downward migration of coloring matter.

Where alternations of light- and dark-red strata occur, the more deeply colored beds are in most cases of finer grain than the others. The occurrence of coarse-grained massive buff sandstones in a series of maroon or chocolate shales has been noted by many writers. This association holds true in many other Red Beds besides the group here under consideration. Thwaites[1] reports it as an almost unfailing relation in the Lake Superior sandstone series of northern Wisconsin, and Geikie[2] mentions its existence in the Triassic New Red Sandstone of Great Britain. The respective tints are understood to be uniform throughout the strata in which they are noted, and not to be merely the surface staining of the beds, which might have a very different origin.

Distribution of greenish colors.—Greenish tints occur in the Red Beds as a fairly even color through continuous beds interstratified more or less closely with red strata, in streaks and blotches in red strata themselves, and occasionally in strips following joint planes. The completely greenish strata, and likewise the mottled beds, include both shales and sandstones, and are described from many districts. Green spots in red strata are as a rule irregularly ellipsoidal in shape, somewhat flattened parallel to the bedding, and indefinite in outline. They may vary in diameter from a few millimeters to several inches.

Variations in color along the strike are as common and as much to be expected as similar variations in texture, cross-bedding, or any other stratigraphic feature. The Red Beds of the Southwest are noted for their inconstancy and frequency of change along the strike; those of Central Wyoming and the Black Hills are fairly continuous in lithologic characters for considerable distances. Where other features are variable, the color is variable also; and where other features are constant, color likewise is constant.

Nature of the coloring matter.—Available data as to the chemical composition of the green bands and spots and other variations in color in the western Red Beds are very meager; but many of the same phenomena occur in roofing slates, whose commercial value has been the cause of painstaking investigation of their occurrence and character. The close dependence of color upon chemical

[1] F. T. Thwaites, "Sandstones of the Wisconsin Coast of Lake Superior," *Bull. Wis. Geol. and Nat. Hist. Survey No. 25*, 1912, p. 31.

[2] Archibald Geikie, *Text-Book of Geology* (London: Macmillan, 1903), p. 1064.

composition is brought out strikingly by the following analyses, which are at least sufficient to show that the differences in color in the Red Beds are caused by the same differences in chemical composition as those which cause corresponding differences in color in slates. The analyses are plotted graphically in the diagram (Fig. 2).

The following analyses are taken from Dale:[1]

		Fe_2O_3	FeO	Net Fe	Ratio Fe‴: Fe″	Free Carbon
Red slates	J.	5.36	1.20	4.69	4.04 :1.00	(No free carbon found in any of the red or purple slates)
	K.	5.61	1.24	4.89	4.09	
	L.	3.48	1.42	3.54	2.29	
	M.	3.86	1.44	3.83	2.42	
	K²*.	7.10	1.00	5.75	6.37	
	Average	5.26	1.21	4.62	3.91 :1.00	
Purple slates	G.	4.10	2.71	4.99	1.36 :1.00	
	H.	5.16	2.54	5.59	1.84	
	II.	6.63	1.20	5.58	5.00	
	Average	5.30	2.15	5.38	2.22 :1.00	
Green slates	A.	0.81	4.71	4.23	0.156:1.00	
	B.	1.34	5.34	5.09	0.226	Trace
	C.	1.23	4.73	4.54	0.234	Trace
	E.	1.12	6.58	5.90	0.155	
	F.	1.24	6.81	6.16	0.165	
	O.	1.47	3.81	3.99	0.348	
	XIII.	1.33	5.64	5.31	0.213	Trace
	XIV.	2.24	4.07	4.73	0.496	
	Average	1.35	5.21	4.99	0.232:1.00	
Black slates	P.	0.52	4.87	4.15	0.095:1.00	0.46
	VII.	....	9.03	7.02	0.000	1.79
	XI.	1.98	3.65	4.23	0.490	0.77
	XII.	0.53	3.52	3.11	0.135	1.54
	Average	0.75	5.27	4.63	0.129:1.00	1.14
Spotted slates	M*.	3.86	1.44	3.83	2.42 :1.00	
	Q*.	1.79	1.19	2.18	1.34 :1.00	
	R*.	1.09	1.06	1.58	0.927:1.00	

* K² is same slate as K, but finer grained. M = red slate near green spot. Q = purple rim of spot. R = green part of spot.

[1] T. N. Dale, "The Slate Belt of Eastern New York and Western Vermont," *Ann. Rept. U.S. Geol. Survey No. 19*, 1899, Part 3, pp. 232, 246–53, 257, 264; and "The Roofing Slates of the United States," *U.S. Geol. Survey Bull. No. 275*, 1905, pp. 34–36.

The following analyses are taken from W. J. Miller:[1]

VERNON FORMATION, CENTRAL NEW YORK

	Fe_2O_3	FeO	Net Fe	Ratio Fe''' : Fe''
Red shale	2.25	0.75	2.16	2.72:1.00
Green spot in red shale	0.00	1.19	0.93	0.00:1.00

The following analyses were furnished by Eliot Blackwelder:[2]

CHUGWATER FORMATION, WIND RIVER VALLEY, WYOMING

	Fe_2O_3	FeO	Net Fe	Ratio Fe''' : Fe''
Red sandstone	3.50	1.04	3.26	3.02:1.00
Greenish sandstone*	1.03	1.04	1.53	0.89:1.00

*The greenish sandstone of the Chugwater in this case is a strip of the ordinary red sandstone, leached along a joint crack.

The following analyses are taken from Richardson:[3]

SPEARFISH FORMATION, BLACK HILLS

	Fe_2O_3	FeO	Net Fe	Ratio Fe''' : Fe''
Green shale	1.85	1.04	2.02	1.78:1.00
Red shale, adjacent to green	4.61	1.24	4.55	3.72:1.00
Red shale	3.64	0.65	3.05	5.04:1.00
Red shale	2.04	0.18	1.57	10.20:1.00

The black color in the slates is due, not directly to any peculiarity of the iron content, but to the presence of carbonaceous matter, which incidentally brings about the reduction of iron oxide to the ferrous form. Black shales are very rare in the western Red Beds, but highly carbonaceous and even coal-bearing strata occur in the Newark series of the Atlantic Piedmont. The typical Newark clastics are quite intensely red, many of them with a purplish tone, but the carbonaceous strata are always gray or black.

The color of the prevailing red strata in the Red Beds series is due to the presence of ferric oxide. The iron of the coloring matter

[1] W. J. Miller, "Origin of Color in the Vernon Shale," *Bull. N.Y. State Museum*, No. 140, in *63d Ann. Rept. N.Y. State Museum, 1909*, I, 150–56.

[2] U.S. Geol. Survey, Division of Chemistry, Analysis No. 2530.

[3] G. B. Richardson, "The Upper Red Beds of the Black Hills," *Jour. Geol.*, XI (1903), 365–93.

is chiefly in the ferric state in light- and dark-red, buff, and yellowish strata. A gray or green color, on the contrary, signifies a low proportion of ferric oxide, and usually a preponderance of ferr*ous* over ferr*ic* compounds. The mineral composition of the coloring matter is difficult to determine accurately because of its fine division. A green color is "common with silicates in which ferrous iron is prominent,"[1] and silicates may be important where the ratio of ferrous to ferric iron is high.

IS THE FERRUGINOUS MATERIAL AN ORIGINAL CONSTITUENT OF THE SEDIMENTS, OR A LATER INTRODUCTION?

Hypothesis of introduction of iron from igneous magmas.—If the ferruginous matter was an integral part of the original sediments, we have no more difficulty in explaining its presence than in accounting for any other common mineral constituent of sedimentary rocks. Its source was most probably in the same rocks which gave rise to other materials of the series, such as quartz, feldspar, and calcite, and the agencies of transportation were the same as those which were responsible for the entire series. If, however, we postulate that the iron has been introduced since the completion of sedimentation, after the series of Red Beds was otherwise complete, we shall find it very difficult to reconstruct in imagination any natural agency which might have brought about such a result, and we shall be puzzled to find an adequate source for this vast amount of iron.

There is one hypothesis of this kind which received credence and vigorous support in America for several decades of the nineteenth century, in explanation of the red stain in the Newark series of the Connecticut Valley.[2] The close association, in that series, of clastic red sediments with contemporaneous extrusive and intrusive basic igneous rocks of great thickness and extent made it a natural suggestion that the exceptional color of the sedimentary members was connected directly with igneous action. The absence of any

[1] E. S. Dana, *A Text-Book of Mineralogy* (New York: John Wiley & Sons, 1909), p. 472.

[2] See J. D. Dana, *Manual of Geology*, ed. 1880, p. 764; and also his review of Russell's bulletin on the "Subaerial Decay of Rocks" (*U.S. Geol. Survey Bull. No. 52*, 1889), in *Am. Jour. Sci.*, 3d Ser., XXXIX (1890), 319.

strong evidence in support of this hypothesis, aside from that of association with igneous rocks, and the discovery of various lines of evidence (among those outlined below) in direct opposition to it, however, caused it to fall into disrepute. In the case of the western Red Beds there is not even the association with igneous rocks to suggest such an explanation. There are no contemporaneous igneous rocks in any part of the Red Beds group, and in the greater part of the area in which the group occurs there are no later igneous rocks known. In no case is there a relation comparable to that in the Connecticut Newark.

Where the effect of later intrusions upon Red Beds has been observed carefully, that effect is not to heighten, but to destroy, the red color. This action has been noted in the Tenmile district[1] and in the Anthracite-Crested Butte district,[2] Colorado.

Later introduction of iron by meteoric waters.—There is no apparent reason why the Red Beds should have been favored by post-sedimentational iron-bearing solutions while other clastic series in the same region, both older and younger, were not stained. It might be expected that the coloring matter would be most abundant in the most pervious strata, especially along the lower surface of such strata, where they are in contact with less pervious rocks. It is quite true that color boundaries in the series follow bedding planes very closely; but, unfortunately for the hypothesis of later introduction, the more highly ferruginous strata of the Red Beds are as a rule, and with few exceptions, the more impervious. As noted above (pp. 158–59), in a series of alternating sandstones and shales it is almost invariably the shales which are deeper in color.

Ferric hydrates are not being introduced into the Red Beds strata along the present joint planes. The analyses of Chugwater sandstone given on p. 161 (see also footnote) show a marked leaching of iron along a joint. Nor is iron commonly concentrated along joints in paler sediments underlying the Red Beds.

[1] S. F. Emmons, Tenmile District Special Folio (No. 48), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1896.

[2] G. H. Eldridge, "Description of the Sedimentary Formations," Anthracite-Crested Butte Folio (No. 9), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1894.

Deposition of coloring matter contemporaneous with sedimentation.—If the ferruginous material which furnishes the color was concentrated in the sediments chiefly at the time of their deposition, this association of high color with fine sediment is explained readily, as follows:

In the weathering of igneous rocks, ferruginous material is separated out chiefly by the chemical decomposition of iron-bearing silicate minerals, and is therefore at the time of separation in a very fine state of division. At the same time ferrous salts of iron usually are altered to ferric oxide or hydrate. During surface transportation and sorting it is segregated in whole or in part, by reason of this fine division (if it persists) and in spite of its high specific gravity, along with other finely divided materials constituting muds and "clays."

This does not apply to iron occurring in the parent rock in the form of magnetite or other very stable minerals, which in most cases are concentrated with the coarser products of mechanical disintegration, such as sands and sandy shales. Ferruginous materials firmly cemented to sand grains during weathering may also be transported and deposited with the sand. Iron taken into solution will have yet a different history.

In the weathering of sedimentary rocks, the behavior of their ferruginous content is dependent upon the behavior of that material in a former sedimentary cycle, and thus ultimately upon the conditions already outlined for the weathering of the igneous rocks. Ferric oxide, the form in which iron occurs most abundantly in sediments, is, because of those conditions, usually finely divided, and in a second cycle of transportation and deposition will be concentrated again chiefly with the muds. In so far as assortment is imperfect, the ferruginous material may be deposited with any type of sediment.

Because of the usual absence of any commercial value in the series, there is an unfortunate dearth of analyses of Red Beds shales and sandstones. The fact of the concentration of ferruginous matter in the fine-grained sediments is well illustrated, however, by composite analyses of shales and sandstones from all sources. The following figures from Clarke[1] are to the point:

	Percentage Fe_2O_3	Percentage FeO	Total
Average of 78 shales (mean of two composites) . .	4.03	2.46	6.49
Composite analysis of 253 sandstones.	1.08	0.30	1.38

See also analyses K and K[2], on p. 160, *supra.*

Microscopic evidence.—Russell[2] has presented evidence to show that the red coloring matter in sandstones of the Newark series in Virginia occurs as a coating on the sand grains, and that it existed in that form even before the transportation of the sand from the residual soils from which it was derived. Since much of his argument would apply equally well to the red sandstones of western Red Beds, it is worth investigation in this connection. In a few thin sections of Newark sediments from Virginia which have been available for study by the writer, it is shown clearly that ferruginous matter exists there, both in the form described above and as a later interstitial filling between grains. Many of the sand grains, both of quartz and of feldspar, are well rounded. Most of them are surrounded by a thin coat of hematitic material, whose outer surface is smooth and even, but whose inner border may show slight irregularities penetrating into the body of the grain. This red film may not be entirely continuous around the grain; and this fact, together with the smoothness of its outer surface, suggests, as Russell maintained, that the coating was acquired by the sand grain before its final deposition, and that the coating suffered wear during transportation, without being completely removed.

In a number of instances it was found that part of the cementation of the rock had been accomplished by enlargement of the original grains of quartz and feldspar in optical continuity, outside of the red coating; and that outside of the enlargements there existed other bodies of hematitic matter, irregularly scattered

[1] F. W. Clarke, "The Data of Geochemistry," 2d ed., *U.S. Geol. Survey Bull. No. 491*, 1911, chaps. iii, v, vi.

[2] I. C. Russell, "Subaerial Decay of Rocks," *U.S. Geol. Survey Bull. No. 52*, 1889.

through the interstitial spaces. This material may have filtered in during the process of cementation; or it may have been present at the time of sedimentation and have been thrust out of the way by the growing crystals during enlargement. Occasional specks of red-stained material are found within the area of the enlargements and distinct from the inner coating of the original grains; and where the enlargement is missing, the interstitial hematitic matter may be difficult to distinguish from that of the primary coating. The stained areas probably do not represent pure ferric oxide, but ferric oxide in such ratio to silica or clayey material as to render the mixture nearly opaque and quite uniformly red or reddish brown; for chemical analyses of the same rocks show the percentage of ferric oxide in the rock to be much lower than the percentage of red-stained area in the sections.

A similar microscopic investigation has been made by Richardson[1] in his study of the Spearfish formation of the Black Hills. He says: "Amorphous red pigment is prominent in the slides. It irregularly coats and spots the minerals, and . . . . constitutes the chief interstitial substance."[2] He also presents an analysis to show that the ferric oxide of the pigment is essentially anhydrous.

Thin sections of Red Beds from all parts of the West are not available at present, and it has not been practicable, therefore, to make a thoroughgoing microscopic study of the group. Richardson's description suggests a relation of pigment to cementation similar to that found in the Newark sandstones: a twofold relation, indicating that part of the pigment was transported and deposited as a coating on sand-grains, and that the remainder constitutes an important part of the cementing material of the rock and is coeval with the rest of that material.

But what was the time of cementation? Was this process completed before the exposure of the Red Beds series to erosion, or is it still going on, or did it cease at some intermediate time? In so far as this question affects the iron content of the Red Beds we really have answered it already; for if any considerable part of the iron had been introduced as a cement later than the time of sedimentation it would not be found most abundantly in the strata which

[1] *Op. cit.* [2] *Ibid.*, p. 379.

afford the least ready passage to water, as is actually the case. The cementing material of the Red Beds, in so far at least as it is ferruginous—and the remainder of it has little or no bearing upon the point in question—was therefore for the most part present in those beds at the time they were deposited as sediments.

Extent of known secondary redistribution of coloring matter.—Although the evidence is convincing that the ferruginous matter in the Red Beds was an integral part of the original sediment, and that it was deposited originally in the series in practically its present distribution and arrangement, it is equally certain that there have been some later modifications of that primary distribution. A large majority of all variations of color within the Red Beds are limited by bedding planes; but there are numerous minor variations in color due to the migration of coloring matter along the lines of movement of ground-water.[1] Reducing solutions locally extract ferruginous matter along joints, or cause a general downward movement of iron. In the western Red Beds, as in Barrell's section of the Catskill formation in Schuylkill County, Pennsylvania,[2] the lower boundaries of many deeply stained bands are drawn less sharply than the upper. All of these are very minor features, however, in the distribution of the coloring matter of the series as a whole. The analyses (p. 161) furnished by Blackwelder illustrate the effect of leaching along a joint; the color changes from red to greenish, the net iron content is reduced from 3.26 per cent to 1.53 per cent, and the ratio of ferric to ferrous iron drops from 3.02:1.00 to 0.89:1.00.

IS THE FERRUGINOUS MATERIAL IN THE SAME FORM AS AT THE TIME OF SEDIMENTATION?

Variations in degree of oxidation.—Is the color due to recent oxidation in weathering? It has sometimes been asserted that the color of the Red Beds is a superficial matter, due to the weathering of originally dull-colored sediments. In support of this idea drill records have been quoted, showing that beyond a certain depth

[1] Cf. Richardson, *op. cit.*, p. 376.

[2] See Joseph Barrell, "The Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, 4th Ser., XXXVI (1913), 437 ff.

below the surface the rocks are no longer red. S. F. Emmons states, respecting the Maroon formation of the Tenmile district, Colorado,[1] that "in depth, as shown in underground workings, the red color generally gives way to a greenish gray." In another paragraph of the same folio, Emmons states that igneous or hot-water alteration destroys the red color. Inasmuch as the ores of this district are related intimately to igneous and hot-water action, it is natural to suppose that mine workings would be the most likely of all places in which to find such effects. The relation here described is probably a local and abnormal phenomenon.

In his description of the sedimentary rocks of the Anthracite and Crested Butte quadrangles, where the general situation is similar to that in the near-by Tenmile district, Eldridge[2] states that "the upper division [of the Maroon conglomerate] is of a peculiar red or chocolate color, except in regions of local metamorphism" of the kind mentioned also by Emmons.

Drilling explorations in the oil regions of Oklahoma and Texas recently have given us some additional information on the behavior of the color with depth. Gould[3] tells of a well some 3,300 feet deep in southeastern Oklahoma, in which "the last of the typical Red Beds was encountered" at a depth greater than 2,000 feet. The underlying strata were dull-colored sediments like those outcropping along the eastern (lower) margin of the Red Beds. Nowhere does he mention any change in color due to depth.

A well sunk 3,095 feet at Ashland, Wisconsin, passed through typical red sandstones of the Lake Superior group all the way, without any suggestion of a change in color with depth.[4]

It is to be remembered that most of the western Red Beds series are not colored uniformly throughout, but include many lighter-colored strata; and that many of the Red Beds successions include gray and green members. Any drill cutting through such a series would find, of course, changes in color with depth, but they would not be progressive, and they would have no causal connection with depth whatsoever.

[1] *Op. cit.* [2] *Op. cit.*

[3] C. N. Gould, "Petroleum in the Red Beds," *Economic Geology*, VIII (1913), 768–80.

[4] Data from F. T. Thwaites, *op. cit.*

This variegation itself constitutes one of the most unanswerable arguments against weathering in the present cycle as the cause of the red color. The distribution of gray and green beds among the red does not appear to have any definite relation to coarseness of grain, as in the case of intensity of the red color, nor to any other single stratigraphic feature; and it certainly bears no constant relation to the topographic surface.

Origin of mottling.—The green spots present in some otherwise red strata have been explained, on the hypothesis that the red color is due to recent oxidation in weathering, as remnants of the original color of the beds; but, as will be shown presently, it is much better in accordance with fact to explain them as spots in originally red sediments, deoxidized by the agency of some particle of organic matter which was present in the original sediment.

Dale[1] discusses the origin of the green spots in red and purple slates in part as follows:

> The difference in color from the green to purple to red is manifestly due to the differences in the amount of hematite. [See analyses, p. 160.] The green fossil impressions in purple slate may throw some light on the origin of these spots. In this case the effect of organic matter, whether the carbonaceous matter of the lining of an annelid boring or from a marine alga, has been to diminish the quantity of Fe_2O_3 in the slate. The increase of the carbonates may be directly connected with the production of CO_2 by decaying organisms and the consequent decrease of the Fe_2O_3. In view of all these facts and indications, the spots may be safely regarded as probably produced by chemical changes consequent upon the decay of organisms.

The same conclusion is reached by Miller with respect to green spots in the red Vernon shale (Silurian, central New York). Miller[2] finds dark organic centers in many of the spots, and attributes the color of green shales associated with the red strata to more abundant dissemination of organic matter.

It is probable that a very small quantity of organic matter may reduce or prevent the oxidation of a considerable amount of iron. The ferruginous matter necessary to stain a sediment is so small in amount that the quantity of organic matter necessary to accomplish the reduction of a patch less than an inch in diameter, like

[1] T. N. Dale, The Slate Belt of Eastern New York and Western Vermont, *Ann. Rept. U.S. Geol. Survey No. 19*, 1899, Part 3.

[2] *Op. cit.*

most of the green spots in Red Beds, is so small that it could easily be effaced or removed. A tiny fragment of vegetable fiber or the remains of a few minute organisms of any kind probably would suffice.

Cause of gray and green bands in red beds: Barrell's hypothesis.—Barrell[1] states that in the Catskill formation of eastern Pennsylvania gray and green colors are typical of sandstones, and red colors of shales. He therefore suggests a causal relation between coarseness of grain and condition of the iron content, as follows:

> These relations show that there was a tendency toward deoxidation during the formation of the beds of sand, of oxidation during the deposition of the Catskill muds. Where the clay and iron oxide were sparing in quantity, the deoxidation was effective. The conditions which accompanied the deposition of clay and iron oxide also permitted oxidation to dominate over deoxidation.[2]
>
> The lack of oxidation of the iron in the sandstones, in spite of its lesser quantity, suggests that more abundant ground-waters in the sands may have kept out the air and permitted the organic matter to accomplish its effects, or perhaps that here the ratio of organic matter was in excess of the ferric oxide.[3]
>
> A few rare carbonaceous streaks have been observed in the Catskill and the plant impressions are in places found in deoxidized shales. Coaly and pyritiferous plant fossils are also preserved in some of the olive sandstones.[4]

No actual remnants of organic matter are reported to have been found in *red* strata, though markings interpreted by Barrell as rootlet marks are noted by him in certain horizons of red shales.

That physical conditions of deposition alone should have favored oxidation in the finer-grained sediments and retarded it in the coarser seems highly improbable. Where meteoric water moves most freely, there the most oxygen is carried in solution. The more rapid the circulation of ground-waters, the more effective are those waters as oxidizing agents, instead of vice versa, as suggested by Barrell.

For the lesser quantity of iron in the sandstones we already have offered an explanatory hypothesis (p. 164). The smaller the amount of ferric oxide present in a sediment, the smaller, of course, is the amount of organic matter necessary to bring about its reduction—or the reduction of a sufficient part of it to mask the color of the remainder. If organic matter were distributed equally among

[1] *Op. cit.* [2] *Ibid.*, p. 458. [3] *Ibid.*, p. 469. [4] *Ibid.*

all the sediments of the series, it would cause gray and green colors in the sands rather than in the muds, by reason of the mechancial concentration of ferric oxide in the latter. The ratio of ferruginous materials to organic matter seems to be the dominating factor in determining the colors of ferruginous beds. Barrell's second suggestion in the foregoing quotation, dealing with this point, deserves more careful investigation.

Much of the organic matter carried as sediment in surface waters tends to be concentrated with the muds, for reasons analogous to those already suggested in the case of ferruginous material (i.e., fine division); but the proportion so concentrated is probably smaller in the case of organic matter than in that of ferruginous material, because of the indiscriminate distribution of driftwood, the growth of vegetation in most regions of clastic deposition, and other similar factors. In any of these cases organic matter in large quantities may enter into the composition of sands and muds alike, and thus bring about a higher ratio of organic to ferruginous matter in the sands than in the muds.

These controlling factors are so complex that no constant relation between coarseness of grain and distribution of organic matter is to be expected. It is evident from the quotations on p. 170 that definite organic remains in the section there under consideration are confined chiefly to gray and green strata; and it is also evident that such strata include both shales and sandstones. An examination of the detailed section[1] of the Catskill formation published by Barrell in this paper reveals a somewhat less uniform relation between coarseness of grain and color of beds than one would understand to be the case from reading the text or the labels on the graphic columnar section.[2] Of the 3,864 feet of beds definitely described as of one or the other type, 2,179 feet (56.4 per cent) bear out Barrell's generalization that gray and green colors are typical of sandstones and red colors of shales, 901 feet (23.3 per cent) are noncommittal, and 754 feet (20.3 per cent) are in opposition to the rule. This variability is in better accord with the complexity of the factors controlling the distribution of organic matter in sediments than a more constant relation would be; and suggests

[1] Barrell, *op. cit.*, pp. 451–56. [2] *Ibid.*, p. 457.

that even here the distribution of organic matter may be a controlling influence in determining the colors of the individual strata.

Dawson,[1] in discussing the Triassic (?) Red Beds of Nova Scotia, says of the gray sandstones and shales interstratified with them, that "where thick, they always contain either fossil plants, bituminous matter or thin seams of coal, or all of these. The following sentence from Geikie,[2] relative to the Old Red Standsone of the British Isles, is also interesting in this connection: "It may be observed also that where gray shales occur intercalated among the red sandstones and conglomerates they are often full of plant remains, and may contain also ichthyolites and other fossils which are usually absent from the coarser red sediments."

Organic matter the controlling influence in the case of the western Red Beds.—Nowhere in the literature on the western Red Beds is there suggested such a definite and relatively constant association of green and gray colors with sandstones, and of red with shales, as that which Barrell sees in the Catskill formation, and as that which is described as occurring in the Siwalik formation of India.[3] In the foregoing quotation from Geikie, the opposite relation is implied in the Old Red Sandstone series of Great Britain. In the Red Beds of the western United States variegation is perhaps more common in shales than in sandstones, though it occurs to a marked extent in both.[4] The distribution of gray and green colors in the Red Beds coincides very closely with the distribution of organic remains in the same series, in so far as such remains are present; and this close association, together with the chemical probabilities of the case, suggest that organic remains now obliterated explain at least the greater part of the remaining gray and green areas and strata. The decolorization of these sediments may, therefore, have been complete before their burial under later strata. The

[1] J. W. Dawson, "On the Colouring Matter of Red Sandstones and of Greyish and White Beds Associated with Them," *Quar. Jour. Geol. Soc. London*, V (1848), 25–30. Quotation from p. 26.

[2] Geikie, *op. cit.*, p. 1003.

[3] Medlicott and Blanford, *A Manual of the Geology of India*, II (1879), 524–26. Quoted by Barrell, *op. cit.*, pp. 463–64.

[4] Cf. Permian of the Pecos Valley and of the Zuni and Colorado plateaus; and the Jura-Trias Painted Desert sandstone of the latter plateau.

occurrence of traces of organic matter in red strata may be explained by an unusually high content of ferric oxide in those strata, or by later reoxidation of iron at one time in the ferrous state. The fact that much the greater part of the occurrences of colors characteristic of ferrous compounds are in distinct beds with definite boundaries, indistinguishable in most other characteristics from other beds which are not so colored, is good evidence that this distribution of ferrous and ferric compounds, or of the substances responsible for these compounds, was accomplished for the most part at the time of sedimentation. It is well to remember that the gray and greenish strata are very subordinate in the Red Beds of the western United States.

The general conclusion to be drawn from the preceding discussion is that there has been in the western Red Beds no extensive change of ferrous to ferric iron, or vice versa, since the time of sedimentation; and also that the original distribution of these compounds in the series was influenced most largely by the distribution of organic matter.

Variations in hydration of ferric oxide.—That various degrees of hydration exist in the ferric oxide of the Red Beds today is clear from the variety of red, brown, and yellow hues which appear in some members of the group. The major part of the ferric oxide in the Red Beds is no doubt but poorly hydrated.[1] The bright- and deep-red and red-brown colors (which are most common in the western series) may be attributed to hematite (anhydrous Fe_2O_3) or to turgite ($2Fe_2O_3 \cdot H_2O$). The lighter browns, yellow-browns, and yellow tints are referable to göthite ($Fe_2O_3 \cdot H_2O$) or limonite ($2Fe_2O_3 \cdot 3H_2O$), or possibly in some cases even to xanthosiderite ($Fe_2O_3 \cdot 2H_2O$).

The freer passage of water through the sandstones as compared with the shales makes the constituents of the former, after consolidation, more susceptible of hydration than those of the latter. It is entirely probable that in some cases at least this factor of porosity heightens the contrast in color between coarse and fine sediments; but it apparently has not affected the greater part of the Red Beds, in which the ferric oxide is relatively anhydrous. Van

[1] Cf. Richardson's investigation, discussed on p. 166.

Bemmelen has shown that chemically prepared ferric hydrate, after being partially dehydrated, if placed in a medium saturated with water vapor, at ordinary temperature, takes up again part of the lost water.[1] Brescius went so far as to say that "when nearly dry, ferric hydrate has almost as great a tendency to take up water as oil of vitriol itself."[2] This does not appear to be true, however, of hematite found in nature. Once *completely* dehydrated, ferric oxide becomes a stable compound.

It remains to inquire into the means by which dehydration of the more hydrous compounds might have been accomplished to produce the low hydrates, in case these were not originally in the same condition. The first agent of dehydration which presents itself is that of heat. Elsden makes the following statement:

> The influence of temperature and moisture upon the iron hydrates is well known. In the case of laterite in India, the yellow xanthosiderite soon weathers to reddish-brown turgite, owing to dehydration. In the hot and arid regions of South California the soils are dark red in colour, the iron being in the form of hematite instead of the hydrous forms, göthite or limonite. Dehydration also takes place in the hot regions of the Southern Appalachians, where the air is comparatively humid. It is only the deeper portions of the soil which retain the iron in a hydrated form.[3]

In all of the above mentioned cases, the source of the heat which produces the reaction in question is the sun's rays. Its action in the soils is limited to a superficial stratum rarely more than 15 feet in maximum depth.[4] Obviously, the direct influence of insolation cannot be responsible for any extensive dehydration in the Red Beds, whose characteristic colors are known to extend to depths of more than 2,000 feet.[5]

[1] J. M. Van Bemmelen, "Sur le colloide de l'oxyde ferrique," *Recueil des travaux chimiques des Pays-Bas et de la Belgique*, VII (1888), 112.

[2] E. Brescius, "Researches on Ferric hydrate," abstract in *Jour. Chem. Soc. London*, XXIV (1871), 497.

[3] J. V. Elsden, *Principles of Chemical Geology* (London: Whittaker & Co., 1910), p. 97.

[4] W. O. Crosby, "On the Contrast in Color of the Soils of High and Low Latitudes," *Amer. Geologist*, VIII (1891), 74; E. A. Smith, *Geol. Survey of Alabama, Rept. for the Years 1881 and 1882*, p. 186.

[5] See p. 168.

Another source of heat which might be suggested is that of igneous intrusions. The absence of igneous rocks in the greater part of the western Red Beds, including the regions where drilling has shown the colors to be unchanged at depth, proves that this has not been a factor of widespread importance. Heat due to regional metamorphism or to structural deformation of any sort must likewise be discredited here, as the Red Beds are substantially flat-lying over vast areas, and are nowhere intensely deformed or metamorphosed, except locally in the immediate neighborhood of igneous bodies.[1] That compression due to the weight of overlying sediments may have created sufficient heat for the accomplishment of extensive dehydration must be recognized as a possibility, although in many areas where the Red Beds occur the requisite overlying sediments are not known ever to have existed, and the uppermost members of the series in these localities are as brilliantly red as any below them. Furthermore, pressure creates heat only by the performance of mechanical work, and microscopic study of the Red Beds reveals no evidence of internal deformation.

Crosby[2] concludes that the process of dehydration of ferric oxide is largely a spontaneous one, which goes on independently of any outside influence whatsoever, though aided by high temperatures. He states as evidence in support of this hypothesis that the red sedimentary formations and the red iron ores of the world occur in the older systems chiefly, while in the younger systems ferruginous formations and ores are commonly yellow. There are, however, many exceptions to this rule, such as the buff Cambrian sandstones of the Mississippi Valley, the modern red residual iron ores of Cuba, and the dark-red hematitic bog ores in Sweden and elsewhere; and furthermore, the dehydration of the pre-Cambrian red sandstones and argillites may be attributed in some cases partly to regional metamorphism, which has not affected the younger beds.

Richardson[3] has given much weight to this "essentially spontaneous" process. He states that "the dehydration of ferric hydrates tends to go on under ordinary conditions without any unusual cause."[4] "This has been repeatedly demonstrated by experiment."[5] But none of the experimenters to whom Richardson

[1] See p. 168. [2] *Op. cit.* [3] *Op. cit.*, p. 392. [4] *Ibid.* [5] *Ibid.*

refers[1] appears to have considered the observed dehydration as truly "spontaneous"; and certainly they have shown the process to be closely dependent upon external conditions. The chemically precipitated colloidal ferric hydrates possess, when first formed, a higher content of water than any of the forms known to occur as minerals. According to Van Bemmelen,[2] on standing in a dry medium at ordinary temperatures these colloids gradually approach the composition $2Fe_2O_3 \cdot H_2O$, beyond which the percentage of combined water is not reduced without the application of much higher temperatures. Under water, or in air of moderate humidity, they have not been shown to lose water beyond the composition $Fe_2O_3 \cdot 2H_2O$ except at temperatures above 50° C.,[3] and heating at 50–60° C. for 2,000 hours failed to bring about dehydration beyond the composition $2Fe_2O_3 \cdot H_2O$.[4] Temperatures as high as these cannot be assumed to have existed, except locally, in the Red Beds sediments since burial. The so-called spontaneous dehydration observed in the laboratory is probably subject to the terms of Van Bemmelen's conclusion: "The red-brown substance, which has been considered to be a hydrate, is a colloid . . . . which has no stable composition; it maintains an equilibrium with the tension of the water vapour in the surrounding medium."[5] Since burial, the great mass of the Red Beds sediments, except in the most arid districts of the West, have been saturated with ground-water, a condition decidedly unfavorable to dehydration at the temperatures there existing.

Yet another agent of dehydration is mentioned by Elsden:

> The presence of any substance in solution which lowers the vapour tension of water will lower the inversion temperature of gypsum. . . . . Even solid

[1] J. M. Van Bemmelen, "Sur le colloide de l'oxyde ferrique," *Recueil des travaux chimiques des Pays-Bas et de la Belgique,* VII (1888),106–14; Edward Davies, "Action of Heat on Ferric Hydrate in Presence of Water," *Jour. Chem. Soc. London,* XIX (1866), 69–72; G. C. Wittstein, "Über das Verhalten des Eisenoxyhydrates unter Wasser," *Vierteljahrreschrift für praktische Pharmacie,* I. Band (1852), 275–76.

[2] *Op. cit.*, pp. 110–11.

[3] T. Carnelly and James Walker, "The Dehydration of Metallic Hydroxides by Heat," *Jour. Chem. Soc. London,* LIII (1888), 89; D. Tommasi, "Ferric Hydrates," abstract in *Jour. Chem. Soc. London,* XLIV (1883), 24.

[4] Davies, *op. cit.*, p. 70.

[5] Van Bemmelen, *op. cit.*, p. 114. Translated from the French.

gypsum . . . . can be changed into anhydrite by a concentrated solution of sodium chloride. . . . . These facts are of interest as pointing to the possibility of dehydration of minerals in rocks, in contact with salt solutions, at a temperature considerably below their normal inversion point.[1]

. . . . The occurrence of red ferruginous sandstone in conjunction with layers containing brown hydrated ferric oxide is less readily explained [than the superficial dehydration of soils, mentioned in the quotation on p. 174, *supra*], but the dehydration of certain beds may have been effected by contact with salt solutions, as in the case of gypsum already referred to above.[2]

Dehydration by contact with salt solutions presumably would affect the more porous beds first; whereas in the western Red Beds, as already described,[3] it is generally in the more porous beds that the lighter colors occur, and the shales are in general of deeper hue than the sandstones. Just how far the action of salt solutions may have been effective, both during and since sedimentation, in accomplishing dehydration in the neighborhood of such saline deposits as occur in the Red Beds, it would be difficult to say; but for the group as a whole it appears that this agency cannot have been of general importance.

In summation, it may be said that while widespread dehydration of iron oxide in the Red Beds since sedimentation cannot, at present, be proved not to have taken place, the greater weight of evidence now at hand is opposed to it; that the opposite process, hydration, may well have been active in the more pervious beds of the series; and that, therefore, the probabilities are quite as much in favor of a lower degree as of a higher degree of hydration, on the average, in the Red Beds at the time of sedimentation than at present.

WAS THE COLORING MATTER A CHEMICAL OR A MECHANICAL SEDIMENT?

Having determined as nearly as the available evidence permits the condition of the coloring matter of the Red Beds at the time of their deposition, we may proceed to inquire as to the geographic conditions which gave rise to sediments so colored. The first

[1] Elsden, *op. cit.*, pp. 85–86. See also H. Stremme, "Zur Kenntnis der wasserhaltigen und wasserfreien Eisenoxydbildungen in den Sedimentgesteinen," *Zeit. für prakt. Geol.*, January, 1910, pp. 18–23.

[2] Elsden, *op. cit.*, p. 97. [3] P. 158–59.

question to be answered in this connection is: Was the ferruginous matter deposited as a mechanical or as a chemical sediment?

The general absence of coloring matter from the non-clastic members,[1] which are in very large part inorganic chemical precipitates, indicates quite clearly that the conditions favoring free chemical deposition of calcium and magnesium carbonate or of calcium sulphate were not those under which the coloring matter was usually deposited. The close limitation of ferruginous material to the clastic sediments proves that the conditions under which clastic sedimentation took place favored the deposition of iron oxide also, and strongly suggests that that material itself was carried and deposited as a mechanical sediment, for the most part at least. In this connection it is of interest to note that Dawson[2] drew a similar conclusion as early as 1848 with reference to the contrast in color between the clastic and non-clastic strata of the Red Beds of Nova Scotia.

The condition of the ferric oxide in the Red Beds sediments, as revealed by the microscope, is one of very fine division. Since fine division is to be expected from the mode of origin of the ferric oxide in soils,[3] this cannot be taken as evidence that it is a chemical precipitate, in place, in the rocks. If it were the latter, definite orientation of crystals of hematite with respect to peripheries of grains might be looked for. I never have seen this phenomenon in thin sections of Red Beds sediments. The microscopic evidence is therefore rather noncommittal as regards the present question.

The processes of weathering leave much the greater part of the iron content of all types of rock as a residue in the soil, subject to mechanical transportation. All of the other common chemical constituents of rock, with the probable exception of alumina, are leached from the soil more rapidly than ferric iron. The scarcity of iron in any form in the surface waters of the continents, abundantly shown by the analyses of lake and river water published by Clarke,[4] and its even greater scarcity in the ocean,[5] testify to the

[1] See p. 157. [2] *Op. cit.* [3] See p. 164.

[4] F. W. Clarke, "The Data of Geochemistry," 2d ed., *Bull. U.S. Geol. Survey No. 491*, 1911, chap. iii.

[5] *Ibid.*, chap. iv.

fact that chemical deposition of salts of iron is only exceptionally an important process in earth metamorphism. Glauconite, the most common of such deposits at the present time, is of such peculiar nature as to be readily recognized where it occurs in older sediments: it certainly is not involved to any appreciable extent in the origin of the Red Beds. Bog iron ore, the only other common type of ferruginous chemical precipitate at present, is connected intimately, in origin, with abundance of vegetation and with peculiar and limited topographic conditions; and although deposits of this type are scattered over many parts of the world, none of them is comparable in extent or in thickness to even the smallest of the Red Beds areas. Furthermore, no deposits similar in textural character to bog ores are known in the western Red Beds.

In view of the facts above stated, it seems a safe conclusion that the coloring matter of the Red Beds was transported and deposited almost if not quite wholly as a mechanical sediment; and, therefore, without danger of serious error, we may limit investigations of possible conditions of origin of this coloring matter to those which would produce it as a mechanical sediment purely. This applies to the gray and green members of the Red Beds series as well as to those in which the iron is present chiefly as ferric oxide; for if the ferrous iron in the former be explained as the result of the action of organic matter deposited in those strata,[1] the ferruginous matter may have been in the ferric form during transportation, quite as well as in any other.

[1] See pp. 170–72.

[*To be continued*]

STUDIES IN HYDROTHERMAL ALTERATION

PART I. THE ACTION OF CERTAIN ALKALINE SOLUTIONS ON FELDSPARS AND HORNBLENDE

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In the study of ore deposits from a genetic standpoint the subject of attendant wall-rock alteration has received deserved attention from geologists. Profound changes of a chemical and mineralogical character have been recorded at many places, and the relation existing between the various types of wall-rock alteration accompanying ore deposition led to the suggestion that a knowledge of the conditions which bring about such alteration would throw great light on the problem of ore genesis. The data obtained in regard to the temperatures, pressures, and nature of solutions would also be of value in interpreting the geologic history of such occurrences.

The most important of these alteration minerals are kaolin, sericite, and chlorite, and the knowledge concerning their origin is chiefly confined at present to speculations based on their modes of occurrence and their associated minerals. There is especially great difference of opinion[1] as to the origin of kaolin. By some writers kaolinitic alteration is attributed to the action of meteoric waters rich in carbonic acid, by others to meteoric waters which have made a cycle of underground courses, and by still others to the emanations from a cooling magma while these are possibly yet in a gaseous state. In regard to sericite and chlorite associated with ore bodies there is nearly general agreement that these have been formed by the action of the solutions which deposited the primary minerals, whether these solutions be magmatic or meteoric, upon the feld-

[1] Bibliographies of the literature on kaolin are given by Rösler, *Neues Jahrb.*, Beil. Bd. XV (1902), 231, and by Lazarevic, *Zeit. prakt. Geol.*, XXI (1913), 345. An introduction to a discussion of the origin of kaolin was initiated by Lindgren, *Econ. Geol.*, January, 1915.

spars and the ferromagnesian minerals. Calcite and quartz are also prominent products of these reactions. Further, the relations of these minerals to the ores indicate that the processes of alteration and ore deposition have gone on contemporaneously. This is shown by the progressive decrease in the intensity of the alteration laterally from the veins, and by changes in the character of the alteration in the same direction. For example, the following extract from the report by F. L. Ransome[1] on the "Economic Geology of the Silverton Quadrangle" illustrates these points.

At points 150 feet east of the lode the country rock is fine-grained and faintly mottled, showing only a few pale phenocrysts of feldspar and an occasional tiny grain of quartz. Under the microscope the rock reveals the character of a much-altered andesitic tuff or fine breccia. The feldspars have been completely altered to aggregates of sericite and calcite, while areas of calcite and chlorite probably represent former phenocrysts of augite. The groundmass is a rather indistinct aggregate of secondary quartz, sericite, and chlorite with a little apatite and rutile. The rock is wholly recrystallized into a secondary aggregate while retaining the gross structure of the original.

At a distance of 100 feet from the vein the . . . . chlorite and calcite are abundant, but much of the plagioclase is still recognizable. Sericite and quartz are not such prominent constituents. . . . .

At 50 feet from the vein . . . . the feldspar phenocrysts have been changed to aggregates of calcite and sericite, while areas of chlorite and calcite with sometimes rutile are all that remain of the phenocrysts of augite or biotite. The groundmass also, while preserving the outlines and in small part the substance of former lath-shaped feldspars, is now an aggregate consisting chiefly of quartz, chlorite, sericite, and a little rutile and apatite. . . . .

At 2 feet from the vein . . . . it is seen that alteration has been more thorough. . . . . The forms of the phenocrysts are preserved by pseudomorphous aggregates of sericite with some chlorite, calcite, and rutile apparently after biotite, and quartz, sericite, and chlorite in varying proportions after augite and plagioclase. The groundmass is entirely recrystallized . . . . and the dominant minerals are quartz and sericite.

A specimen taken from the wall of the vein showed more evident alteration . . . . and the rock is wholly recrystallized. The former phenocrysts of feldspar are replaced by pseudomorphus aggregates of quartz and sericite. . . . . Of the augite no trace remains, but some sericite inclosing rutile is apparently pseudomorphous after biotite. The groundmass is a finely crystalline mosaic of quartz and sericite. The notable feature of this wall rock is the absence of calcite and chlorite. . . . .

[1] F. L. Ransome, *Bull. 182, U.S. Geol. Survey,* pp. 116–18.

To sum up then, the alteration involves the change of the feldspars to sericite, calcite, and quartz; of augite to calcite and chlorite; and of biotite to chlorite, sericite, and rutile.

Chloritic alteration appears to precede sericitic alteration and to require less intense or less prolonged action or solutions of a different character, so that sericite is found closer to the veins than chlorite, and chlorite dominates farther from the veins. It may be in place here to note that many consider the solutions which emanate from the magma in its final stages acidic in character while others hold that they are alkaline. A study of volcanic gases and of the sublimates present in craters indicates that the volcanic vapors are quite certainly acid, and Day and Shepherd[1] found that the magmatic waters which they collected from the small dome within the crater at Kilauea were acid. However, to conceive of these solutions as remaining acid for a long journey through rock masses after their escape from the magma requires a high degree of acidity, and geologists have been loath to accept such a view.

It is clear then that the experimental formation of these alteration products from the feldspars and ferromagnesian minerals will give some clew as to the nature of the solutions and the temperature and pressure conditions that obtained during the deposition of the associated primary ore bodies. A study of the literature bearing on the subject of the hydrothermal alteration and syntheses of various silicates leaves the reader somewhat at a loss to discern the geologic application of much of the data. Some of the experimental work is of great interest chemically but not geologically. Hydrothermal investigations that begin with mixtures of oxides instead of with distinct mineral species may have in many cases comparatively little geologic significance. When the definite mineral can be prepared synthetically from pure materials, nearly ideal conditions may be obtained, with results that are beyond question. However, since many of the minerals whose investigation is of paramount interest and importance in their relation to the analysis of geologic processes cannot be prepared synthetically, the next

[1] A. L. Day and E. S. Shepherd, *Bull. Geol. Soc. Am.*, XXIV, 593.

[2] This literature is ably reviewed by G. W. Morey and Paul Niggli in *Jour. Am. Chem. Soc.*, XXXV, No. 9 (September, 1913), 1106–30.

best course to adopt is to use minerals of as high degree of purity as are available. The fusion of such a mineral before its investigation must be vigorously condemned because it is well established that the minerals which crystallize from a melt are not always like those which were originally fused, and in many cases several distinct minerals are produced by this process from a single species. If the glass that is formed by the fusion is used, it may differ chemically from the original mineral by the loss of volatile gases, and it must differ in its energy content.

For example, Lemberg's[1] important work is in part open to these criticisms, though the volume of data supplied by him is remarkable. Other work of this sort has been carried on in glass containers which of themselves may have furnished a most important source of error. Further, the concentrations of the solutions which have been used, as a rule, have been far in excess of those known to exist in ground or hot spring waters. Just how much difference this would make in the results obtained is not yet clear, though it is highly probable that the solutions as they come direct from the magma are far more concentrated than those which appear at the surface in the form of hot springs. It is also recognized that such solutions, after having been in contact with the wall rock throughout their courses, have probably changed notably their compositions and concentrations and may bear but small traces of some of their original constituents. As a result of these considerations it is at present an open question how much geologic significance is to be attached to investigations carried on with such concentrations as Lemberg used, though his results have thrown much light on methods of attacking the problem of mineral alteration. Other investigators, especially Thugutt,[2] Königsberger and Müller,[3] Friedel and Grandjean,[4] Baur,[5] and Chroustschoff,[6] have contributed highly suggestive data.

[1] J. Lemberg, *Zeit. deut. geo.. Ges.*, Vols. XXXV, XXXVII, XXXIX, LX.

[2] J. S. Thugutt, *Zeit. anorg. Chem.*, II, 64–107, 113–16; *Neues Jahrb. Min. Geol.*, Beil. Bd. IX, 554–624.

[3] Königsberger and Müller, *Centralbl. Min.*, 1906, pp. 339–48, 353–72.

[4] Friedel and Grandjean, *Bull. Soc. Min.*, XXXII, 150–54.

[5] Emil Baur, *Zeit. physik. Chem.*, LXI, 567–76; *Zeit. anorg. Chem.*, LXXII, 119–61.

[6] K. von Chroustschoff, *Compt. Rend.*, CXII, 677–79.

At the suggestion of Professor W. H. Emmons, the writer began in 1912 a series of investigations of a hydrothermal character with particular reference to the geologic application of the results. It was hoped to contribute something concerning the temperatures, pressures, nature, and concentrations of the solutions which produce new materials from the feldspars and from some of the ferromagnesian minerals.

PLAN OF THE WORK

The plan of the work has been to try the effect of various simple dilute solutions upon the feldspars and one ferromagnesian mineral at various temperatures and pressures. This has been done up to 280° C., at intervals of about 50°. It is planned to work on up to about 500° C. if the results justify such a course. The solutions have been tried at various concentrations, for different lengths of time, besides the different temperatures.

The minerals used have been nearly pure species. A high-grade adularia from the St. Gotthard tunnel, albite from the Amelia Court House locality, orthoclase from Elam, Delaware County, Pennsylvania, microcline from C. A. F. Kahlbaum (locality not known), and an aluminous hornblende from Renfrew, Ontario, Canada. These have in all cases been powdered to pass a 100-mesh sieve, and portions exactly or approximately one gram in weight have been used for each experiment.

THE OVEN

For work at temperatures above 100° C., the oven described as follows was constructed (Fig. 1). A box $28\frac{1}{2} \times 15 \times 16$ inches (outside measurements), made of sheet iron, is fastened at the edges to a similar box $26\frac{1}{2} \times 13 \times 15$ inches placed inside of it, with the space between packed with asbestos. A door at the front extends the full length and height of the oven, opening outward with hinges along the bottom. Two holes are cut in the top at H and H', Fig. 2, for the insertion of thermometers. A number of holes, o and o', about $1\frac{1}{2}$ inches in diameter are also cut in one end of the box, Fig. 3. When the oven is in use these holes are closed with loosely packed asbestos wool.

The heating arrangement consists of six coils of No. 22 nichrome wire wound on asbestos boards $\frac{1}{2}$ inch thick, 1 inch high, and 7 inches long. Each coil has a carrying capacity of three amperes and is securely fastened to the bottom in order that the box may be used in any position. Three of these coils are connected to a three-way snap switch *A*, and three with a similar switch *A′*, Fig. 4. By this means from three to eighteen amperes may be in use at one

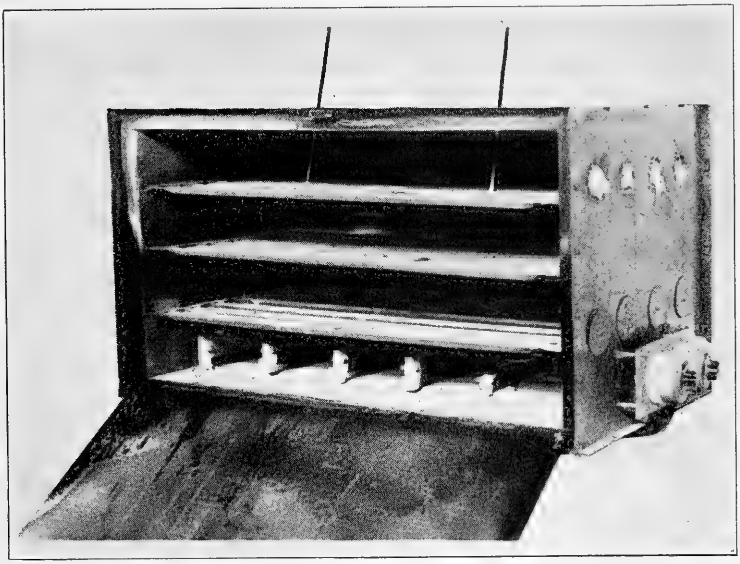

FIG. 1.—A view of the oven

time. The return wire is *L*, Fig. 4, which is also grounded on the box. The connections of coils Nos. 3 and 5, Fig. 4, pass to the thermo-regulator, *T*, Fig. 2, at *R* and *R′*, thence through the screws *K* and *K′*, Fig. 5, to the platinum contacts *Pt*, through the strip *S* to the box and out via the lead wire *L* to *B*, the socket, Fig. 4.

The construction of the thermo-regulator is as follows. A strip *S*, consisting of an above piece of copper 0.022 inch thick, is brazed to a piece of steel of the same thickness, and split longitudinally for an inch back from the free end so as to produce two contacts. *S*, Fig. 6, is fastened to the under side of block *B*, Fig. 5, which is pivoted between *E* and *E′*. The latter are inset along the sides of the base plate *A*. *D* is a brass rod brazed to the block *B*, making *D–B–S* a continuous piece pivoted at *V*, Fig. 6. *S′*, Fig. 6, is a steel spring pressing firmly against the under side of *D* so that

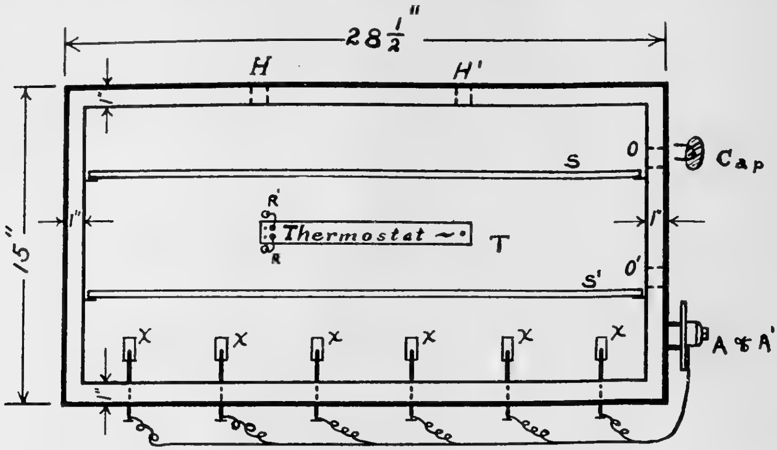

Fig. 2.—Front elevation of the oven

it is held close to the tip of screw *C* even when the contacts *Pt* are broken. *M* and *M′* are mica strips insulating *R* and *R′* from the rest of the device. *W* is a copper washer. *H*, Fig. 6, represents holes in the base plate *A*, through which bolts pass that hold the regulator against the back of the oven. A small condenser, not shown, is shunted around *K* and *Pt*, Fig. 6.

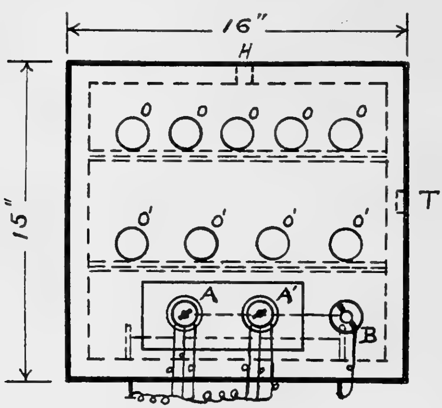

Fig. 3.—End elevation of the oven

Since the temperature coefficient of copper is greater than that of steel, a rise in temperature causes the strip *S* to bend the contacts *Pt* away from the tips of the screws *K* and *K′*, and thus cut out the coils Nos. 3 and 5. The fall of temperature which results causes a reversal of the bend of the strip until the contacts are again made at *Pt*, and the temperature rises. To adjust the oven for operation at higher or lower temperatures the screw *C*, Fig. 6, is turned in and the oven allowed to come to constant temperature. This requires about one hour. If the temperature so obtained is too low, the screw must be turned in still farther and such adjustments continued until the desired point is reached. Since the sensitiveness of the oven is much greater with both contacts acting together, and the expansion of the metals produces some torsion, it is necessary to adjust the screws at *K* and *K'*, until both coils Nos. 3 and 5

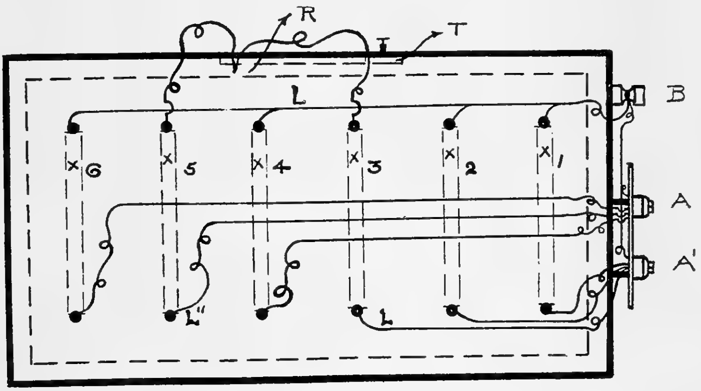

FIG. 4.—Under side of oven, showing wiring and arrangement of coils

come on or off together. Parts of the regulator not otherwise described are made of brass.[1]

This oven has proved highly satisfactory when used on an ordinary 110-volt power or lighting circuit. At the highest temperature at which it has been used, 300° C., the variations during several weeks have not been more than 3°. It has been in use as long as three months continuously, with similar slight variation, at about 180° C. Greater sensitiveness can be obtained by lengthening the strip *S*. The device has also served as an efficient drying oven. When but one of the six coils is being used—preferably No. 4, because it is centrally placed—it maintains a temperature averaging around 110° C., without having the regulator in the circuit.

[1] The writer is indebted to Captain A. De Khotinsky of Kent Chemical Laboratory for the greater part of the work in the design and construction of the oven.

In the early part of the investigation Jena glass tubes were used, provided with an inner tube of copper open at one end, in which the minerals and solutions were placed. This prevented contact of the solutions and the glass when the apparatus was placed in a nearly vertical position, but left only a small part of the solutions in direct contact with the mineral powder. Where glass tubes were used, these were first placed inside of steel tubes made of ordinary steam pipe $1\frac{1}{2}$ inches inside diameter, closed at one end by a screw

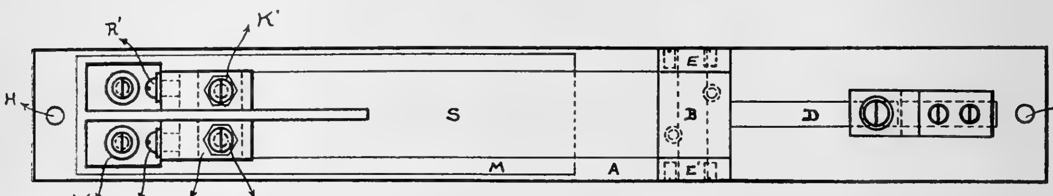

Fig. 5

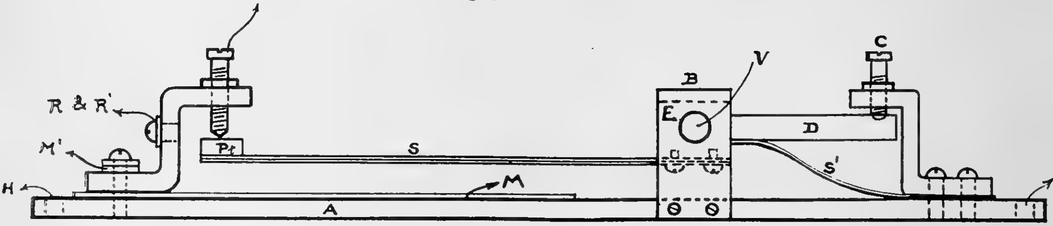

Fig. 6

FIG. 5.—Thermo-regulator, plan. FIG. 6.—Thermo-regulator, side elevation

cap and placed in the oven with the open end against one of the holes *o* and *o'*, Fig. 3. Accidents to the thermo-regulator from possible explosions were thus prevented, though the trouble caused by bursting of the glass tubes led to their abandonment. In their place copper tubes about 18 to 22 inches long with $\frac{5}{8}$ inch inside diameter and $\frac{1}{16}$-inch walls were used. One end of each of these was closed with a plug of copper about $\frac{1}{8}$ inch thick driven in about $\frac{1}{8}$ inch past the end of the tube and the end then sealed in an oxy-acetylene flame. The solution and the mineral powder were then placed in the tube, a plug of copper inserted as above, and the end then sealed while the tube was partly immersed in a freezing mixture.

These tubes have a calculated bursting strength of 6,000 pounds to the square inch and have proved highly satisfactory. They have been practically unattacked except by sulphide solutions, in which cases the tubes were found lined with beautiful chalcocite crystals.[1] They cost after sealing about one-half as much as Jena bombs of similar size and can be used repeatedly. The oven will accommodate about fifty such tubes at one time.

EXPERIMENTAL WORK

Group I: Effect of pure water on feldspar and hornblende.—In many hydrothermal processes it is not yet clear how significant a rôle is played by the water independent of the dissolved matter. Hence the first step in this investigation was an attempt to determine the efficiency of pure water in such processes. Accordingly the powdered minerals were covered with 300 c.c. of distilled water in open nickel crucibles with a device for maintaining the water at constant volume. The crucibles were placed on electric hot plates

TABLE I

No.	Mineral	Time	Vol. of Solution	Vol. Tube	Temp.	Press. Atm.	Results
1......	Adularia	14 days	300 c.c.	....	100° C.	1	No alkalinity
2......	Hornblende	14	300	....	100°	1	" "
3......	Adularia	82	50	80 c.c.	183°	11	" "
4......	Hornblende	82	50	80	183°	11	" "

and the water kept boiling for 14 days. At the end of that time the solutions were tested for alkalinity with neutral litmus paper and phenolphthalein. No change of color appeared after five minutes' standing. A similar pair of experiments at 180° C. in the sealed copper tubes ran for 82 days and at the end of that time the solutions were similarly tested and again no alkalinity developed. The minerals were then examined under the microscope and compared with slides of untreated mineral (Table I). No change could be detected. These results are not quite in accord with those of

[1] In certain cases a small amount of copper recrystallized on the plugs, probably owing to the fact that the drawn copper has a higher solution tension than crystalline copper.

Clarke[1] and Steiger,[2] who found that the solutions obtained by allowing various minerals—including orthoclase—and rocks to stand in contact with water containing a few drops of phenolphthalein developed more or less alkalinity. Cornu[3] obtained an alkaline reaction toward moist litmus paper from various powdered minerals. Königsberger and Müller[4] found also that adularia was but little attacked at 300° C. by pure water, the chief attack being parallel to the principal cleavage. Up to this temperature water alone is not to be considered an important reagent toward adularia or hornblende.

Group II: Effect of sodium carbonate solutions on feldspars.—The efficiency of carbonate solutions in hydrothermal processes is commonly conceded; this conclusion is based on the abundance of carbon dioxide in certain hot spring waters, and the presence of carbonates in the altered rocks and in the veins. The data given by Clarke[5] and by Peale[6] show not only that carbon dioxide dominates

TABLE II

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
5..	Adularia	3 yrs. 1 mo.	Na_2CO_3	N/2	1,000 c.c.	......	15° C. *ca.*	1	No change
6..	"	90 days	"	"	300	......	100° C.	1	" "
7..	"	82	"	"	50	80 c.c.	183°	11	Analcite
8..	"	18	"	"	40	85	233°	30	"
9..	Microcline	18	"	"	40	75	233°	30	"
10..	Albite	18	"	"	40	85	233°	30	Tube burst

in certain thermal waters but that sodium is generally an abundant metallic ion in such waters. The concentration is low, rarely reaching as much as 1 per cent, though the carbonates make up as much as or even more than three-fourths of the total dissolved matter. In order then to follow the original plan and to use solutions comparable to those found in nature, solutions of sodium carbonate were employed as shown in Table II. The concentration

[1] F. W. Clarke, *Jour. Am. Chem. Soc.*, XX, 739–42.

[2] George Steiger, *ibid.*, XXI, 437–39.

[3] F. Cornu, *Tschermak's Mitteilungen*, XXIV, 417–32.

[4] *Op. cit.*, p. 360.

[5] F. W. Clarke, *Bull. 491, U.S. Geol. Survey*, pp. 180–81.

[6] A. C. Peale, *Bull. 32, U.S. Geol. Survey.*

of one-half normal is equivalent to nearly 2.8 per cent. The minerals in Nos. 5 and 6 showed no change under the microscope. Tube No. 10 burst owing to defective sealing, but the mineral was unchanged. In all the others crystals of analcite formed along the sides of the tubes and around grains of feldspar as nuclei. Solution No. 6 was not saved, but the solutions from Nos. 7, 8, and 9 were placed in paraffin-lined bottles and on examination after several weeks' standing showed heavy gelatinous precipitates. These precipitates were then examined and were found to consist of silica and water. In spite of the fact that tube No. 10 burst, the results obtained from later experiments, notably Nos. 33 and 34, make it certain that similar results would have been secured had no accident occurred.

These facts indicate definite attack and solution of the feldspars with loss of one molecule of silica from each molecule of feldspar together with an exchange of the potash of the adularia for the soda of the solution. The following equations, using empirical formulae, indicate the reactions, which have positive experimental basis.

$$KAlSi_3O_8 + H_2O + Na' \rightarrow NaAlSi_2O_6,H_2O + SiO_2 + K'$$

and

$$NaAlSi_3O_8 + H_2O + Na' \rightarrow NaAlSi_2O_6,H_2O + SiO_2 + Na'.$$

The analcite was identified optically and also by sifting out the unchanged feldspar with its adhering analcite, gelatinizing the remaining crystals with hydrochloric acid, and allowing a small portion of the solution to crystallize out under the microscope as sodium chloride; the remaining portion of the solution was tested for alumina with ammonia water. After drying at 110° C., the crystals yielded water in a closed tube.

Group III: Sodium carbonate solutions on hornblende.—A series of experiments, Nos. 11, 12, and 13, exactly like those in Group II, were then tried with hornblende as the mineral (Table III). In no

TABLE III

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
11..	Hornblende	3 yrs. 1 mo.	Na_2CO_3	N/2	1,200 c.c.	......	15° C. *ca.*	1	No change
12..	"	90 days	"	"	300	......	100° C.	1	" "
13..	"	82	"	"	60	85 c.c.	183°	11	" "

case did there appear, under the microscope, to be any change. No gelatinous silica separated from the solutions after long standing.

Group IV: Potassium fluoride solutions on feldspars and hornblende.—Fluorine has long been looked upon as one of nature's important mineralizers;[1] it occurs in small quantities in the emanations from Kilauea,[2] is abundant as fluorite in metalliferous veins, is a constituent of many minerals such as apatite, amblygonite, lepidolite, topaz, and cryolite, and is considered by Spurr[3] an essential constituent of muscovite. Table IV shows the experiments con-

TABLE IV

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
14..	Adularia	82 days	KF*	N/10	60 c.c.	85 c.c.	183° C.	11	No change
15..	"	18	"	"	50	80	233°	30	" "
16..	Microcline	18	"	"	40	75	233°	30	Minute rods
17..	Albite	18	"	"	30	70	233°	30	No change
18..	Hornblende	82	"	"	60	85	183°	11	Brown iron oxide
19..	"	15	"	"	50	75	233°	30	Tube burst

*This salt contained a small amount of the acid salt HKF_2.

ducted with potassium fluoride. In experiments Nos. 14, 15, 16, and 17 the feldspars showed no change other than a possible slight etching. In No. 16 there appeared some minute bacteria-like rods that were not further identifiable. In No. 18 the hornblende was vigorously attacked. The product is an amorphous brown mass resembling limonite and consisting of hydrated iron oxide together with grains of partially altered mineral. Some of these grains are bleached to isotropic transparency, others have a rim of isotropic matter surrounding ellipsoidal grains in the interior. No gelatinous precipitate appeared in the decanted solution on standing in paraffin lined bottles for several months. In No. 19 the tube burst and the mineral appeared unchanged.

Group V: Mixtures of carbonate and fluoride solutions on feldspars and hornblende.—Since the feldspars were not visibly attacked by the fluoride solutions but had been attacked by the alkaline carbo-

[1] See especially C. Doelter, *Allgem. chem. Min.*, p. 207, and W. Bruhns, *Neues Jahrb. Min. Geol.*, II (1889), p. 26.

[2] A. L. Day and E. S. Shepherd, *Bull. Geol. Soc. Am.*, XXIV, 592.

[3] J. E. Spurr, *Professional Paper 42, U.S. Geol. Survey*, p. 233.

nate solutions, it was deemed advisable to try a mixture of the two solutions to see if the traces of fluoride present would modify the results in any way (Table V). The feldspars in Nos. 20, 21, and 22

TABLE V

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
20..	Adularia	90 days	Na_2CO_3+KF	N/2+N/10	300c.c.	......	100° C.	1	No change
21..	"	41	" "	" "	54	80c.c.	183°	11	" "
22..	"	82	" "	" "	60	80	183°	11	" "
23..	"	18	" "	" "	40	85	233°	30	Analcite
24..	"	15	" "	" "	60	100	280°	65	Needles
25..	Orthoclase	15	" "	" "	50	100	280°	65	Twins of unknown mineral, also needles
26..	Microcline	18	" "	" "	48	100	233°	30	No positive change
27..	Albite	18	" "	" "	48	80	233°	30	Analcite
28..	Hornblende	90	" "	" "	300	......	100°	1	No change
29..	"	41	" "	" "	60	85	183°	11	" "
30..	"	82	" "	" "	60	85	183°	11	" "
31..	"	3	" "	" "	60	85	233°	30	" "

were not visibly attacked and the decanted solutions gave no precipitate on standing. No. 23 showed crystals of analcite. No. 24 showed some needles with parallel, or nearly parallel, extinction and possibly some isotropic forms, though these were not positively identified. No. 25 contained many needles like those in No. 24 with no analcite. These needles have an extinction angle of less than 2°; index in the direction of elongation is 1.490, and at right angles to this 1.517; elongation is negative. The crystals after drying at 110° C. yield no water in a closed tube. Good terminations at both ends are common. No. 25 also contained beautifully twinned crystals, illustrated in the accompanying sketch (Fig. 7) made with a camera lucida. The crystals

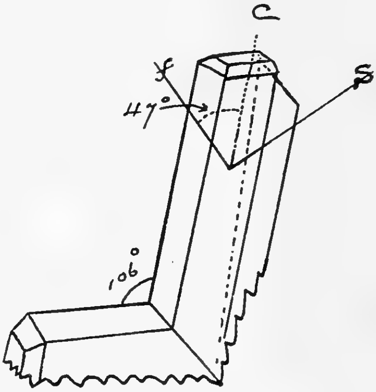

FIG. 7.—Twinned crystals produced by experiment No. 25.

are perfectly transparent, have an index close to but greater than 1.565, an extinction angle of 43°, and are probably monoclinic. In experiment No. 26 no evidence of any change appeared. In experiment No. 27 icositetrahedra of analcite appeared, some free and some including fragments of the feldspar. The hornblende in all of this group of experiments was unchanged. It is concluded that the presence of the fluoride had practically no influence upon the alteration.

Group VI: Sodium bicarbonate solution upon feldspars and hornblende.—These experiments embody an attempt to increase the pressure both by raising the temperature and by increasing the concentration of the carbon dioxide through dissociation of bicarbonates (Table VI). In experiment No. 32 scarcely any feldspar

TABLE VI

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
32..	Adularia	15 days	$NaHCO_3$	N/2	45 c.c.	85 c.c.	233° C.	30	Analcite
33..	"	15	"	"	50	85	280°	65	"
34..	Albite	15	"	"	45	85	233°	30	Analcite and needles
35..	"	15	"	"	60	105	280°	65	Tube burst, but needles formed
36..	Hornblende	15	"	"	45	85	233°	30	No change
37..	"	15	"	"	45	85	280°	65	" "

remained and much analcite appeared as free crystals and as aggregates. Gelatinous silica appeared in the decanted solutions after some time. Similar results with decided etching of the feldspar grains appeared in No. 33 where the pressure was practically doubled. Possibly less analcite formed in this than in the previous experiment at the lower temperature. In No. 34 with albite, analcite also formed with many needles like those in experiment No. 25, Table V. In experiment No. 35 the tube burst where poorly sealed, but the mineral was nearly all altered to needles as in experiments Nos. 24, 25 and 34. These were analyzed qualitatively and found to consist of soda, alumina, and silica and yielded no water in a closed tube. The writer was not able to find any natural sodium aluminum silicate whose properties agree with these. Needles having the same optical properties as these also appeared in experiment No. 46 and are undoubtedly the same thing.

The hornblende was unchanged in experiments No. 36 and 37; the tube in No. 37 burst some time during the course of the heating.

Group VII: Potassium bicarbonate solutions on feldspars and hornblende.—These are similar to the experiments of Group VI, except that potassium bicarbonate solutions were substituted for the sodium bicarbonate solutions (Table VII). In no case either

TABLE VII

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
38..	Adularia	15 days	$KHCO_3$	N/2	45 c.c.	75 c.c.	233° C.	30	No change
39..	"	15	"	"	50	90	280°	65	" "
40..	Albite	15	"	"	45	75	233°	30	" "
41..	"	15	"	"	60	105	280°	65	" "
42..	Hornblende	15	"	"	45	100	233°	30	" "

with the soda or potash feldspar or with hornblende did any change appear in the minerals. The writer is unable to give an adequate explanation of this fact, but it may have some bearing on the question whether potash is introduced or not in hydrothermal processes.

Group VIII: Sodium tetraborate solution upon feldspars and hornblende.—A few experiments were tried with borax solutions with results very similar to those produced by the alkali carbonates (Table VIII). In No. 43 well-formed crystals of analcite as rhom-

TABLE VIII

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
43..	Adularia	15 days	$Na_2B_4O_7$	N/4	50 c.c.	100 c.c.	233° C.	30	Analcite
44..	Albite	15	"	"	50	95	233°	30	No change
45..	Hornblende	15	"	"	50	90	233°	30	" "

bic dodecahedra appeared. No alterations occurred in the other experiments.

Group IX: Sodium sulphide solutions upon feldspars and hornblende.—The presence of the metallic sulphides indicates that at certain phases of the vein-forming process sulphide solutions must be present. Though the solutions are undoubtedly very complex, their efficiency as hydrothermal agents is very probably due to a few components. The physical state of these solutions has been recently shown by Tolman and Clark[1] to depend decidedly upon the composition, at least at ordinary temperatures, and it may also have some decided influence upon the character of the alteration. In the following experiments the copper tubes were vigorously attacked and chalcocite crystals lined the walls of the tubes (Table IX). In No. 46 needles of the anisotropic crystals like those

TABLE IX

No.	Mineral	Time	Solution	Concentration	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
46..	Adularia	15 days	Na_2S	N/2	50c.c.	120c.c.	233° C.	30	Analcite and needles
47..	Albite	15	"	"	50	100	233°	30	Analcite
48..	Hornblende	15	"	"	50	105	233°	30	No change

obtained in experiments Nos. 25 and 34 were formed, together with well-formed analcite crystals. Very little of the original feldspar remained. In No. 47 perfect analcite crystals appeared as icositetrahedra and as combinations of the cube and rhombic dodecahedron. These vary in size from one-half to one millimeter in diameter. The hornblende in experiment No. 48 was not attacked and no pyrite could be identified in the product. No sulphur was obtained by heating the mass in a closed tube. The results with the feldspars are quantitatively greater than in any other experiment; this was probably due to the fact that the hydrogen sulphide is a weaker acid than is carbonic acid and the hydrolysis therefore produces a more strongly alkaline solution.

Group X: Aluminate solutions on feldspars and hornblende.—In the previous experiments the loss of silica from the minerals resulted in an apparent rise of the alumina content of the new minerals. With the thought that possibly an increase in the concentration of the alumina in the solutions might cause the solubility product for

[1] C. F. Tolman and J. D. Clark, *Econ. Geol.*, IX (1914), 559.

compounds richer in alumina to be exceeded, a few experiments with aluminate solutions were tried. These solutions were prepared by taking a weighed quantity of aluminum sulphate, precipitating the aluminum as hydroxide, washing the precipitate and then adding it to normal sodium or potassium hydroxide and diluting

TABLE X

No.	Mineral	Time	Solution	Concentration of K or Ka	Vol. Sol.	Vol. Tube	Temp.	Press. Atm.	Results
49..	Adularia	15 days	Sodium aluminate	N/2	40c.c.	80c.c.	280° C.	65	Analcite
50..	"	15	Potassium aluminate	"	40	85	280°	65	Hexagonal plates and needles
51..	Orthoclase	15	Potassium aluminate	"	60	120	280°	65	Hexagonal plates and needles
52..	Albite	15	Potassium aluminate	"	30	70	280°	65	Hexagonal plates
53..	Hornblende	15	Potassium aluminate	"	35	75	280°	65	No change

one-half. After this had been allowed to stand for several hours it was filtered from its slight precipitate (Table X). In No. 49 analcite crystals formed, which were identified chemically and microscopically. In Nos. 50, 51, and 52 twinned hexagonal plates, with anomalous division into fields under polarized light, resulted, as shown in Fig. 8. These gelatinize with hydrochloric acid and contain sodium, but no aluminum could be detected in them by a microchemical test. The hornblende was not attacked.

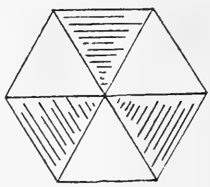

FIG. 8.—Twinned hexagonal plate resulting from experiments Nos. 50, 51, and 52.

Group XI.—Albite and hornblende were heated for 15 days at 280° C., with saturated solutions of calcium bicarbonate. The tubes burst in each case and the minerals showed no change.

GEOLOGIC BEARING

Though the alteration of feldspars to analcite has not been commonly described, in many cases it is very possible that some of the determinations of isotropic minerals as glass may be incorrect, and that analcite has been overlooked. In examining the slides in the University of Chicago collection a slide from a trachyte of Bannberscheid, Westerwald, Nassau, was found which showed the soda feldspars altered to analcite though the original crystal boundaries remained sharp. The alteration does not follow cleavage cracks but appears in irregular patches. Mr. K. F. Mather in a forthcoming paper will describe an eruptive cone of Quaternary age in the canyon of the Mancos River ten miles southwest of Mancos, Colorado—locally known as the "blowout"—which is cut by dikes of augite minette. These dikes carry fragments of granite xenoliths which are deeply corroded and partially assimilated. The feldspars are altered to analcite—identified microchemically. A careful study of rock specimens would probably show that this type of alteration is much more common than has been supposed.

SUMMARY

1. Alkaline solutions of different characters dissolve the feldspars with separation of silica and crystallization of compounds less rich in silica. The solutions are probably hydrolyzed since the reactions are accelerated by the presence of alkalies, by increased concentration of the alkalies, and by higher temperatures.

2. Feldspars and hornblende are not appreciably attacked by pure water at temperatures up to about 300° C. adularia to at least 350° C., showing that the dissolved substances rather than water alone must cause the differences in the nature of the alterations.

3. Albite and orthoclase feldspar seem to respond to the action of the alkalies in nearly identical ways, and hence the conclusion is patent that they have very similar chemical structures.

4. The influence of small amounts of fluoride and borates as mineralyzers has not been found important, at least in the presence of the other substances. This leads to the suggestion that possibly the mineralyzing effect is merely that of causing solution at temperatures where the silicates in question would otherwise be much less soluble.

5. It is notable that no kaolin or kaolin-like substance forms from alkaline solutions at temperatures up to 280° C. The sugges-

tion seems necessary that since pure water has practically no effect on the feldspars, and that since the alkaline waters produce minerals other than kaolin, kaolin probably forms by the action of acid solutions upon the feldspars. The literature bearing on the field occurrences of kaolin shows a striking lack of references to association of carbonates and kaolin, though this would be expected if carbonated waters are the cause of the formation of kaolin from the feldspars.

6. The general agreement of the data obtained throughout the range of temperatures used shows that the silicates may be studied with the apparatus described, up to 300° C., with gratifying results and without great mechanical difficulties, and also without the necessity of contamination from undesirable sources such as glass tubes.

The writer is indebted to Professor W. H. Emmons for suggesting the problem and to Professor A. D. Brokaw for sincere interest and many suggestions during the progress of the work. Further work of a similar sort is in progress and the next paper will deal with the action of various acid solutions, especially hydrofluoric acid on the same group of minerals.

ZONAL WEATHERING OF A HORNBLENDE GABBRO

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In connection with a study of the alteration of the so-called trap or diabase dikes at La Grange, Georgia,[1] one of the writers collected some interesting specimens showing a weathered zone in which the decomposition is extreme, with an abrupt transition into fresh rock, practically free from the effects of weathering. This paper is concerned with the description of a typical specimen, and with the results of chemical analyses of the fresh rock, the partly altered material, and the extreme phase of alteration present.

La Grange is in the extreme western edge of the state, not many miles from the southern end of the belt of crystalline rocks which extends from Maine to Alabama. The country rock is for the most part gneiss, cut by granitic intrusions. Both gneiss and granite are cut by pegmatites and basic dikes, the latter usually called diabase, and supposed to be of Triassic age. At La Grange there is a series of dikes, only a few feet apart, ranging up to forty feet in width, with an average of about four to six feet. The dikes have a general north-south trend, and are abundant over an area of a little more than half a square mile.

The older crystalline rocks are very deeply weathered. The basic dikes have been considerably altered at the surface, and in many instances may be traced by the strong iron stain they have imparted to the soil. In some excavations, however, material showing no appreciable effects of weathering may be obtained. In some cases weathering has been strongly marked along joints, changing the character of the material for an inch or less, beyond which the rock is fresh. Fig. 1 shows a specimen in which the zone of alteration is about an inch thick. Analyses were made of the

[1] L. P. Smith, *Alteration of Diorite by Weathering*, Dissertation, University of Chicago, 1915.

outside, much-altered portion, and of the part of the weathered zone adjacent to the fresh material. A specimen from an entirely fresh portion of the same dike was analyzed for a comparative study.

The fresh rock is finely grained, holocrystalline, nearly black in color, with small white feldspar crystals evenly distributed through

FIG. 1.—Specimen showing zone of weathering $\times\frac{1}{2}$. Circle shows approximately the part from which the slide shown in Fig. 3 was taken.

the mass, which is dominantly hornblende. Small garnets, irregularly distributed, and small crystals of pyrite are present. Microscopically, the rock is found to consist of hornblende (65 per cent), which may be secondary, labradorite (32 per cent), with small amounts of orthoclase and augite, and accessory magnetite, pyrite, titanite, and apatite. One of the typical slides is shown in Fig. 2. The rock is a hornblende gabbro.

The partly altered material is notably lighter in color than the fresh rock. Most of the hornblende has been weathered, leaving brown iron stains and a small amount of chlorite, but some particles of apparently fresh hornblende are to be seen. The feldspar has been changed to a chalky white material in an iron-stained matrix. Microscopical study reveals some unchanged hornblende, but for the most part only alteration products are discernible. Limonite, white mica (probably also gibbsite), chlorite, zoisite, and a small quantity of magnetite make up the mass. The weathered zone is sharply set off from the fresh material even in thin section. In Fig. 3 the fresh portion is shown on the left, changing to altered on the right.

FIG. 2.—Section of fresh hornblende gabbro ×20. (Two rather large cracks appear as light bands.) Ordinary light.

FIG. 3.—Slide showing transition from fresh to altered portion of specimen. ×25. Crossed nicols.

The most completely weathered portion is a friable, earthy, non-plastic mass, strongly iron stained, and so thoroughly disintegrated that the original texture of the rock is practically lost. No microscopical study of this material was undertaken.

The results of chemical analyses, made in duplicate in every case and in triplicate in a number of determinations, are given in Table I. The following recognized effects of weathering are well illustrated: loss of silica, apparent increase in alumina, increase in ferric iron, decrease in ferrous iron, loss of bases, increase of combined water, and decrease in specific gravity. The very small development of carbonates may be due to the fact that most of the available carbon dioxide has formed soluble bicarbonates in removing lime, magnesia, and alkalies.[1]

TABLE I

	1*	2†	3‡		1*	2†	3‡
SiO_2	45.16	26.02	23.34	TiO_2	.31	.18	.15
Al_2O_3	17.52	28.60	32.70	MnO	.47	.51	tr.
Fe_2O_3	3.12	11.38	21.77	CO_2	none	.12	.52
FeO	6.99	4.00	none	S	.10	.04	none
MgO	4.67	3.03	.57				
CaO	17.50	7.96	.75	Total	100.10	100.23	100.20
Na_2O	2.39	1.54	.39				
K_2O	1.37	.81	1.19	Total Fe	7.62	11.78	15.24
H_2O-	.04	.87	3.77	Sp. Gr.§	3.020	2.813	2.340
H_2O+	.46	15.17	15.05				

* Fresh Rock.
† Altered near the fresh rock.
‡ Altered; most decomposed portion.
§ Pycnometer method.

On the assumption of constancy of alumina[2] the analyses may be recalculated, and gains and losses estimated, as shown in Table II. The change in total iron is worthy of note, in that there is a slight loss shown in 2, with a marked increase in 3. A suggested explanation is that during the early stages of alteration some soluble ferrous compound was formed, which migrated, perhaps by capillary action, to the outer zone before it was precipitated by oxidation to

[1] In this connection it may be noted that wells in or near the dikes are said to yield water containing considerable amounts of lime, while those in the gneiss, farther from the dikes, yield comparatively soft water. Unfortunately, no quantitative data on these waters are available.

[2] G. P. Merrill, *Rocks, Rock Weathering and Soils*, p. 208.

the ferric condition. That the removal of ferrous iron may take place in the early stages of alteration has been commonly recognized.[1]

TABLE II

	1	2	Gain	Loss	3	Gain	Loss
SiO_2	45.16	15.94	....	29.22	12.51	....	32.65
Al_2O_3	17.52	17.52	....	....	17.52	....	....
Fe_2O_3	3.12	6.97	3.85	....	11.66	8.54	....
FeO	6.99	2.45	....	4.54	none	....	6.99
MgO	4.67	1.86	....	2.81	.31	....	4.36
CaO	17.50	4.87	....	12.63	.34	....	17.16
Na_2O	2.39	.94	....	1.45	.21	....	2.18
K_2O	1.37	.50	....	.87	.64	....	.73
H_2O-	.04	.53	.49	....	2.36	2.32	....
H_2O+	.46	9.29	8.83	....	8.06	7.60	....
TiO_2	.31	.11	....	.20	.08	....	.23
MnO	.47	.31	....	.16	tr.	....	.47
CO_2	none	.07	.07	....	.28	.28	....
S	.10	.02	....	.08	none	....	.10
Total	100.10	61.39	....	....	53.95	....	....
Total Fe	7.62	7.21	....	4.05	9.33	1.71	....

Essentially the same relations are shown by the "straight line" diagrams of Mead.[2] In Fig. 4 the analyses of the altered portion are compared with that of the fresh rock. The full line represents analysis 2, and the broken line analysis 3. In general, 3 is merely an accentuation of 2, except for potash and total iron, both of which show a change of sign in the direction of change. It is apparent that in the later stage of alteration the removal of bases continues, and that it is out of proportion to the further removal of silica as compared with 2. The retention of potash is by no means unusual.

In Table III the analyses are recast to molecular proportions to emphasize some of the chemical and mineralogical features. It is to be noted that even in analysis 2 the amount of silica is insufficient to combine with all of the alumina to form kaolin. The alumina : silica ratios are as follows: 1, 1:4.36; 2, 1:1.57; 3, 1:1.19. For kaolin 1 : 2 is required. On the extreme assumption that all of the silica in 3 is present in the form of kaolin, the analysis may be said to

[1] C. K. Leith and W. J. Mead, *Metamorphic Geology*, p. 22, Henry Holt & Co. (1915).

[2] W. J. Mead, *Econ. Geol.*, VII (1912), 141–44.

represent (by weight) kaolin, 50 per cent; limonite, 25 per cent; bauxite, 18 per cent; other substances, 7 per cent. It is highly probable that part of the silica is present in some compound not containing alumina, and if so the amount of bauxite is correspondingly greater. This lends a distinctly bauxitic-lateritic aspect to the alteration.

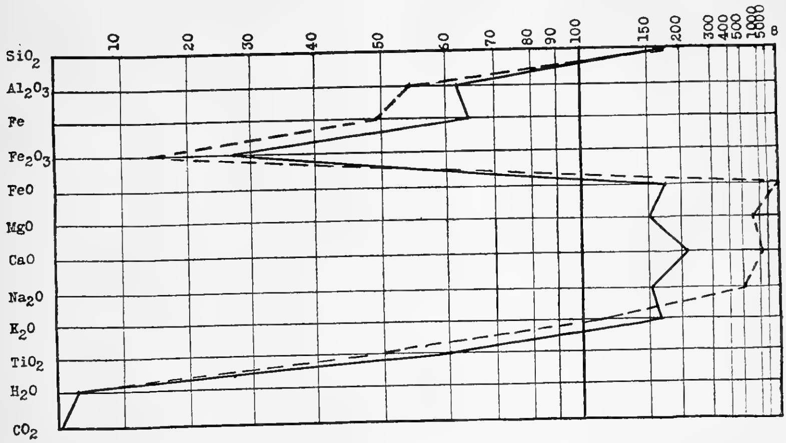

FIG. 4.—"Straight line diagram" showing changes in composition with alteration. The full line represents analysis 2, the broken line analysis 3, compared with the analysis of the fresh rock.

TABLE III

Per cent÷mol. wt.

	1	2	3		1	2	3
SiO_2	.747	.431	.387	CaO	.312	.142	.013
Al_2O_3	.172	.280	.320	Na_2O	.039	.025	.006
Fe_2O_3	.020	.070	.136	K_2O	.015	.008	.013
FeO	.097	.056	.000	H_2O+	.026	.845	.836
MgO	.116	.075	.014	CO_2	.000	.003	.012

Specimens similar to the one studied are not uncommon in the weathered part of the dikes, and the changes shown are believed to be fairly typical for the rock in question. It is to be noted that the fresh rock is much richer in iron than rocks which yield bauxite deposits, and richer in alumina than those yielding high grade laterite deposits.

Reviews

Lockatong Formation of the Triassic of New Jersey and Pennsylvania. By A. C. Hawkins. Annals N.Y. Acad. Sci., XXIII. 145–76, Plate 1, January 27, 1914.

The Lockatong formation is the middle member of the Newark series of the Triassic, extending from a point just west of Phoenixville, Pennsylvania, to Princeton, New Jersey. The rocks of the formation are dense, fine-grained, massive argillites, with some shales. The formation as a whole has a decidedly lens-like character. On the basis of the general structure, lithologic character, and type of fossils, which include estheriae, fish-scales, ostracods, and plant remains, it is concluded that the sediments were laid down near the center of an inland basin. The particles of the argillite are for the most part cemented by silica, which renders the formation very hard and a pronounced ridge-maker. The color of the beds is due to iron in various states of oxidation. The boundaries of the Lockatong are very uncertain, owing to the fact that it passes by a series of transitional dovetailing strata into the other formations of the Newark. Since part or all of the Lockatong may be contemporaneous with portions of the Stockton and Brunswick formations elsewhere, it seems that as a definite geological time unit the Lockatong is valueless. There are three principal joint directions in the Lockatong formation, the most important of which is remarkably constant, and extends into the borders of a diabase mass near Rocky Hill, which is interpreted as an extension of the Palisade sill. Titanium minerals, brookite and ilmenite, are found in this major joint series, apparently far removed from the diabase. Analcite and barite also occur. That these minerals are derived from the igneous rocks is indicated by similar occurrences in New Jersey elsewhere. Parts of the Lockatong argillite are very well adapted for commercial use.

R. C. M.

Geological Map of Tennessee. Compiled by Olaf P. Jenkins, A. H. Purdue, State Geologist.

This map represents Archean, Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, Cretaceous (Upper), Eocene, Pleistocene, and Recent formations. Few states have so wide a range of systems, Proterozoic, Permian, Lower Cretaceous, Miocene, and Oligocene only being absent. Pliocene (Lafayette) is indicated in the legend of the map but not shown on the map itself, and the legend seems to be intended to throw doubt on the validity of the formation in Tennessee.

Under the designation "Columbia Formation," loess, loam, and loose sand are grouped. This seems to us an unfortunate classification. The "Terrace Deposits" of the map are quite as appropriately classed as "Columbia" as the loess and loam which are so classed. We are of the opinion that the use of the term "Columbia Formation" should be discontinued (though possibly the term "Columbia Series" may be useful to include all Pleistocene non-glacial formations). What was originally grouped under the name Columbia included several formations of which the probable equivalents of the Terrace Deposits of this map were a chief member. "Loess" would seem to be an adequate designation of the deposits included under that term, without classing them as Columbia. Their classification as Pleistocene seems altogether adequate. The loess, of many regions at least, is of very different ages, and all of it does not belong to one formation in the chronological sense.

The map is distinct and represents sufficient change from its predecessors to be welcome. It is accompanied by elaborate explanatory legends and by four cross-sections which represent well the structure of the formations in the state.

The map may be had by application to the State Geologist, Nashville, Tennessee. Postage, 8 cents.

R. D. S.

Cretaceous Deposits of the Eastern Gulf Region, and Species of Exogyra from the Eastern Gulf Region and the Carolinas. By L. W. Stephenson. U.S. Geol. Surv., Prof. Paper 81, 1914. Pp. 75, pls. 21, charts 8.

In eastern Alabama and Georgia à terrane, previously regarded as forming the eastward extension of the Tuscaloosa series of western Alabama, has been shown by its unconformable relations with overlying formations, lithologic character, and contained plant fossils to be of Lower Cretaceous (Comanchean) age, though probably somewhat younger than the Patuxent. Belonging to the Upper Cretaceous (Cretaceous) of the eastern Gulf region are four formations, Tuscaloosa (regarded as Lower Cretaceous), Eutaw, Selma chalk, and

Ripley. The first, consisting of irregularly bedded sands, clays, and gravels, has an estimated thickness of 1,000 feet and rests unconformably on a basement of Paleozoic metamorphics, and in the east on Pre-Cambrian crystalline rocks and in part on Lower Cretaceous. The Eutaw formation, somewhat similar to the Tuscaloosa in lithologic character, is believed to be entirely marine, though much of the formation was doubtless laid down in very shallow water. It is 400–500 feet thick, rests conformably on the Tuscaloosa, and is overlain conformably in part by the Selma chalk, and in part by the Ripley formation. The Selma chalk consists mainly of more or less argillaceous and sandy limestones rendered chalky by their large content of foraminiferal remains. It is abundantly fossiliferous in certain portions, yielding large numbers of the *Exogyra* described in the latter portion of the paper. The Selma grades into the sandy member of the Tuscaloosa, and the clastic beds of the Ripley formation when followed along the strike. A thickness of 930 feet of the chalk formation has been measured in western Alabama. The Ripley formation, 250–350 feet in thickness, consists typically of calcareous and glauconitic sands, sandy clays, and impure limestones and marls of marine origin. It extends through parts of the Gulf states from southern Illinois to Georgia. A study of the faunas of the various formations is detailed, and correlations with other Cretaceous regions indicated by chart.

A description of the genus *Exogyra,* which includes three species with two varieties, constitutes the second portion of the paper.

R. C. M.

The Jurassic Flora of Cape Lisburne, Alaska. By F. H. Knowlton. U.S. Geol. Surv., Prof. Paper 85, Part D, 1914. Pp. 25, pls. 4.

The Jurassic of the Cape Lisburne area is estimated to have a very great thickness, 15,000 feet, and contains from 40 to 50 coal beds which range in thickness from 1 or 2 feet to over 30 feet. Plant collections from this area show 17 species of well-defined Jurassic types. The close similarity or identity of a number of forms with species from eastern Siberia and Mongolia is noteworthy. The flora indicates a warm-temperate or subtropic climate and the geographic range, especially into the Arctic and Antartic, is suggestive of the uniform mildness of the Jurassic earth-climate.

R. C. M.

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THE

JOURNAL OF GEOLOGY

APRIL-MAY 1916

ORVILLE A. DERBY

JOHN C. BRANNER
Leland Stanford Junior University

Orville Adelbert Derby, for many years one of the associate editors of this *Journal*, was born at Kelloggsville, New York, on July 23, 1851, and died by his own hand at Rio de Janeiro, Brazil, on November 27, 1915.

After graduating at the high school, Derby entered Cornell University in 1869, taking what was then called the scientific course. While he was yet a Freshman, however, he became so interested in geology and was such a promising student that he was selected by Professor Charles Fred Hartt, then professor of geology at Cornell, to accompany him on a trip to Brazil in the summer of 1870. That was the first trip made to Brazil by Derby; it determined both his career and the whole course of his life. On his first voyage he visited Pernambuco, and made the first considerable collection of fossils ever made at Maria Farinha, a locality that has since been looked upon with especial interest by students of the Mesozoic history of South America.

In the summer of 1871 he went to Brazil with Hartt again, this time visiting the Amazon valley and making an important collection of Carboniferous fossils from the limestones at Itaitúba on the lower Tapajos River.

In 1873 he graduated from Cornell University with the degree of Bachelor of Science, and the year following he continued his geological studies for the Master's degree, which he received in June, 1874. His thesis was "On the Carboniferous Brachiopoda of Itaitúba, Rio Tapajos," and was published as No. 2 of Vol. I of the *Bulletin of Cornell University*, Ithaca, 1874. That was Derby's first publication on the geology of Brazil, and it is not only a valuable paper in itself, but it is especially interesting in view of subsequent developments. The Itaitúba fossils were in compact limestone, but as they were silicified they could be obtained in satisfactory form only by dissolving away the surrounding rock —a long and tedious process which would have thoroughly discouraged most young men of Derby's age. The spires of many of the specimens of these brachiopods have seldom been surpassed for delicacy and perfection.

The art of illustration was far from being so well developed in those days as it is now, and we thought ourselves very fortunate in being able to make and use the crude photographs with which that paper was illustrated.

In 1873 Derby was appointed instructor in geology at Cornell, and in the summer of 1874 Professor Hartt made arrangements to go to Brazil again. Leave of absence was obtained, Derby was placed in charge of the work of instruction in the department, and in September, 1874, Hartt went to Brazil again, taking Branner with him as his only assistant and going by way of Europe. It is often said that Hartt went to Rio on the invitation of the Brazilian government or of the Emperor D. Pedro II. As a matter of fact he went entirely on his own responsibility and without invitation from anyone, but with the idea of inducing the Brazilian government to establish a geological survey under his direction.

Arriving in Rio de Janeiro, he at once devoted all his energies to interesting the leading men in a geological survey of the empire, and by the end of the year the survey was authorized and provided for, and O. A. Derby, Richard Rathbun, and E. F. Pacheco Jordão were named as assistants of the new "Commissão Geologica do Imperio do Brasil." In December, 1875, Derby reached Rio de Janeiro and began his work under the government. He held this position less than two years, for through a change of ministry the survey was abolished in 1877, and Hartt died in Rio that same year. Shortly after the suspension of the survey, however, Derby was given a position in the National Museum at Rio as curator in charge of geology, a position which enabled him to continue his studies on the geology of Brazil, and, to a certain extent, to preserve the results of the work of the extinct survey. He remained in the museum until 1886 when he was made state geologist of the Brazilian state of São Paulo.

The establishment of the São Paulo survey was a step of great importance to geological science in Brazil, for Derby's knowledge of and interest in the geology of the country as a whole enabled him to grasp more firmly the geological problems of that particular state, and at the same time he became and remained, up to the time of his death, the leading authority on the geology of Brazil. He was state geologist of São Paulo until 1904, when he resigned.

In 1907 a new federal geological service was provided for, and Derby was made its chief, a position he held during the rest of his life.

The first edition of Branner's *Geologia Elementar*, a work prepared especially for Brazilian students of geology, was thus dedicated: "To Orville A. Derby, who has devoted his life to the study of the geology of Brazil, and has done more than anyone else to solve its many problems, this work is affectionately dedicated." This is a brief and mild statement of Derby's great services to Brazil and to the science of geology, without mentioning his many other services to science and to that country.

First and last Derby was a paleontologist. He had no fondness for administrative work; he was but little interested in structural geology or in its methods; he was forced by circumstances into some acquaintance with microscopic petrography; but his interest in paleontology was genuine, deep, and all-comprehensive. From all the cares of office and the worries of life he found relief and happiness in boxes of poorly preserved fossils that most paleontologists would have put away as not worth while.

It was chiefly to this interest of his in paleontology that we owe Dr. C. A. White's *Contributions to the Paleontology of Brazil*, published at Rio in 1887; John M. Clarke's *Trilobites of the Ereré and Maecuru Sandstones*, Rio, 1896; *Upper Silurian Fauna of Rio Trombetas*, Rio, 1899; *Devonian Mollusks of the State of Pará*, Rio, 1899; and *Devonian Fossils of Paraná*, Rio, 1913. Besides these excellent works there are many smaller papers on paleontology that cannot be mentioned here, and there still remains unpublished an important volume by D. S. Jordan on the Cretaceous fossil fishes of Ceará.

During the last eight years Derby gave much of his time to the study of *Psaronius* and its relationships. The last of his published papers was on the stem structure of *Tietea singularis*, and appeared in the *American Journal of Science* for March, 1915, pp. 251–60.

Because he had to undertake work in regions but poorly supplied with maps, one of his first and most important duties, when he became state geologist of São Paulo, was the inauguration of topographic work. This work was intrusted to Horace E. Williams, an able and energetic young American to whom the state of São Paulo and the scientific world are indebted for an excellent series of topographic maps on a scale of one to 100,000, to say nothing of his explorations of the western portions of São Paulo, his work on the Serra da Canastra, etc.

Derby's own list of publications on the geology of Brazil numbers 125 papers. Naturally they embrace a wide range of subjects. Ten of his papers relate to the geology and genesis of the Brazilian diamonds. One of these, on the geology of the diamond and carbonado region of the state of Bahia, was the first publication to give an idea of the geology of that little-known district.

He became interested in the early cartography of Brazil, and published a number of papers on that subject.

As an author and as a scientific reasoner he was an extremely cautious man, so much so that the word "hedge" was constantly on his lips both for his own guidance and as a warning to his assistants.

The last evening I spent in his rooms at Rio de Janeiro he referred to this personal trait, and remarked that it had prevented his marrying—that he was too cautious to take the risk. This cautiousness of his was probably the real reason for some of the long delays in publishing his results, delays which led to the tying up of his own results and those of his assistants. Without doubt he hoped that the delays would enable him to put everything beyond question and to make his reports final and complete instead of preliminary and tentative. But the delays were prolonged from year to year until his assistants became discouraged and the government more or less exasperated at the lack of practical results for such great and long-continued expenditures. It was probably this long delay that finally led to his resignation as state geologist of São Paulo.

Derby never felt obliged to show results. After he had been state geologist of São Paulo for ten or twelve years, and had published next to nothing on the geology of that state, I asked him point blank, and with some feeling, where his results were. He replied: "They are in my head." We had to change the subject. But the important fact behind his delays is that the geology of São Paulo is difficult and involves problems that he had not been able to settle to his own satisfaction, and he was unwilling to commit himself definitely to paper and thus lay himself open to adverse criticism.

It seemed unfortunate for Brazil, for himself, and for the cause of science that he was unable to bring himself to take an active interest in the economic geology of the country. But his first and only interest in geology was in geology as a pure science. To him a fossil was a thing of beauty, of interest and value, and a joy forever, but a mine or an industry was, after all, only an industry whose main object was money-getting.

Derby was a man of unlimited grit. When once he decided upon a course of action nothing turned him to the right or to the left. His whole life is a demonstration of his power to make good in spite of obstacles that would have been insurmountable for most men—his determination to be the leading authority on the geology of Brazil, cost what it might.

How many of us would have lived for forty years, in a foreign country, cut off, as he was, from all personal contact with the geologists of the world at large and from the people of his own race and from his own family? And yet, from the time he went to Rio in 1875 to the day of his death he visited the United States only twice. One of these visits was in 1883 when he spent three months at Washington; the other was in 1890 when he attended the meeting of the American Association for the Advancement of Science at Indianapolis.

When the Commissão Geologica was abolished in 1877 the rest of us took to our heels. Not so Derby; he was not to be stampeded by a simple lack of funds or of employment; he meant to save the results of the work of Hartt and of his colleagues, and, in so far as it could be done, he did it.

Personally Derby was one of the kindest-hearted and most affectionate men I have ever known. His last dollar was at the service of his friends, and his right hand knew nothing of the kind deeds done by his left. The beggars in the streets found him their easiest victim.

He was held in the highest esteem in the community in which he lived. He stood for uprightness and honorable dealing, and he was never the willing tool of designing adventurers. For many years he has been justly regarded as the leading geologist in South America, and his standing is due, not to the fact that there are but few first-class geologists in South America, but to his ability and to his excellent work.

In 1892 he was awarded the Wollaston prize of the Geological Society of London, while his distinguished services led to his being made one of the associate editors of the *Journal of Geology* and to his election to membership in various learned societies in different parts of the world. He was a frequent contributor to the *American Journal of Science* and to this *Journal.*

A list of his papers on the geology of Brazil up to 1909 is given in the *Bulletin of the Geological Society of America,* XX, pp. 36–42. To that list should be added thirteen additional titles of papers that have appeared since its publication.

TYPES OF PRISMATIC STRUCTURE IN IGNEOUS ROCKS[1]

ROBERT B. SOSMAN
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The question of the cause of columnar or prismatic jointing in igneous rocks was thought to have been satisfactorily settled by the writings of Thomson, Mallet, Bonney, Iddings, and others, until it was reopened recently by the investigations of several French physicists. As the subject seems to be in need of further discussion and experimental study, I have brought together observations on several hypotheses of prismatic jointing, hoping to show that the study of these structures may yield much more precise information than is now available as to the original conditions of occurrence of the igneous rocks in which such structures are found.

CRYSTALLIZATION HYPOTHESIS

The first hypothesis as to the origin of prismatic structure which had any experimental or observational basis was that of Gregory Watt,[2] and may be entitled the "crystallization hypothesis." Watt, in 1804, observed that a large mass of basalt which he had melted down in a reverbatory furnace crystallized radially from centers which were fairly regularly spaced in a horizontal plane; the intersections of these radially growing fibrous bundles formed a network of hexagonal partings through the mass, leading Watt to the conclusion that this manner of crystallization, by its vertical extension upward from the base of a mass of basalt, must have been the cause of the prisms found in the Giant's Causeway, Fingal's Cave, and elsewhere.

[1] Presented before the Geological Society of Washington, April 28, 1915.

[2] Gregory Watt, "Observations on Basalt, and on the Transition from the Vitreous to the Stony Texture," etc., *Phil Trans.*, 1804, pp. 279–314. Watt also explains clearly the contractional origin of such structures as mud and starch prisms.

This explanation seems to have been satisfactory to many of the earlier authors of geological treatises,[1] but before many years had passed doubts began to arise as to whether this process could have been an efficient cause of the numerous cases of columnar structure which began to accumulate in geological literature as travel became more extensive and observations multiplied. James Thomson[2] in 1863 urged that contraction of a homogeneous mass was a sufficient cause for all columnar structure, and that the hypothesis of crystallization from centers was unnecessary and improbable. Mallet[3] discussed the contraction hypothesis in detail, showing how it would account, in his opinion, for all of the structures found in columnar rocks. Bonney,[4] Iddings[5] and others have followed the same lines of argument.

CONTRACTION HYPOTHESIS

The radial-contraction hypothesis is still the explanation generally accepted by the textbooks, and perhaps applies in the majority of cases of prismatic structure. But a much more complete discussion of this hypothesis than has yet been published could be profitably made, for there has been no attempt at any quantitative application of it to actual occurrences. It has served hitherto simply as a qualitative explanation. The relation of the size, shape, curvature, jointing, and other properties of the columns to the original temperature, viscosity, and rate and manner of cooling of the rock is capable of more exact definition.

For instance, the time factor in cooling in its relation to the elastic properties of the rock does not seem to have been considered

[1] More or less vaguely associated with this definite hypothesis was the idea of a "concretionary force" which is frequently referred to. The idea that columns might be due to the mutual compression of actual spheroids of lava (now understood as "pillow" lava) was also more or less confused with the crystallization hypothesis. Watt's idea of the matter seems to have been perfectly clear, but Mallet, for instance, misunderstands Watt's "mutual compression of spheroids" to mean actual compression (*Phil. Mag.*, L [1875], 221–24); the words "mutual interference of radially growing spheroids" state Watt's meaning more clearly.

[2] *Brit. Assoc. Rep.*, 1863, Abstract, p. 89.

[3] *Phil. Mag.* (4), L (1875), 122–35, 201–26.

[4] *Quar. Jour. Geol. Soc.*, XXXII (1876), 140–54.

[5] *Amer. Jour. Sci.*, XXXI (1886), 321–31.

in previous discussions. If the mass is cooling slowly, the crystallized shell may be able to adjust itself by a slow movement to the stress produced by contraction, so that the strain does not for some time pass a given value. If the cooling is rapid, on the other hand, the strain may be rapidly raised through the inability of the mass to flow as rapidly as the stress is applied. Under conditions of rapid cooling, therefore, the temperature at which the stresses become sufficient to produce rupture will be higher than under conditions of slow cooling.[1]

Another point concerns the conditions of rupture. Published discussions of formation of columns by contraction have tacitly assumed that the condition of rupture is that the *extension* shall exceed a certain limiting value. This is only one out of several possible conditions of rupture. Various hypotheses have been proposed by physicists (limiting tension, limiting positive or negative strain, limiting shear), of which the best founded experimentally is that of Tresca and Darwin, according to which rupture occurs when the maximum difference of the greatest and least principal stresses reaches a certain limiting value.[2] Although the acceptance of this condition of rupture as the fundamental one does not simplify the problem of calculating the actual physical magnitudes of temperature, temperature gradient, stress, and strain in any given case, yet it should permit a more complete analysis of the kinds of structure that will result from different conditions of cooling. Such an analysis is, however, beyond the scope of the present article.

CONTRACTION OF PHYSICALLY HETEROGENEOUS MATERIAL

Prismatic structure is very common in materials which are heterogeneous as regards their state of aggregation (such as mud and wet starch), that is, in which solid matter is suspended in or mixed with a liquid. It is a question whether the formation of a prismatic structure in such materials is strictly comparable with most cases of contraction prisms in igneous rocks. The principal

[1] The above-mentioned effect of the rate of cooling is quite distinct from the commonly recognized effect, which appears in the *temperature gradient* away from the surface of the cooling mass.

[2] Love, *Theory of Elasticity*, 1906, p. 119.

difference is in the strength of the materials. Very considerable stresses may accumulate in a glassy or crystalline rock before rupture occurs, and when it does occur, the crack extends suddenly a considerable distance into the mass. A layer of wet mud, on the other hand, accumulates practically no stresses, as the forces of cohesion and liquid surface tension to be overcome are very small. The cracks therefore form much more gradually, and grow little by little as desiccation proceeds. They have even been observed to form under water,[1] probably as a result of freezing and melting.[2]

It is possible that some basalt prisms have been formed in the same way as the slowly formed mud cracks, by the slow shrinkage of a material which is partly solid and partly liquid, for the normal course of crystallization of an igneous rock consists in the separation of certain portions as crystals while the remainder stays liquid until a lower temperature is reached. It has been commonly observed, however, that the boundaries of contraction columns frequently cut across the crystals of the rock, showing that solidification was practically complete before the crack formed.

An example of prismatic, although not columnar, structure produced in this manner is probably to be found in the "apparent sun-crack structure in diabase," described by Wherry as occurring in the upper surface of the great diabase sill of Pennsylvania, west of Philadelphia.[3] He explains it as due to contraction jointing followed by the penetration of still liquid material into the cracks from below. At first sight this occurrence has some of the characteristics of prismatic structure due to liquid convection accompanied by segregation, but a re-examination of the structure by Dr. Wherry and the author in May, 1915, showed that the angles and polygons

[1] Moore, *Am. Jour. Sci.*, XXXVIII (1914), 101–2.

[2] Mud cracks may also belong to the other types of columnar structure. Where the deposit is very fine grained and homogeneous, the walls of the columns may show the feathery patterns characteristic of a fractured solid, resulting from breaks (either sudden or slow-growing) which occurred when the material was nearly dry, and indicating the existence of tensional stresses. On the other hand, a prismatic structure of apparently convectional origin has been observed by Guillaume (*Soc. Franc. Phys., Bull. Seances*, 1907, pp. 50–51) in mud flows in sub-Arctic regions.

[3] E. T. Wherry, "Apparent Sun-Crack Structures and Ringing-Rock Phenomena in the Triassic Diabase of Eastern Pennsylvania," *Acad. Nat. Sci., Philadelphia, Proc.*, LXIV (1912), 169–72.

are those produced by contraction, not by convection (see p. 225). A photograph of the occurrence is shown in Fig. 1. An examination by Wherry of the cross-section of one of the small "dikes" shows that it has an irregular boundary, that it grades off without a sharp break into the surrounding rock, and that it is more coarsely crystalline than the surrounding material. It appears to be, therefore, a case of prismatic structure due to contraction in physically heterogeneous material, and quite distinct from the usual type of contraction prisms. Dr. N. L. Bowen, of this laboratory, informs me that he has seen a similar structure in the upper surface of a diabase sill north of Lake Superior.[1]

CONVECTION HYPOTHESIS

E. H. Weber[2] described in 1855 a phenomenon observed by him on microscope slides on which a solid was being precipitated from alcohol-water mixtures. The liquid was observed to circulate and to divide itself up into regular polyhedral cells. A similar phenomenon was observed by James Thomson[3] in 1882, in a soap solution. It remained for the French physicist Bénard,[4] in 1900, to make a really thorough study of the subject, and his experiments have brought out a number of new and interesting facts.

A polygonal structure is easily produced in a layer of liquid which is shallow in comparison with its horizontal extent, and which is losing heat from its upper surface or is gaining heat from its lower surface. If the top surface is cooler than the bottom, then the colder and denser liquid at the top tends to sink and the warmer bottom layer to rise, and convection currents must be set up. If the conditions are uniform and constant, a *steady state of flow* of some kind must ultimately be set up. In a flat liquid sheet of indefinite extent this state of flow must take the form of parallel rising and descending currents, and these will flow with minimum

[1] Canada, Bur. Mines, *Ann. Rep.*, XX (1911), 125–26.

[2] *Pogg. Ann.*, XCIV, (1855) 452–59.

[3] *Phil. Soc. Glasgow, Proc.* XIII, (1882), 464–68. Thomson recognized the similarity of the pattern to that of the Giant's Causeway.

[4] H. Bénard, *Les tourbillons cellulaires dans une nappe liquide*, etc., thesis, Paris, 1901; *Rev. gén. Sci.*, XI (1900), 1261–71, 1309–38.

FIG. 1.—Prismatic structure due to contraction in physically heterogeneous material. Top of diabase sill west of Philadelphia, Pennsylvania.

friction only when they divide the liquid into hexagonal cells, as can be shown by the same line of argument as is used to prove that a uniform shell, under tension due to its own contraction, breaks with minimum energy expenditure when it divides into hexagons.

Fig. 2 is a cross-section of one of these hexagonal cells, showing how the currents rise in the middle of each prism and flow down at

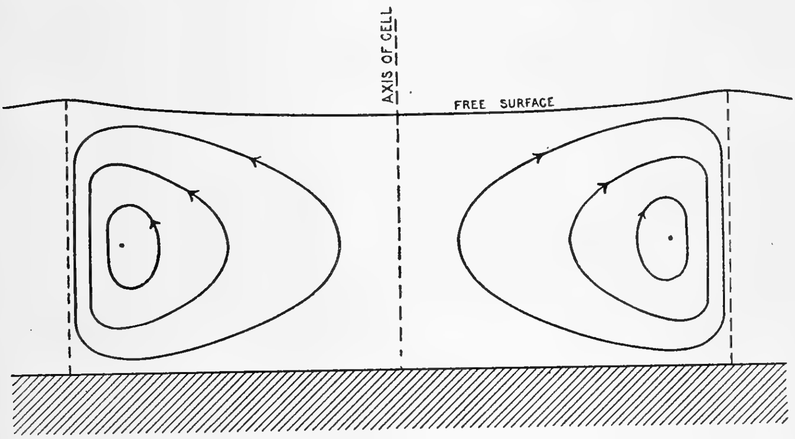

FIG. 2.—Cross-section of a hexagonal cell, showing how the currents rise in the middle of each prism and flow down at the boundaries.

the boundaries. The contour of the surface of the liquid is exaggerated in the figure, but the relief is quite sufficient to permit the structure of the circulating liquid to be observed by various optical methods. Fig. 3 shows three examples of these structures in a melted wax, taken under different conditions of temperature and thickness and before the final steady state of circulation had been attained.

A state of subdivision into irregular cells of from four to seven sides is attained in a few minutes, even in a viscous oil. These cells then join and subdivide repeatedly until finally, if the conditions are constant, a perfect system of hexagonal cells is produced. Even when the liquid is originally in motion, convection cells form which show little or no trace of the original direction of movement of the liquid as a whole.

Waxes and oils were used for most of Bénard's experiments, because at his working temperatures of 100° and lower the requisite conditions as to viscosity and low volatility could best be obtained with these materials. By suspending in them finely powdered substances such as graphite or lycopodium, Bénard was able to show visually and to photograph the cells produced, without the aid of special optical devices.

As is to be expected, the dimensions of the cells depend upon the thickness of the liquid layer, the temperature difference between top and bottom, and the viscosity and temperature of the liquid.

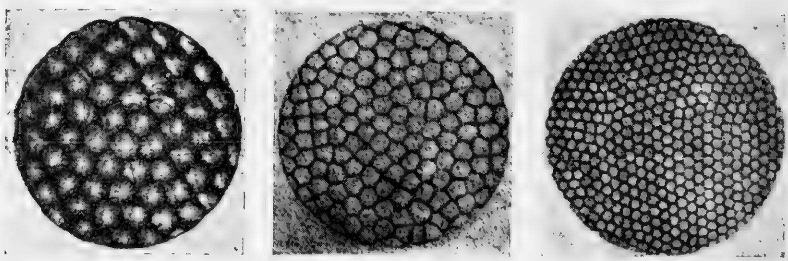

FIG. 3.—Three examples of hexagonal cells formed in a melted wax, taken under different conditions of temperature and thickness and before the final steady state of circulation had been attained.

In a given liquid at a given temperature, and at a constant temperature difference, the ratio of diameter to height is found to be constant. Other laws governing the form and size of the cells were found by Bénard, but it is unnecessary to discuss these in detail.

Following Bénard, Dauzére[1] in 1907 showed that crystallization in salol and wax mixtures begins on the boundaries of the convection cells. A mixture of beeswax and stearin, on solidifying, separates spontaneously into hexagonal prisms coinciding with the original convection cells. In pure stearin, also, crystallization begins at the corners of the cells. In every case the cells leave a permanent record of their existence in the crystallized solid, although in some cases the structure is quite invisible, and only

[1] C. Dauzére, *Jour. physique*, VI (1907), 892–99; VII (1908), 930–34; *Assn. franc. av. sci.*, 1908, pp. 289–96.

appears when the wax is bent. Dauzére pointed out the strong probability that certain symmetrical columns in Auvergne have been due to convection in the basalt in which they are formed.[1]

In a horizontal sheet of molten rock which has come to rest after extrusion or intrusion it is obvious that we have some at least of the conditions necessary for the formation of convection cells. If the cells succeed in leaving any permanent record of themselves when the sheet solidifies, then subsequent contraction may bring out the structure by cracking the rock along the boundaries of the cells.

In general there are two ways in which the convection cells might impress themselves on the crystallized rock. In the first case the axes of the liquid convection cells and of the solid prisms are coincident. Bénard found that a finely powdered substance which is heavier than the liquid tends to gather on the bottom of the vessel in little heaps situated on the axes of the convection cells, giving an appearance from above of uniformly spaced round spots. A floating substance, on the other hand, gathers along the boundaries of the cells at the surface. A substance in suspension gathers within the interior portion of the closed curves of Fig. 2, so that the liquid shows transparent both on the axes and along the boundaries of the cells. In a mixture, therefore, in which different crystalline phases are separating at different temperatures, a certain amount of segregation is to be expected, and the solid prisms will coincide with the convection cells.

In a substance which crystallizes as a unit, on the other hand, whether it be a pure substance or a considerably undercooled mixture, prisms may be formed without segregation. Bénard observed that in spermaceti the crystallization began at the corners of the cells. In pure stearin Dauzére found that crystallization beginning at centers on the cell boundaries extended uniformly in all directions until the growing cylindrical groups intersected to form prisms. It is evident that in this case the prisms will not coincide with the convection cells, but will nevertheless be symmetrical and regularly spaced.

[1] C. Dauzére, *Assn. franc. av. sci.*, 1908, pp. 436–38; also Longchambon, *Bull. Soc. Geol. Fr.*, XIII (1913), 33–38.

It is of interest to note that this convection-crystallization hypothesis explains the original observation of Watt on the formation of columns in a cooling artificially melted basalt mass (see p. 215). He accounted for his columns on the assumption that they were produced by the mutual interference of radially-growing crystal bundles, uniformly spaced in a horizontal plane. Why the crystallization centers should be uniformly spaced he was unable to say. The existence of convection prisms in the still liquid basalt provides the missing link in the series of phenomena. Crystallization may have begun at the axes of the convection prisms where a few early separating crystals had collected, or at the corners as observed by Bénard; in either case the crystallization centers would be uniformly spaced horizontally.[1]

If liquid convection is really the cause of all or any of the familiar naturally occurring basaltic columns, then it is important to know what criteria will help to decide the question in a given case. Furthermore, a systematic examination of natural columns will throw light on their history, whatever may be their mode of origin. What are the important characteristics of a given occurrence which should be observed in the field?

CHARACTERISTICS OF CONTRACTION AND CONVECTION PRISMS

1. *Attitude.*—The original attitude of columns formed by convection should be vertical, or very nearly so. Contraction columns, on the other hand, are usually perpendicular to a cooling surface; irregular conditions of cooling, furthermore, may cause them to curve in a great variety of ways.

2. *Dimensions.*—Convection columns should be much wider, in proportion to their length, than contraction columns, which are commonly very long and narrow. The columns at Murols described by Dauzére are 1.5 to 2 m. wide and 5 to 10 m. high; those measured by O'Reilly in the Giant's Causeway are 0.4 to 0.5 m. in width; the Causeway columns vary from 3 to 25 m. in total height. Scrope describes columns near La Queuille as much as 5 m. in diameter, and 10 m. or less in height.[2] The common contraction

[1] See Longchambon, *Bull. Soc. Geol. France*, XIII (1913), 33-38.

[2] *Volcanoes of Central France*, London, 1858, p. 136.

columns, on the other hand, are usually about 0.2 m. or less in diameter; their length is often 20 m. without a joint, and their total length may be over 40 m. It should be noted, however, that the composition of the rock may have a considerable effect on the size of columns under given conditions of cooling, the more salic rocks forming larger columns than the more femic rocks.

3. *Shape of cross-section.*—Convection columns, if perfect, should all be hexagonal. The more uniform the conditions have been, the greater the proportion of hexagons; in any case, the hexagonal sections will be in the majority. Seven-sided figures will be common, produced by the trunkation of one angle of a hexagon; pentagons will also occur frequently, by the elimination of one side of a hexagon. But three- and four-sided figures will be very rare.

In contraction columns, on the other hand, pentagons are likely to be the prevailing type, and four-sided figures are fairly numerous, while hexagons become less important. This distribution of polygons arises from the fact that a mass cracking under the stresses of its own thermal contraction, although theoretically it should break into perfect hexagons of equal area, actually tends to yield by the formation of master-cracks which are then joined up by the formation of shorter cracks.[1] An example of thermal contraction prisms on a large scale is seen in the soil polygons of Arctic regions; a map of a set of these polygons, in a recent article by Leffingwell,[2] shows clearly the contraction-type fissures described above.

The relative frequency of polygons in some of Bénard's artificial convection cells,[3] in the Giant's Causeway,[4] and in a columnar dike[5] is shown in Table I.

[1] "The rock may rather be said to be divided into numerous perpendicular fissures, than to be prismatic, although the same picturesque effect is produced."—Lyell, description of Torre del Greco.

[2] E. De K. Leffingwell, *Jour. Geol.*, XXIII (1915), 653.

[3] The photograph used for this computation was one taken while the liquid was cooling and the polygons were undergoing gradual changes, leading to the formation of 5- and 7-sided figures. Under steady conditions of heat flow the cells were hexagons almost without exception.

[4] J. P. O'Reilly, *Roy. Irish Acad. Trans.*, XXVI (1879), 641–734.

[5] A. Geikie, *Ancient Volcanoes of Great Britain*, illustration, p. 459.

Bénard[1] has recently shown photographically the identity of pattern between his convection cells and the cross-section of the basalt columns of the flow of Estreys (Haute-Loire), and has also pointed out the qualitative differences between this pattern and that produced by contraction.

TABLE I

COMPARATIVE FREQUENCY OF POLYGONS (PERCENTAGE)

No. of Sides	Artificial Cells	Giant's Causeway		Columnar Dike
		Along a 50-Meter Line	Within Measured Area	
3	0	0	0	5.2
4	5.5	2.0	3.5	28.4
5	36.3	30.7	24.8	43.1
6	45.2	47.1	50.5	20.7
7	12.7	19.6	19.2	2.6
8	0.3	0.6	2.0	0
Total number counted	292	153	206	116

4. *Frequency of angles.*—The angles of convection columns should approximate to 120°, while contraction columns will have a large proportion near 90°. While the frequency of angles is a much more logical criterion than the frequency of different polygons, it is much more difficult to apply on account of the large number of angular measurements to be made. Such a series was made with great care by O'Reilly on the Giant's Causeway, and I have summarized his results in Table II. O'Reilly's deduction from his

TABLE II

FREQUENCY OF ANGLES IN 206 POLYGONS OF THE GIANT'S CAUSEWAY

Range	No. of Occurrences	Range	No. of Occurrences
64° to 75°	9	115° 30′ to 125°	238½
75° 30′ to 85°	19½	125° 30′ to 135°	236½
85° 30′ to 95°	56½	135° 30′ to 145°	143
95° 30′ to 105°	103½	145° 30′ to 155°	18½
105° 30′ to 115°	215	155° 30′ to 175°	5

measurements was that the form of the columns had been governed by the principal angles of the constituent minerals of the basalt, a view which has not met with general acceptance.

[1] *Compt. rend.*, CLVI (1913), 882–84.

5. *Difference in composition and texture between the axis and the periphery of the columns.*—Obviously, no variation whatever should appear in contraction columns. If the columns are due to convection, however, there might or might not be a differentiation, depending upon whether the rock crystallized practically as a unit, or whether it crystallized in stages which permitted of segregation in the convection cells (see p. 223).

In 1914 Dr. H. S. Washington, of this laboratory, examined, in the museum of the University of Catania, a polished section of a column from one of the prehistoric basaltic flows of the Mount Etna region, and observed no variation of texture across the section. From their shape and manner of occurrence, these columns at Etna would seem to be due to pure contraction, and no variation is to be expected.

On the other hand, evidence is not lacking in geological literature of what seems to be a differentiation between the border and axis of some basalt columns. Scrope, in his description of the volcanoes of central France, states that "occasionally (as for example at La Tour d'Auvergne, in the Mont Dore), the columns show a cylinder of compact black basalt within a prismatic case of lighter colour and looser texture, a segregation of dissimilar matter having accompanied the concretionary action."[1] Delesse[2] made in 1858 an interesting comparison of the density of the interiors and exteriors of a variety of columns, the results of which are shown in Table III. Here again a difference between the interior and exterior is indicated in some of the columns, though not in all. Unfortunately the source of the samples which showed small differences is not stated; it may be that they are columns of the narrow contraction type. Delesse took care to assure himself that the differences were real and were not due to weathering of the columns, but it is not impossible that the differences are really due to weathering, since he had not the modern microscopic facilities for examining the individual minerals in thin section.

[1] *Volcanos*, 1862, p. 100. In speaking of "concretionary action" Scrope seems to be referring to the rather vague hypothesis of columnar structure which prevailed at the time (see note, p. 216).

[2] Delesse, "Variations dans les roches se divisant en prismes," *Compt. rend.*, XLVII (1858), 448–50.

The regularity and symmetry of the columns of the Giant's Causeway suggests the convectional origin. It seemed of interest, therefore, to examine a polished cross-section of one of these columns for evidence of differentiation. Through the kindness of Dr. G. P. Merrill, of the United States National Museum, a polished section was cut for us from a Giant's Causeway column in the Museum, and also one from a column from near Bonn on the Rhine.

TABLE III

DIFFERENCE IN DENSITY BETWEEN AXIS AND SURFACE OF BASALT COLUMNS (DELESSE)

	Density		Difference of Density
	Center	Outside	Per Cent
Trachyte, Iceland	2.494	2.478	0.64
Trachyte, Isle Ponce	2.469	2.439	1.21
Phonolite, Isle Lamlash	2.541	2.509	1.26
Trap, Antrim	2.911	2.857	1.85
Basalt	2.930	2.933	−0.10
Basalt	3.030	3.030	0.00
Basalt	2.924	2.916	0.27
Basalt	3.053	3.030	0.75
Basalt	3.044	3.008	1.18

The Bonn column was five-sided, with a maximum cross dimension of 18 cm. The cross-joint near which the section was cut showed fracture lines radiating from one corner, and the joint passed straight across. What appeared to be an inclusion about 16 mm. in diameter showed near the center, and another of similar size seemed to have been cut in two by one face of the column. A sharp weathered zone 3 mm. wide showed clearly, but no other difference between center and border appeared.

The Giant's Causeway column was also five-sided, with a maximum cross-dimension of 37 cm. The section was cut near the convex side of a shallow ball-and-socket joint; the fracture of this joint seemed to have radiated from the *center*, not from any point of the border. The rough surface gave an appearance of finer grain at the border than at the center. On the polished face, however, no such gradation was visible. There was a sharp weathered zone 3 mm. wide, inside of which was a zone varying from 6 to

22 mm. in width, with an ill-defined wavy border. This also may have been due to weathering. Within the central eighth of the area appeared 5 amygdules from 2 to 4 mm. in diameter, and filled with a greenish opalescent mineral. Five others, from 1 to 2 mm. in diameter, appeared in the remaining seven-eighths of the area, none being closer than 25 mm. to the border. The section therefore offers no decisive evidence of a differentiation, although markedly different in character from the Bonn column.

6. *Types of cross-jointing in the columns.*—A differentiation due to convection might be expected to affect the cross-joints of the columns. The peculiar convex-concave or cup-and-ball joints are seldom found in irregular narrow columns of the typical contraction type, and might have some direct connection with a convection structure. Another type of cross-jointing of columns is the "platy" variety, which is sometimes very regular; its origin has not been satisfactorily explained from the physicist's standpoint.

Certain special peculiarities of the cross-jointing may also have to do with the mode of origin of the columns. For instance, James Thomson[1] observed that the symmetrical concave-convex joints of columns from the Giant's Causeway have their origin in a small spot or knob which lies at or near the axis of the column, and differs in texture and hardness from the rest of the rock; from this origin the crack has spread outward, as shown by the radial fracture lines. This same form of fracture has just been described above, as occurring in the National Museum's specimen from the Giant's Causeway. Dauzére mentions the same peculiarity in the columns at Murols, and compares it with the core (*noyau*) which forms in the convection prisms of his wax-salol mixture.

There seems to be good foundation for the opinion that some sort of original structure is responsible for the spheroidal weathering of columns, and that it is not due solely to the rounding off of jointed blocks by weathering, as some have claimed. Thus Bonney cites numerous examples of spheroids formed from columns which showed no cross-joints whatever.[2] Whether these latent spheroids have any connection with the manner of growth of the column it is

[1] *Belfast Nat. Field Club, Ann. Rep.*, VII (1869), 28–34.

[2] *Quar. Jour. Geol. Soc.*, XXXII (1876), 140–54.

as yet impossible to say. Longchambon[1] suggested that the superimposed spheroids are due to a breaking up of long liquid convection cells into a number of shorter ones, each with its own local circulation, but there is no experimental evidence to support this.

7. *Irregularities of faces of prisms.*—Some basalt prisms show the "feather-patterns" characteristic of fractures in homogeneous solids. Their occurrence points strongly to a purely contractional origin. They have been observed in the joint planes of slates, and have been made the subject of an interesting study by Woodworth.[2]

SURFACE STRUCTURE PRODUCED BY INTERNAL EXPANSION

In addition to the prismatic structures produced by contraction and convection or by convection combined with crystallization and contraction, still another type needs to be considered, namely that due to *expansion.*

The accompanying photograph of a polygonal structure in a cement briquette (Fig. 4) is an illustration of the formation of this structure by internal expansion. This sample, which was kindly furnished us by Mr. A. A. Klein, of the Bureau of Standards in Pittsburgh, was made from a cement which contained free lime; this by its hydration and absorption of carbon dioxide from the air has expanded and destroyed the briquette.

It is possible that the "weather-crack" structure on the surface of diabase bowlders is likewise caused by internal expansion. Wherry[3] has shown that there is no visible difference in texture underlying these weather-cracks. Expansion of the surface by hydration has been assumed as the cause of the structure; but this would produce *compression* in the surface, accompanied by the formation of shells (as indeed often occurs), whereas the "weather-crack" structure is one indicating *tension.* It is necessary for hydration to proceed into deeper portions of the rock before tension

[1] *Soc. Geol. France, Compt. rend. somm.*, 1912, pp. 181–83; *Bull.*, XIII (1913), 33–38.

[2] *Proc. Boston Soc. Nat. Hist.*, XXVII (1896), 163–83. For an extended study of these feather fractures in glass and metals see Ch. de Fréminville, "Recherches sur la fragilité; L'éclatement," *Rév. metallurgie,* 1914; also Mallock, *Proc. Roy. Soc.*, A, LXXXII (1909), 26–29.

[3] *Loc. cit.*

is set up in the surface; the cracks then produced are soon widened by solution. A photograph of an excellent example of this type of structure in diabase is given in Fig. 5. Internal expansion may also account for the prismatic surface structure of "bread-crust bombs," although this remains to be proved.

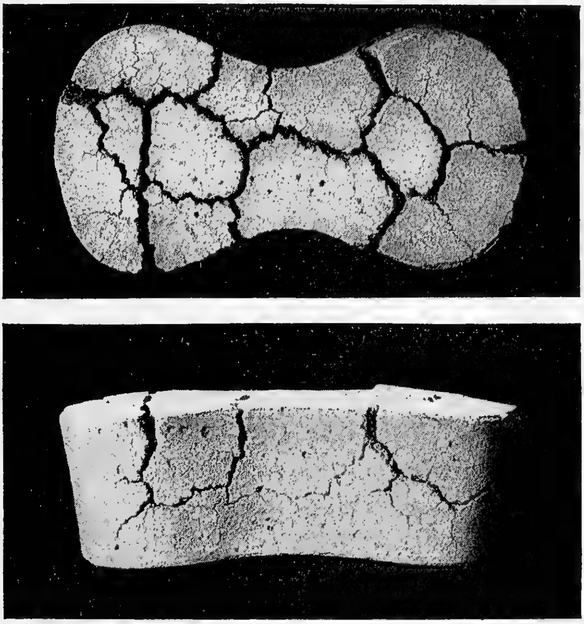

Fig. 4.—A polygonal structure in a cement briquette, caused by internal expansion.

SUMMARY

From the physical standpoint, several types of prismatic structure in igneous rocks can be distinguished. The first and most common is due purely to thermal contraction in the crystallized rock; examples are numerous and familiar. A subordinate type of contraction structure is produced when the contraction and separation occur while the magma is still partly crystalline and partly liquid; this type is illustrated by an occurrence in a diabase sill in eastern Pennsylvania.

Fig. 5.—"Weather-crack" structure on the surface of a diabase bowlder

The second general type is produced by convectional circulation of the magma while still liquid. The cells so produced persist until solidification begins, and may leave a record in the rock either by causing segregation in the cell walls and axes, or by originating regularly spaced centers of crystallization. The experimental and observational data on the occurrence of this type in igneous rocks are suggestive, but cannot yet be said to amount to decisive proof.

A third type of prismatic structure is produced by internal expansion. It has been produced artificially, and is offered as the explanation of the "weather-crack" structure seen in diabase bowlders.

In the study of these structures, the following field observations are those which will be of greatest interest in the further study of the problem: (1) attitude of prisms, (2) their diameter and length, (3) frequency of four-, five-, six-, and seven-sided polygons, (4) frequency of angles (especially 90° and 120°), (5) variation, if any, of composition and texture in the cross-section, (6) types of cross-jointing (platy, concave or convex, spheroidal), (7) spacing of cross-joints, (8) peculiarities of cross-joints (e.g., whether cracked from center or from borders), (9) degree of irregularity in sides of prisms, (10) other peculiarities, such as tapering, partial longitudinal jointing, etc.

The primary object of this discussion is to call attention to the possibilities of the prismatic structure of a given rock body as an index of its conditions of formation. Quantitative data on columnar structures are very scarce; yet quantitative measurements must precede quantitative deductions. We wish to know the temperature of the rock when it was intruded or extruded; its viscosity when it began to cool and when it began to crystallize; the amount and kind of gases which it released; if extrusive, the climatic conditions under which it cooled; if intrusive, the properties of its inclosing strata at the time of intrusion. These and other facts are deducible only from the present properties of the rock, among which its prismatic structure will prove of great importance.

Equally necessary with the field data are experimental studies of the structures produced in a cooling magma under conditions that can be controlled and measured. Such experiments will require the melting and handling of larger quantities than it has been customary to use for laboratory experiments, but the difficulties ought not to prove serious. Even in the absence of such experimental data, much can be learned from a careful field examination of prismatic and columnar structures.

ELLIPSOIDAL LAVAS IN THE GLACIER NATIONAL PARK, MONTANA[1]

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Geological Survey, Ottawa, Canada

The paper by Capps on "Some Ellipsoidal Lavas on Prince William Sound, Alaska,"[2] recalls to my mind a similar occurrence which I visited in 1907. The locality is now so accessible and the flow is so clearly subaqueous in character that a brief description of it may be of interest. Its outcrop appears in the ridge (Shepard Mountain) northeast of Flattop Mountain, Glacier National Park, Montana, and the features described are in that portion of the bed which overlooks the Shepard Glacier. The lava, to which the name Purcell lava has been commonly applied, interrupted the sedimentation of a flat-lying, greenish argillite which forms the uppermost part of the Siyeh formation of the pre-Cambrian. This argillite lies in normal position, and the portions above and below the lava bed are macroscopically identical.

The Purcell lava is approximately 150 feet thick on Shepard Mountain and can be traced for miles to the southeast, north, and northwest. It is composed of six or more successive flows, each of uneven and more or less ropy surface, separated by small and more or less local accumulations of shale. The lower 25 or 30 feet of the flow is composed of a conglomeration of dense, homogeneous, spheroidal masses averaging 1 to 2 feet in diameter. They preserve their shape in the lower layers, being separated from each other by chert or drusy cavities, and many individuals have displaced considerable portions of the mud upon which they were rolled or shoved, even to the extent of complete burial. The bottom of the flow is therefore exceedingly irregular. Toward the top of this bed the individual spheroids yield more or less to the

[1] Published by permission of the Deputy Minister of Mines.

[2] *Jour. Geol.*, XXIII (1915), 45–51.

pressure of their fellows, and they unite to form an upper surface of moderate unevenness. The upper part of the entire flow is composed of a bed about 20 feet thick, which, though massive in character, is very porous. Vesicles are common near the base of several of the individual flows in the lower portion of the lava.

On Mount Grinnell, 10 miles to the southeast, Finlay[1] gives the thickness of the lava bed as 42 feet, but does not mention the ellipsoidal masses which Daly later describes from the same locality.[2] Finlay records the discovery of five genetically connected dikes on Flattop Mountain close to the localities where the ellipsoids are present. Elsewhere, though the lavas reached the surface through numerous widely scattered dikes, ellipsoidal structure has not been recorded. This period of igneous activity has been described[3] as having genetically connected extrusive and intrusive phases, and it is interesting to note that strata, upon whose upper subaqueous surface lava was being extruded, should have been able, at a depth of only 600 feet, to accommodate themselves to the essentially contemporaneous intercalation, along single planes, of intrusive sills scores of square miles in extent.

This flow seems to afford an excellent opportunity for determining the value of certain criteria for distinguishing (1) subaerial from subaqueous flows, and (2) the top from the bottom of subaqueous flows. Here the normal attitude of the flow and its including sediments is unquestionable, and the bottom of the bed in which the ellipsoidal structure is developed is far more uneven than the top, an observation which lessens the importance of one of the criteria advanced by Capps. Furthermore, the silting up of cracks in the surface of the flow would seem more natural than the upward penetration, into cracks several feet in height, of mud sufficiently resistant to flatten the bases of individual ellipsoids. That the latter is true for the Prince William Sound locality[4] merely illustrates the difficulty of obtaining competent and unconflicting criteria.

[1] *Bull. Geol. Soc. America*, XIII (1912), 350.

[2] *Memoir Geol. Survey Canada*, No. 38, Part I (1912), p. 217.

[3] Daly, *ibid.*, pp. 218–20.

[4] Capps, *Jour. Geol.*, XXIII (1915), 49.

So far as the Glacier National Park exposure of the Purcell lava is concerned, the following criteria would seem to indicate the bottom of a subaqueous flow: (1) discreteness of the basal spheroids and their relative competence to resist mashing; (2) comparative unevenness, with reference to the top; (3) the irregular displacement of the underlying shale by the basal spheroids; and (4) the presence of vesicles near the base of the individual flows. Criteria indicating the top are: (1) the common ropy structure; (2) more or less complete fusion of the individual spheroids; (3) comparative evenness, with reference to the bottom; (4) silting up of hollows in the top by strata whose laminae parallel those of the adjacent strata; and (5) the absence of vesicles in the upper portions of the individual flows.

The flow under discussion covers an area hundreds of square miles in extent, and while its extrusive character has been recognized by various observers, the ellipsoidal structure has only been found at the localities described. It may have been subaqueous in places, subaerial in others (the Siyeh argillites are abundantly ripple-marked and sun-cracked in places), but many lines of evidence seem to prove its subaqueous character at the locality described, and indicate that ellipsoidal structure is a competent criterion of subaqueous extrusion.

THE ORIGIN OF RED BEDS

A STUDY OF THE CONDITIONS OF ORIGIN OF THE PERMO-CARBONIFEROUS AND TRIASSIC RED BEDS OF THE WESTERN UNITED STATES

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PART II

CONDITIONS OF DEPOSITION OF RED CLASTIC SEDIMENTS: MODERN TYPES

Seven distinct types of partly or wholly clastic modern red sediments have come to the attention of the writer, some of which, however, are closely related. The occurrence of each one of these types and its application to the Red Beds of the western United States is discussed in the following paragraphs.

Red clay of the deep-sea bottom.—This material is invariably very fine-grained, it contains little or no terrigenous matter of any kind, and it accumulates very slowly indeed, so that a thickness of it comparable to the total thickness of shales in any series of the western Red Beds is practically inconceivable. Nearly every part of all the series included in the Red Beds group exhibits incontestable evidence of shallow-water deposition, while the oceanic red clays are exclusively abysmal deposits. Such arguments could be multiplied almost indefinitely; it is quite clear that deep-sea red clay is not related to our problem in any way whatsoever.

Stream deposits derived from pre-existing Red Beds.—This type of deposits is illustrated by the flood-plain deposits of the Red River of the South, in Texas, Oklahoma, and Louisiana. This type cannot be dismissed so easily, for there are yet in existence masses of pre-Cambrian red sediments within the possible drainage areas tributary to some of the areas of the Red Beds. One objection to this source for the ferruginous matter of the Red Beds is that there were other sources for the sediments in question, nearer than the pre-Cambrian series, and that much of the material of the Red Beds is known to have been derived from other rocks.

Arkosic stream deposits.—These are illustrated by deposits of limited extent in and downstream from the region occupied by the Sherman granite of Wyoming, which weathers to a coarse pink gravel, owing its color to a high content of undecomposed pink orthoclase. It is obvious that much the greater part of the color of the Red Beds is not due to pink feldspar; but in some of the very arkosic sediments of the Cutler and Dolores formations, and probably elsewhere, this is an element not to be ignored.[1]

Stream deposits deriving their coloring matter from ferruginous residual soils.—The fourth type of modern red sediments is exemplified by the continental portion of the deposits of the lower Amazon, and by smaller deposits in some of the rivers of the United States. Russell says:

> Each grain [of sand in residual soils left by the decomposition of crystalline rocks in the southern Appalachian Piedmont] is coated with a thin shell having a brownish or red color. Prolonged washing fails to remove this superficial coating, a fact which is well illustrated by the color of the sands deposited by the streams of Virginia and the Carolinas in the regions underlaid by crystalline rocks.[2]

Russell appears to assume that all of the ferric oxide produced by the decay of the crystalline rocks of this area is attached to grains of other minerals in this way. That which fills interstices between grains of sand in the final deposit,[3] as distinct from that which occurs in coatings on the grains, probably persisted independently, however, and was transported as a fine sediment like clay.[3]

The relation between surface weathering of the Piedmont crystalline rocks and the color of the Newark clastics in the neighboring areas, as developed by Russell, is very much the same as a relation recently advocated by Beede[4] between weathering of lime-

[1] Cf. Whitman Cross, Telluride Folio (No. 57), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1899, p. 2.

[2] I. C. Russell, "Subaerial Decay of Rocks," *U.S. Geol. Survey Bull. No. 52*, 1889, p. 14.

[3] See p. 164, this volume.

[4] J. W. Beede, "Origin of the Sediments and Coloring Matter of the Eastern Oklahoma Red Beds," abstract in *Bull. Geol. Soc. America*, XXIII (1912), 723–24.

stones and the color of the Red Beds of eastern Oklahoma. He says:

> The coloring matter is thought to have been derived from the solution of the 7,000 or 10,000 feet of pre-Carboniferous limestone which formerly covered the Arbuckle-Wichita Mountains and much of the surrounding region. The solution of the limestone furnished optimum conditions for the oxidation of its iron content, as it does at the present time in the limestone regions of the Mississippi Valley, southern Europe, West Indies, and elsewhere. Moreover, the solution of the pre-Carboniferous limestones and the conglomerates of the Arbuckle-Wichita region now in progress produces a red residuum practically indistinguishable from Red Beds sediments. The red granites, red porphyries, and other crystalline rocks of the region under discussion contributed their shares of material to the Red Beds.[1]

The Red Beds of the Grand Canyon section are underlain by the famous Redwall limestone, and limestones underlie the Red Beds practically throughout the Plateau province and in the San Juan region. Areas in Colorado of history similar to that of the Arbuckle-Wichita region, in that highlands existed there after the earlier Paleozoic limestones were deposited, and during Red Beds times, may well have played the same part in the central Rocky Mountain region that Beede assigns to the Arbuckle-Wichita uplift in Oklahoma. The existence of such highlands is demonstrated by the great conglomerates in the Colorado Red Beds.[2] Various other land-masses which contributed material to the sediments of the Red Beds[3] may have been quite as efficient as the Arbuckle-Wichita highlands in producing residual soils stained by ferric oxide.

It is evident from the foregoing discussion that stream deposits deriving their coloring matter from ferruginous residual soils are probably of no little importance in the Red Beds, and may constitute a major part of the series of sediments included under that term.

Terrigenous marine clastics.—The fifth type of modern red sediments is illustrated by deposits in the Atlantic Ocean off the mouth of the Amazon River.[4] This is an exceptional occurrence,

[1] Beede, *op. cit.*

[2] See pp. 244-245. [3] See pp. 245-246.

[4] John Murray, *Challenger Reports, Deep Sea Deposits*, 1891, p. 234.

as most terrigenous red muds lose their color on entering the sea. A vivid description of this process of loss of color in the case of certain rivers in Nova Scotia is given by Dawson, as follows:

This harbour [Pictou] receives the waters of three rivers and several smaller streams, which in times of flood carry into it large quantities of reddish mud, which sometimes discolours the whole surface. This mud, with similar sediment from the shore of the harbour, is deposited in the bottom, and there undergoes a remarkable change of colour. A portion of old mud recently taken from the bottom is of a dark grey colour, and emits a strong smell of sulphuretted hydrogen. . . . . The iron of the red clay has entered into combination with sulphur, and this is probably obtained from the sulphates contained in the sea-water, by the deoxidizing influence of decaying vegetable matter . . . . which grows abundantly on the mud flats. . . . . In some parts of the deposit forming in Pictou harbour, the vegetable matter which caused the change of colour is so completely decomposed that no visible fragments of it remain.[1]

The chemical action of marine organic matter is summarized by Clarke in part as follows: "Decomposing organic matter reduces the sulphates of sea-water to sulphides, which by reaction with carbonic acid yield sulphuretted hydrogen. Bacteria also assist in the process."[2]

The interbedding of marine limestones with Red Beds shales in the Texan section is consistent with an origin for the shales similar to that of the semi-oceanic sediments from the Amazon River. The interbedding of gray and green strata with red ones in certain of the Red Beds series indicates an oscillation of dominance between oxidizing and deoxidizing conditions, such as might be caused at the margin of the sea or in the waters of an inclosed basin by variations in the rate of sedimentation or in the abundance of organic matter. The marine type of deposition of red sediments is not to be neglected, therefore, in an attempt at reconstruction of the conditions of origin of the Red Beds; though the complete absence of marine fossils from other parts of this group of sediments, together with independent proof of the continental origin of most of the group, shows that the marine type cannot be of more than subordinate importance.

[1] J. W. Dawson, "On the Colouring Matter of Red Sandstones and of Greyish and White Beds Associated with Them," *Quar. Jour. Geol. Soc. London*, V (1848), 29.

[2] F. W. Clarke, "The Data of Geochemistry," 2d ed., *U. S. Geol. Survey Bull. No. 491*, 1911, pp. 136-137.

Deposits of desert lakes or playas.—For an example of the sixth type of present-day red sediments, deposited under water in desert lakes or playas, we turn to Chinese Turkestan. The following description, by Huntington, relates to the northern extremity of the bed of Lop Nor, near the southern base of the Kuruk-Tagh or Dry Mountains: "Beyond the fatiguing plain of salt [dry bed of the dwindled lake Lop Nor] we found easy traveling for a time. A fantastic red plain, the soft, dry bed of an older expansion of the lake, glittered with innumerable gypsum crystals."[1]

Here we have a recent deposit of gypsum (or, more properly, selenite), in which the crystals presumably are imbedded in a red clay or mud. The relations here described could be duplicated by many minor deposits of gypsum in the Red Beds of the western United States. Farther out toward the center of the lake floor occur the purer non-clastic sediments, which in the case of Lop Nor are described as salt beds. The coloring matter of the clays probably was derived, as in the two preceding types of modern red sediments, from the decay of rocks on the neighboring uplands.

Red dune sands.—The seventh and last type differs from all the others in being an eolian deposit. Red dune sands are exceptional rather than the rule in the desert regions of today, but they occur in sufficient abundance to warrant attention. Their most striking occurrence is in the Nefood or Red Desert of Northwestern Arabia. The following quotation is from Palgrave's narrative of a journey taken in 1862: "We were now traversing an immense ocean of loose reddish sand, unlimited to the eye, and heaped up in enormous ridges, ... undulation after undulation, each swell two or three hundred feet in average height."[2]

The extreme breadth of the Nefood is about 150 miles, its greatest length about 400 miles.[3]

Huntington mentions "an almost absolutely barren area of reddish or yellowish sand dunes, from ten to a hundred or more feet

[1] Ellsworth Huntington, *The Pulse of Asia* (Boston and New York: Houghton Mifflin Co.), p. 254.

[2] W. G. Palgrave, *Central and Eastern Arabia* (London: Macmillan, 1908), pp. 62–63.

[3] See J. A. Phillips, "The Red Sands of the Arabian Desert," *Quar. Jour. Geol. Soc. London*, XXXVIII (1881), 110–13.

high"[1] between Karakir and Keriya River, in the southern border of the Takla Makan Desert, Chinese Turkestan. Some 40 or 50 miles farther north is the district described in the following passage: ". . . . ridge after ridge of sand, fifty to one hundred feet high. . . . . Their gently sloping backs to windward were gray with a cover of rather coarse sand, while their steep fronts to leeward were pale brick-red with the fine sand of the main desert."[2]

There are in the Red Beds of the western states no sandstones of this type of such great thickness as that of the Nefood sands, yet the possibility must be recognized that there may be local sandstone members of this origin in the series. A region dry enough to admit of the production of great bodies of gypsum might easily be transgressed by shifting sands; or the two types of deposition might exist side by side, as they do today in the region of Lop Nor and Takla Makan. The coarsely cross-bedded sandstones of the Chugwater formation along the eastern base of the Wind River Range in Wyoming, for instance, will bear further investigation with this possibility in mind.

EVIDENCE OF FEATURES OTHER THAN COLOR AS TO THE CONDITIONS UNDER WHICH THE RED BEDS WERE DEPOSITED

The wide range in grain shown by the Red Beds of various parts of the West, and the varying quantity of non-clastic sediments in the group, show that a variety of conditions existed in this region during the time the Red Beds were accumulating, as is to be expected from the great extent of the group. What the varying relations were will be pointed out as accurately as possible in the following pages.

Evidence of conglomerates as to the sites of land-masses.—Conglomerates, by the pebbles which they contain, display more clearly than other sediments the source of their component materials. We can therefore determine with some confidence the sites of the land-masses which gave rise to the Red Beds, where these are conglomeratic. In southeastern Oklahoma, Beede[3] has presented facts to show that the lower Red Beds sediments were derived from

[1] Huntington, *op. cit.*, pp. 183–84.

[2] *Ibid.*, pp. 184–85.

[3] *Op. cit.*

the Arbuckle-Wichita region. Near the border of the present Arbuckle and Wichita mountains, limestone conglomerate and conglomerate of crystalline rocks dovetail into Red Beds sediments of finer grain. The limestone undoubtedly was derived from earlier Paleozoic formations, and the crystalline fragments from more ancient rocks, both of which are known to have been exposed in the uplifted region just named. Increasing thickness of sediments toward the mountains testifies to the same relation. To what distance sediments from this isolated highland may have been distributed is largely a matter of conjecture. The entire Red Beds series thins northward from this area to the northern limit of their outcrops in Nebraska, and in the same direction clastic sediments give place in part to limestones: both of which facts signify increasing distance from the source of terrigenous material. The small outlier of Red Beds in central Iowa, which probably is to be correlated with the Cimarron series of Kansas,[1] is composed chiefly of red shale and gypsum, likewise indicating relatively clear-water conditions. It would be an unwarranted assumption, however, to assume that the Kansas and Iowa Red Beds were derived wholly from the Arbuckle highlands. The greater areas of upland which probably existed in the region surrounding and including the pre-Cambrian areas of Minnesota and Wisconsin may have been important sources of material, as may also the ancient Appalachian continent of the East; but it may safely be said that their influence is not exhibited in the strata now available for study, as the influence of the Arbuckle highland so clearly is.

Similar criteria may be applied to the great conglomerates of the Fountain and Wyoming formations of the Front Range, and to those of central and southwestern Colorado. The conglomerates of the Front Range Red Beds and of the Maroon formation of the Anthracite, Crested Butte, and Tenmile districts are made up chiefly of fragments from pre-Cambrian crystallines,[2] which still

[1] Cf. F. A. Wilder, "The Age and Origin of the Gypsum of Central Iowa," *Jour. Geol.*, XI (1903), 723–48.

[2] See Whitman Cross, Pikes Peak Folio (No. 7), *Geol. Atlas of the U.S., U.S. Geol. Survey*, 1894; G. K. Gilbert, Pueblo Folio (No. 36), 1897; and G. H. Eldridge, "Description of the Sedimentary Formations," Anthracite-Crested Butte Folio (No. 9), 1894.

outcrop in wide areas in various parts of the ranges. The Maroon conglomerates include also fragments of quartzite and limestone from older sediments. The composition of these formations renders it certain that their materials were not carried far from their sources; it is therefore certain that there were highlands, and there may have been mountain ranges of no insignificant relief in various parts of Colorado during Red Beds time—which here probably was included for the most part within the Pennsylvanian and Permian periods.

The coarser beds of the Cutler and Dolores formations in southwestern Colorado show by their composition that they also were derived very largely from igneous and metamorphic terranes.[1] The studies of Cross[2] have shown that the northern part of the San Juan region itself, as well as the neighboring Uncompahgre Plateau, was exposed to erosion between early Cutler and Dolores time—at or near the beginning of the Mesozoic era. This upland may have furnished sediment to a considerable part of the plateau province to the west and southwest. Cross is of the opinion that the absence of the Red Beds on the Uncompahgre Plateau is due to post-Dolores erosion;[3] but the conglomeratic character of the Red Beds in the San Juan Mountains demands that a source for those sediments be found close at hand. In the absence of any conclusive evidence that the Red Beds ever were deposited over the plateau in question, it may be regarded at least provisionally as the probable site of that source.

The sediments of the Plateau province, on the whole, do not indicate mountainous topography in the vicinity; but their great thickness (maximum more than 5,000 feet, excluding non-clastic beds) calls for the existence of a land area contributing sediments to this region for a long period of time. Such an area may well have existed toward the south and southwest, in Mexico, southwestern

[1] See Whitman Cross and others, in the following folios of the *Geol. Atlas of the U.S., U.S. Geol. Survey:* Telluride (No. 57), 1899; LaPlata (No. 60), 1899; Silverton (No. 120), 1905; Needle Mountains (No. 131), 1905; Ouray (No. 153), 1907; Engineer Mountain (No. 171), 1910.

[2] Whitman Cross, "Stratigraphic Results of a Reconnaissance in Western Colorado and Eastern Utah," *Jour. Geol.*, XV (1907), 648–49, 654–56.

[3] *Ibid.*, pp. 648–49.

Arizona, and southeastern California, or farther north in the Great Basin, where no sediments contemporaneous with those in question are known to occur.[1] The absence of sediments between the Mississippian and the Cretaceous in the El Paso quadrangle[2] in western Texas may be due altogether to erosion following deformation at the close of the Jurassic period, but this gap in the record makes it possible that land may have existed even here during Red Beds times.

Richardson has concluded from his studies of the Black Hills Red Beds[3] that those sediments were derived chiefly from the Rocky Mountain area to the southwest and west. West of central Wyoming, the Red Beds group thickens, and the quantity of limestone and gypsum in it diminishes, continuously westward across the Idaho border, suggesting a source of sediments in that direction. The great thickness of the group all along the Wasatch Range, wherever it is exposed, extends this suggestion to include a considerable land area trending north and south from southern Idaho into central Utah.

Significance of non-clastic sediments.—The more important limestone members of the Red Beds record the existence of extensive bodies of clear and not excessively salty water during parts of the Pennsylvanian period in central Texas, in the Plateau Province, in the San Juan region, and in southeastern Wyoming; during the Permian, in the region north and east of Great Salt Lake (in the early part of the Permian, marine deposition throughout much of Wyoming, prior to the initiation of Red Beds sedimentation there), and in western Texas; and in the Triassic, in northeastern Arizona.

[1] Cf. paleogeographic maps by the following authors: T. C. Chamberlin and R. D. Salisbury, *Geology* (New York: Henry Holt & Co., 1909), II, 545; III, 3 and 62; W. B. Scott, *An Introduction to Geology* (New York: Macmillan, 1909), pp. 616, 662; Charles Schuchert, "Paleogeography of North America," *Bull. Geol. Soc. America*, XX (1909), Pls. 84–88 inclusive.

[2] G. B. Richardson, El Paso Folio (No. 166), *Geol. Atlas of the U.S. U.S. Geol. Survey*, 1909.

[3] G. B. Richardson, "The Upper Red Beds of the Black Hills," *Jour. Geol.*, XI (1903), 365–93.

The extraordinary development of gypsum in the Permian Red Beds deserves more than passing comment. In association with salt, deposits of gypsum are interpreted as indicating aridity of climate at the time of deposition, and of formation in at least partially inclosed basins by the evaporation of bodies of water not freely connected with the open sea.[1] This occurrence of gypsum, supported by independent evidences of continental origin for the Red Beds, has been the one strongest influence in establishing the idea that the red color itself is an indication of aridity. The absence of gypsum from many series of Red Beds, and its occurrence in series free from Red Beds, make it necessary to investigate the two problems on their own independent merits.

Rock salt is of relatively rare occurrence in the group of sediments under discussion. Since the saturation point of gypsum in aqueous solution is much lower than that for common salt, it is logical to suppose that the deposition of gypsum unaccompanied by rock salt signifies a condition of aridity and of continuous or intermittent supply of normal sea-water or of fresh water such as to maintain a degree of salinity more moderate, for example, than that of Great Salt Lake at present, but sufficient to cause the continued precipitation of gypsum. Such a condition might be kept up by a limited or intermittent connection between the open sea and the basin of deposition.

The relation of the gypsum and salt deposits of the West to the Red Beds proper suggests a relation similar to the relation between marine limestones and terrigenous sediments. The Rustler dolomite and the Castile gypsum of the Texan portion of the Pecos Valley give place northward to typical Red Beds with a few interbedded strata of dolomite and gypsum. May not the gypsum, as well as the dolomite, be but the complements of the red clastic sediments, deposited in the clear central waters of an inland sea, or in lagoons near or at sea-level but partly or wholly cut off from the sea; while clastic sedimentation went on nearer the shores and on river deltas or flood-plains yet nearer to the sources of sediment?

[1] Cf. Wilder, *op. cit.*

The clastics: minor structural features.—Returning to the clastic sediments, we may draw still further inferences regarding the conditions under which they were deposited, from their structural characteristics and mineral composition. Ripple-marks and mud-cracks in the majority of Red Beds sections testify to the prevailing shallowness of the water in which these sediments were laid down. Mud-cracks repeated in layer after layer, as in some parts of the Red Beds, mean complete emergence and at least partial drying, after the deposition of each stratum and before that of the next following. Shallow water means shifting currents, and these too are recorded clearly by cross-bedding in most sandstones of the series, and by rapid variation along the strike in the shaly members as well. We do not have, in the clastic portions of the Red Beds, and seldom do we find in the non-clastic members thereof, the continuity of a single type of sedimentation over wide areas and through long periods of time, which are to be expected in truly subaqueous or marine deposits. Furthermore, imperfect assortment, which is one of the universal characteristics of fluviatile deposits, is the rule in the Red Beds. The sandstones are earthy, the shales sandy, the conglomerates gritty, etc. Each of these characteristics is suggestive of subaerial conditions, and the occurrence of all of them together in the same series, and widely distributed through that series, is conclusive testimony to such an origin.

The clastics: mineral composition.—From the mineral composition of the clastic sediments we may infer something of the conditions of weathering and transportation which preceded their deposition. The high proportion of feldspar in many of the Red Beds shales and sandstones indicates a preponderance of mechanical disintegration over chemical decomposition. The abundance of undecomposed mica flakes in most Red Beds confirms this interpretation. Transportation may precede complete decomposition because of exceptional rapidity of disintegration, exceptional slowness of decomposition, or both. Rapid disintegration may be caused by such factors as high relief and great daily or seasonal range of temperature; slow decomposition by low rainfall or low temperatures. Low temperatures throughout the year explain the slowness of chemical decomposition in polar regions; aridity explains it in the desert, where disintegration is accelerated by great daily range of temperature; and disintegration is accelerated on mountain peaks by all of the factors mentioned. Absence of vegetation, which itself is dependent chiefly on climatic factors, is unfavorable to rapid decomposition of rocks because of the important part played by organic acids in the chemical processes of weathering.

As we have seen, the occurrence of gypsum indicates aridity and high temperatures, so that we may rule out the hypothesis of Arctic conditions as applicable to the Red Beds. The coarse conglomerates in certain parts of the Red Beds are indications of high relief in certain areas and at certain times.

The occurrence of limestone conglomerate in the Red Beds of the Arbuckle-Wichita region emphasizes the predominance of disintegration over decomposition in that area, as limestone is one of the most readily decomposed of rocks. If the limestone conglomerates of the Cutler formation were detrital, it would have the same significance concerning the processes of the San Juan region; but it has been interpreted otherwise.

Evidence supplied by fossils.—It has been stated that marine limestones carrying abundant faunal remains occur in central Texas interbedded with the Permo-Carboniferous Red Beds. The significance of the relations found in this region is well summarized by Chamberlin and Salisbury, as follows:

> The oldest part of the Permian system (*Wichita formation*) indicates that the critical attitude which characterized the surface farther east during the Pennsylvanian period now affected Texas, for the beds are partly of marine and partly of fresh-water origin. These beds are succeeded by a formation of limestone (the *Clear Fork*) of marine origin, which overlaps the Lower Permian. The Upper Permian (*Double Mountain* formation) which follows indicates a reversal of relations, for much of Texas was again cut off from the ocean, and converted into an inland sea, or into inland seas, in which the phases of deposition common to such bodies of water took place. Occasional beds of limestone with marine fossils point to occasional incursions of the sea, while deposits of salt and gypsum point with equal clearness to its absence, or to restricted conditions, and to aridity of climate.[1]

[1] T. C. Chamberlin and R. D. Salisbury, *College Geology* (New York: Henry Holt & Co., 1909), p. 661.

The large and varied vertebrate fauna which has now been described from the clastic members of the Red Beds series in various parts of the Southwest[1] includes no forms requiring other than a land or fresh-water habitat, with the exception of fish remains in some of the marine beds just mentioned. In general, then, it is true that the paleontological evidence corroborates the purely stratigraphic and lithologic evidence for a continental origin for at least the greater part of the Red Beds. In certain places and at certain horizons the fossil remains, both plant and animal, are sufficiently abundant and of such types as to eliminate the possibility of extreme aridity as a continuously prevalent condition. The bone beds and petrified forests of northeastern Arizona, for instance, prove that during the time of deposition of the Shinarump group,[2] at least, there was a water supply in that vicinity sufficient to permit the support of abundant land life, both vegetable and animal. It is possible, however, that this water supply was derived from precipitation in a distant region, like the waters of the Nile delta. In the underlying Permian, which contains more salt and gypsum than the other members of the series in this district, vertebrate remains are absent. The Permian of the neighboring Kanab Plateau has yielded an extensive invertebrate fauna[3] suggesting brackish-water environment.[4]

Summary.—The most salient of the facts and inferences brought out by the foregoing discussion of the significance of features other than color as to the conditions of deposition of the Red Beds may be summarized as follows: (1) rapid erosion on land-masses of considerable relief; (2) decomposition not complete in advance of transportation; (3) sediments diminishing in thickness and in coarseness of grain away from sources of material, and clastic

[1] See especially various publications by S. W. Williston in the *Journal of Geology*, 1903–13.

[2] L. F. Ward, "Geology of the Little Colorado Valley," *Am. Jour. Sci.*, 4th Ser., XII (1901), 401–13. On p. 405 is the following statement: "The Shinarump constitutes the horizon of silicified trunks and there is no part of it in which fossil wood does not occur in great abundance."

[3] See C. D. Walcott, "The Permian and Other Paleozoic Groups of the Kanab Valley, Arizona," *Am. Jour. Sci.*, 3d Ser., XX (1880), 221.

[4] Interpretation by Eliot Blackwelder (personal communication).

sediments giving place to non-clastic in the same direction; (4) fluviatile deposition most important; (5) all deposits in relatively shallow water, or subaerial; (6) oscillating marine and non-marine conditions at edge, non-marine in most of region of deposition; (7) moderate aridity long continued in some parts of the region of deposition, alternating with less arid conditions in other parts.

These conditions coincide to a remarkable degree with those inferred from the study of modern red sediments.

RELATION OF DIASTROPHISM TO RED BEDS SEDIMENTATION

It may well be asked at this juncture why it is that earlier Carboniferous clastics underlying the Red Beds of Oklahoma and other states are not similarly colored. The difference in color, since this has been shown to be a feature dating from the time of sedimentation,[1] must be due to differences of some sort in the geographic conditions of the times when the successive series were deposited. One of these differences is the emergence of the plains of deposition. Another may be found in the fact that some, at least, of the highlands from which the Red Beds derived their materials were not in existence in the earlier part of the Paleozoic era. The Arbuckle-Wichita uplift probably dates from the later part of the Pennsylvanian period; and there may have been mountain-building in Colorado at the same time, as the stratigraphic relationships of the scattered Paleozoic sediments in that state seem to indicate. Dr. Blackwelder[2] calls attention in this connection to the fact that the general trend of the Arbuckle-Wichita folding is directly in line with the suspected areas in Colorado. Local climatic changes influencing the type of sedimentation may have been brought about by these changes in topography. The general continental expansion of North America from Pennsylvanian to Jurassic times leads one to expect extreme types of continental climate, including aridity, the localization of which would depend largely on the configuration of the continent.

The deposition of red sediments derived from ferruginous soils means either the development of red soils and the transportation of the material thereof without hydration, or the development of

[1] See discussion of this point, pp. 162–67, this volume.

[2] Personal communication.

limonitic ferruginous soils and the dehydration thereof during transportation. The development of ferruginous soils is the chief prerequisite to the deposition of Red Beds of the western type.

The areas from which the Red Beds derived their materials certainly included uplands, and in part at least they are known to have been possessed of fairly rugged relief; they were therefore in all probability the sites of more abundant rain than fell upon the plains or delta flats upon which the Red Beds were in large part deposited. The combination of well-watered highlands with less humid or semi-arid lowlands furnishes the conditions for the development of red soils, and at the same time provides for the transportation and deposition of the sediments derived from them. without extensive hydration or reduction of the ferric oxide constituent during the transfer.

An unusually extensive development of red soils during the time of deposition of the Red Beds might have been due, in some part at least, to the higher proportion of oxygen inferred by Chamberlin and Salisbury[1] to have existed in the atmosphere at this time.

SUMMARY

The several steps which have been followed in the interpretation of the color of the Red Beds, and the results obtained, may be summarized as follows:

1. The ferruginous matter which gives the Red Beds their color has been present in the series in very nearly its present distribution and arrangement since the time of sedimentation.

2. This material has suffered no extensive change of ferrous to ferric iron, or vice versa, since the time of sedimentation; the proportion and present distribution of these compounds in the series were influenced most largely by the original distribution of organic matter.

3. Changes in the degree of hydration of the ferric oxide in the Red Beds since sedimentation probably have not been of great importance; and hydration probably has been quite as active as the reverse process during this time.

[1] T. C. Chamberlin and R. D. Salisbury, *Geology* (New York: Henry Holt & Co., 1909), II, 665.

4. The ferruginous matter of the Red Beds was transported and deposited almost, if not quite, wholly as a mechanical sediment, both independently and as a coating upon grains of other material.

5. The types of sediments probably most important in the Red Beds group are stream deposits, submarine fluviatile deposits, and playa deposits, all predominantly of red color, and all deriving at least the greater part of their ferric oxide from ferruginous residual soils. Of these types the first is by all odds the most important.

6. The study of characteristics of the Red Beds other than color bears out the conclusion stated in No. 5.

7. The inauguration and cessation of Red Beds sedimentation probably were connected closely with climatic and topographic changes involved in the orogenic history of the continent.

The colors which distinguish Red Beds from other series are due to a combination of lithologic, topographic, and climatic factors in the regions of denudation and in those of deposition, which have not been reproduced over so great an area in more recent times.

It is apparent that, in accordance with Barrell's view,[1] "red color in sediments is not in itself an indication of aridity"; for the material of red ferruginous soils may be transported and deposited in regions of high rainfall, or even under the sea, without change of color; and red soils themselves develop in regions of heavy rainfall. But since the dehydration of the limonitic material of non-red ferruginous soils, as well as the continuance of the relatively anhydrous condition of the hematitic material of red soils, is favored by aridity in the regions of transportation and deposition, therefore red sediments should form a larger part of the sediments of arid than of humid regions.

[1] Joseph Barrell, "Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, 4th Ser., XXXVI (1913), 437.

THE ACADIAN TRIASSIC

SIDNEY POWERS
Troy, New York

PART III

STRUCTURE OF THE ACADIAN TRIASSIC

The Newark rocks in the Acadian area exhibit a monoclinal structure, with a prevailing northwesterly dip, interrupted by broad, low folds. The monocline is broken by numerous faults with a small displacement and by occasional faults with a displacement of hundreds of feet. The other areas of Newark rocks have undergone deformation of a similar nature, but the direction of the monoclinal tilting differs in the various areas. In the case of the Connecticut Valley, the Pomperaug Valley (Connecticut), the Deep River (North Carolina), and the Wadesborough (North Carolina) areas, the dip is southeast, where as in all the other areas it is northwest.

The two structural features, the folds and faults, will be treated separately and finally some attention will be given to the theories of origin of this structure.

FOLDS

The most important and the most conspicuous fold in the Acadian area is that shown by the hook in North Mountain which incloses Scots Bay. The point of the hook forms Cape Split, and the back of the hook, Cape Blomidon. This syncline pitches down on the north side and is cut off on the north by a fault shown in cross-section DD, Fig. 28. The syncline is shown principally in the North Mountain basalt which dips toward Scots Bay on all sides of the Bay at angles of about 5°. Under the basalt flows the Blomidon shale is seen following the erosional escarpment, on the south side of North Mountain, around to Cape Blomidon, near which point it disappears under the waters of Minas Basin, as shown in Fig. 27. Above the North Mountain basalt comes the Scots Bay formation, the youngest formation in the Newark group of the Acadian area. The Scots Bay formation is exposed on the south side of the Bay, as shown in Fig. 27.

The eastern extremity of Minas Basin, east of Economy Point (the area shown in Fig. 23), also forms a syncline which has been disturbed by faulting at various points. The beds of red sandstone on either side of Cobequid Bay dip toward the bay at angles of about 3°–5° except where they have been tilted by faulting. This gentle dip must simulate that of the strata when they were first deposited in the slowly subsiding geosyncline.

A syncline, which is well shown in a shore section, is found at Quaco, between West Quaco and Melvin's Beach, on the north side of the Bay of Fundy (see cross-section BB, Fig. 7). The sediments of the Quaco section are readily identified by the Quaco conglomerate in the center. This conglomerate is exposed on the shore near Vaughan Creek with a dip of 30° to the north and again a mile inland (northwest) with a corresponding dip to the south. The syncline is cut off obliquely on the north by a fault in such a way that the axis of the syncline is shown in the shore section near Melvin's Beach, but the Quaco conglomerate of the northern limb does not reappear.

At Split Rock a low anticline is shown, at Martin Head a syncline, and at Waterside an anticline and the adjoining syncline. In each of these cases the folds are cut off by faults. The folds are at a low angle with broad arches or troughs.

Cape d'Or shows a small syncline in the basalt flows where the basalt ridge turns, from its east-west course, to make the Cape on the south. Horseshoe Cove has been formed at the axis of the syncline. The basalt is also faulted as is shown in Fig. 12.

Everywhere in the sea-cliff exposures there are minor flexures in the Acadian Triassic, both in the sediments and in the igneous rocks. In Fig. 19, an example of the folds in the sediments west of Five Islands is given. In the North Mountain basalt, gentle folds are shown at Scots Bay, where the Scots Bay formation is preserved in synclines (Fig. 29), and at Digby Gut, where a long syncline is shown at Victoria Beach.

FAULTS

The disturbance at the close of the Newark sedimentation threw the rocks of this group into fault-blocks with a monoclinal tilting toward the northwest. With such a structure, the major faults would tend to assume a northeast-southwest trend, and some of the more important faults should bound the formation on the north and northwest.

The faults at the margin of the Triassic area are confined to the northern and western sides. Thus the basalts of Grand Manan are faulted down on the west side, while the pre-Triassic rocks on the east side of the island are probably tilted up. The older formations against which the basalts were downthrown have since been eroded away, because they were less resistant than the basalts, and Grand Manan Channel has been formed in them.

The northern and northwestern sides of the Triassic areas at Split Rock, Quaco, Martin Head, and Waterside are all dropped down as fault-blocks against older rocks. At Martin Head the pre-Cambrian rocks form Martin Head itself, which is south of the exposure of the Triassic sediments. This exposure of older strata may be explained either as a horst or as the basement upon which the southern limb of the Triassic syncline rests. The latter view is favored, making the Triassic and the exposure of pre-Cambrian part of one fault-block, with a fault south of the pre-Cambrian. There also appears to be a minor fault in the axis of the Martin Head syncline.

The fault of greatest displacement in the Fundy region is the Cobequid fault (shown on the general map of the region), which stretches from West Advocate, north of Cape d'Or, to a point northeast of Truro, a distance of 90 miles. On the north side of the fault is the Cobequid group of sedimentary and igneous rocks which composes the Cobequid Mountains. On the south side of the fault are Triassic sandstones at West Advocate and Advocate Harbour, and Pennsylvanian rocks east of Advocate Harbour. The displacement of this fault is probably 2,000–3,000 feet.

South of the Cobequid fault is another east-west fault which bounds the Triassic on the north from Cape Sharp to the Chiganois River (northeast of Truro). The displacement of this fault appears to be greatest on the west, with a downthrow of 1,500 feet or less. Parallel to this fault is another at Clarke Head which has brought the Triassic down on the north against older rocks on the south, forming a small graben shown in Fig. 17. All the rocks at Clarke Head are intensely faulted.

The remnants of North Mountain basalt at Cape Sharp and at Partridge Island appear to be faulted off on the south side. The throw of this fault is uncertain in direction, but it may be a continuation of the southernmost fault at Clarke Head.

The exposure of North Mountain basalt at Cape d'Or exhibits several faults in a north-south direction, as shown in Fig. 12. The end of Cape d'Or is probably on an east-west fault line. This same fault may extend eastward.

The Five Islands region exhibits complex block-tilting with blocks of relatively small size. Besides the fault bounding the Triassic on the north, and the Cobequid fault farther north, an east-west fault is shown at Gerrish Mountain (Figs. 20, 22). The Five Islands are each separated by faults and are each tilted in different directions. These faults on the north become lost in a greatly slickensided region shown in detail in Fig. 21. The slickensided surfaces are usually vertical and have a north-south direction. The major movement appears to have been in a horizontal plane, but the stratification shows that there also has been vertical movement. Many other north-south faults are shown along the shore from Clarke Head to Five Islands, and a typical section is shown in Fig. 19.

Near Lower Economy a strike (east-west) fault brings the Triassic down into contact with a mass of Pennsylvanian strata on the north on which the Triassic rests unconformably.

The hook of North Mountain, at Cape Split, is cut off by a northeast-southwest fault which gradually cuts across this limb of the Scots Bay syncline.

North Mountain is composed of basalt flows tilted to the northwest so that an erosion escarpment is produced on the south side of the mountain and a gentle dip-slope on the north side. The sea-cliffs on the north side are never very high for this reason. With a continuation of the dip-slope, the erosion top of the flows appears to extend under the Bay of Fundy. The coast charts do not show any pronounced submarine ridges parallel to North Mountain, such as some authors have referred to, and therefore there is a lack of evidence of any major fault parallel to North Mountain. Moreover, no geological structure under the Bay of Fundy appears to be deducible from the submarine topography.

Cross-faults in North Mountain are readily shown by offsets in the ridge of basalt flows because the flows are dipping at a low angle northwest. The offsets are at Digby Gut, Bay View, Gulliver's Cove, Petit Passage, Grand Passage, and southwest of Brier Island. The line of these faults is north-south. The displacement of the flows by these faults, with the exception of the first and last faults, is to the north on the west side of the fault. These offsets are shown on the accompanying general map of the region. The offset at Digby Gut is shown on Fig. 30, and that southwest of Brier Island is shown by the position of a short submarine ridge on the coast chart.

As shown by Daly[1] and by Haycock,[2] these fault lines across North Mountain, and also the depressions at Parker Cove and Sandy Cove were occupied by rivers at the time that the Summit peneplain was being developed over the region. When the peneplain was uplifted the rivers became rejuvenated and persisted in their courses until the present valleys were cut. Headward erosion up the valley which is now St. Mary's Bay diverted the streams flowing across the basalt south of Bay View, and the more rapid erosion in Digby Gut caused the abandonment of the Bay View and Parker Cove valleys.

THEORIES OF ORIGIN

The faults which traverse the rocks of the Newark group are of deep-seated origin, extending into the older formations. The character of the underlying formations varies with the different areas. Thus the Acadian Triassic is underlain in part by Carboniferous folded sediments, in part by Silurian and Devonian slates and

[1] R. A. Daly, "The Physiography of Acadia," *Bull. Mus. Comp. Zoöl., Harvard College,* XXXVIII (1901), 92.

[2] E. Haycock, "Records of Post-Triassic Changes in Kings County, Nova Scotia," *Trans. N.S. Inst. Sci.,* X (1900), 297.

Devonian granite, and in part by pre-Cambrian slates (the Meguma series) and other metamorphic rocks (the pre-Cambrian complex of New Brunswick). The Connecticut Valley area is underlain by gneisses and schists, the New Jersey area by gneisses and some Paleozoic sediments, and the Richmond area by gneisses and granites. A theory which accounts for the structure of the Newark beds must therefore suit the various basement rocks.

Davis,[1] in studying the Connecticut area, reached the conclusion that the origin of the monoclinal fault structure was the slipping of blocks of the underlying crystalline rocks on each other along cleavage planes. As pointed out above, although the Connecticut area is underlain by gneisses and schists, the other Newark areas are not. Suitable cleavage planes would therefore not be expected in the other areas.

In the Minas Basin region, the crystalline rocks are several thousand feet below the base of the Triassic. Furthermore, the planes of slipping in these crystallines are parallel to the main structural lines of the formation. These lines run at an angle to the axis of Minas Basin, as is seen in the nearest exposures of the crystallines (the Meguma, or Gold-bearing series). The theory proposed by Professor Davis does not seem, therefore, to apply to the Acadian area.

Hobbs[2] considers that Professor Davis' theory does not suit the facts in the Connecticut Valley or in the Pomperaug area. For the latter area, Hobbs proposes another theory to account for the peculiar system of quadrangular block-faults. As this detailed faulting is not typical of all the Newark areas, the theory is of limited application.

Professor Barrell[3] has recently ascribed the origin of the Connecticut Valley Triassic area to the gradual development of a fault on the east side of the geosyncline, contemporaneously with the

[1] W. M. Davis, "The Structure of the Triassic Formation of the Connecticut Valley," *U.S. Geol. Surv., 7th Ann. Rept.*, 1888, pp. 486–89.

[2] W. H. Hobbs, "The Newark System in the Pomperaug Valley, Connecticut," *U.S. Geol. Surv., 21st Ann. Rept.*, Part 3 (1901), pp. 122–33.

[3] J. Barrell, "Central Connecticut in the Geologic Past," *Proc. Wyo. (Penn.) Hist. and Geol. Soc.*, XII (1912).

filling of the basin with sediments. This fault is supposed to have been initiated after sedimentation commenced, and to have increased in displacement with the accumulation of the sediments.

In the Acadian area a corresponding fault is found on the north and west, but there is no evidence that this fault developed until sedimentation ceased. No completely satisfactory theory to account for the structure has yet been presented.

IGNEOUS ROCKS

DISTRIBUTION

A description of the igneous rocks in each locality has been given in the description of the general stratigraphy of the region, and therefore merely a summary is attempted here. The flows at Cape d'Or have been especially studied, and will be considered in a separate paper by Professor Alfred C. Lane and the writer.

All of the igneous rocks associated with the Acadian Triassic are of a basaltic composition. From the form of occurrence, they are grouped into dikes and flows. According to the time of formation, they are classified as the Five Islands volcanics and the North Mountain basalts. Dikes are so rarely exposed that it is necessary to consider the rocks from the point of age, rather than form.

In Nova Scotia, outside of the Triassic area there are some diabases and basalts which are probably of Triassic age. At Cheverie, near the Avon River, there is a sill of diabase intruding Pennsylvanian strata.[1] Again, in Guysborough County, near Guysborough, Fletcher has mapped on the sheets of the Geological Survey of Canada masses of diabase cutting the Union-Riversdale series. The nature of these masses is described by Fletcher[2] as partly amygdaloidal, partly dioritic.

Dikes of Triassic age occur in a number of places between Nova Scotia and the Connecticut Valley. The large majority of them are of diabase composition.

[1] Verbal communication from Mr. W. A. Bell, of the Geological Survey of Canada.

[2] H. Fletcher, *Geol. Surv. of Canada, Annual Report*, 1886, pp. 101–3 P; also *Geol. Surv. Canada, Maps, Nova Scotia*, Nos. 30, 31, 35, 36.

FIVE ISLANDS VOLCANICS

Under the heading Five Islands volcanics are included the tuffs, agglomerates, and basalt flows in the vicinity of Swan Creek and the Five Islands. The thickness of the volcanics is estimated as at least 350–400 feet. One associated dike is exposed at Gerrish Mountain.

The Gerrish Mountain diabase dike is almost vertical and about 20 feet or more in thickness. The diabase shows marked columnar jointing, the columns being rather short and largely horizontal or dipping at a low angle to the horizontal. The dike is connected with the basalt flow which caps the sandstones of Gerrish Mountain, and it has evidently furnished the material for this flow and perhaps for a large part of the other igneous rocks for the vicinity.

The basalt flows associated with the Five Islands volcanics are found at Gerrish Mountain, on four of the Five Islands, on Two Islands, and at Portapique Mountain (east of Gerrish Mountain). It is noteworthy that the relation of these flows to the agglomerates is unknown, and that there is no proof that they are not connected with the North Mountain basalt instead of with the Five Islands volcanics. The structure of these flows is in large part columnar, and the base and the top of each individual flow is marked by amygdaloid. The basalts are the usual fine-grained, dark-gray, heavy rocks composed of augite and plagioclase with accessory amounts of magnetite and occasionally olivine. A more detailed petrographical description will be given below for the North Mountain basalt, which will apply equally well to these flows.

Only one flow is exposed in Gerrish Mountain. This has a thickness of over 75 feet. Three flows are exposed on the north side of Moose Island, the upper one being agglomeratic. A portion of a single flow is exposed on Diamond Island and on Long Island. Two flows are seen on Pinnacle Island. The northern of the Two Islands consists of three flows, the southern of probably only one.

The base of the series of flows is exposed on the eastern side of Moose Island and on Gerrish Mountain. Under the amygdaloid which marks the base of the flow is a layer of green ash 2–3 feet in thickness. A similar ash-bed is exposed west of Swan Creek under the agglomerate flow mentioned below. The thickness of the flows on Gerrish Mountain may be considerable, as the basalt covers a large area.

The agglomerate beds, with associated tuffs, are exposed from Greenhill eastward to Five Islands, in disconnected areas. The relation of these remnants of flows and volcanic ejectamenta to the sandstones is a problem only partly solved because of the faulted contacts, with possibly minor thrust-faults, and the landslides which are especially abundant in the tuff. The tuff underlies the agglomerate in most cases. The thickness of the tuff varies from a few feet to 50 feet, and that of the agglomerate flows from 20 to 150 feet or more. Exposures show that the agglomerate is overlain by red sandstone, and is therefore older than the North Mountain basalt.

The agglomerates consist of a mass of angular fragments of basalt and amygdaloid in a dark-green matrix of a basaltic composition. The exact character of the matrix is difficult to determine because it is everywhere so badly weathered that a solid specimen could not be procured. The field evidence, however, indicates that this matrix is in part tuffaceous and in part a normal basalt. At the sides of some of the masses of agglomerate are blocks of angular basalt and amygdaloid imbedded in a red sandstone matrix, showing that the breccia was either blown out into the area where sandstone was being deposited, or washed out from a bed of tuff and breccia. The cross-cutting contacts at one side of the masses of agglomerate in two instances give them the appearance of intrusive bodies rather than of flows. If the agglomerates are intrusive, rather than extrusive, they probably fill volcanic necks.

NORTH MOUNTAIN BASALT

Under the term North Mountain basalt, used in a generic sense, are included the basalt flows of Grand Manan, Isle Haute, Cape d'Or, Cape Sharp, Partridge Island, and North Mountain. The series of flows at these localities are correlated either for structural reasons or because they are underlain by shale correlated with the Blomidon shale.

In each locality there are several flows, indicating successive extrusions within such a short time of each other that no sediments were deposited between the flows. It is impossible to state whether any single flow originally covered the geographical area over which the remaining exposures indicate that the formation once extended. The Palisade diabase formes one sill 100 miles long on the out-croping edge, while North Mountain is 120 miles long. In the former case the igneous material was intruded at some distance below the surface and had to push up this great weight of rock, which, however, acted as a blanket over the feeder. In the latter case the igneous material was extruded at the surface, with no roof to sustain, but the feeders were constantly subjected to the great heat loss by radiation at the surface, which would tend to freeze them up.

Dikes associated with the North Mountain basalt are rare. Several were reported on Grand Manan by Bailey,[1] but they were not observed by the writer. The largest of these is 50 feet wide, and occurs at Flag Cove, near Swallow-Tail Light.

Other narrow dikes occur on the south side of Scots Bay, just east of the Scots Bay formation exposures. These dikes cut the basalt within 25 feet of the top of the upper flow. From the other exposures of this flow it is judged to be at least 100 feet thick, and, if so, it is quite evident that the dikes cut the upper flow and are not the feeders. With the dikes are many fissures filled with vein material which is seen under the microscope to consist largely of silica stained red with hematite. The width of both the veins and the dikes varies from one to ten inches, and in the field they look very much alike.

In thin-section the dikes are seen to consist of a very fine-grained diabase, greatly altered and stained with limonite. The rock is similar to that of the flows near the center, but shows some glass.

From the field evidence of the dikes and veins side by side in the upper part of this thick flow, and from the microscopic evidence, it is concluded that the dikes were formed from the basalt of the upper flow after the crust of the flow had solidified and while the

[1] L. W. Bailey, *Geol. Surv. Canada, Report of Progress*, 1870, pp. 216–21.

center of the flow was still liquid. The crust appears to have become fissured, with some of the fissures reaching down to the still molten rock, and other of the fissures having no great depth and therefore being filled with quartz from above at a later stage.

The structure of the flows is similar to that of all basalt flows. The individual sheets are clearly distinguished by a relatively thin amygdaloidal base and a relatively thick amygdaloidal top. Flows composed entirely of amygdaloid were observed only at Cape d'Or. The basalt is closely jointed and columnar joining is frequently developed. The angle at which the columns and planes between the sets of columns stand with respect to the vertical and horizontal, respectively, indicates the dip of the flow. Faulting in the sheets is frequently obscured by jointing.

In North Mountain, from Cape Blomidon to Cape Split, and along the Victoria Beach shore of Digby Gut, the thickness of the flows may be estimated. A partial section is exposed at Sandy Cove and at Freeport, on Long Island, and at Tiverton, on Brier Island. In most of the sections the lowest flow is the thickest, and at the top of the series are several thin flows.

The section from Cape Blomidon to Cape Split shows two and probably three flows, each with an estimated thickness of 150–300 feet. The top of the upper flow is exposed around the edge of Scots Bay. It exhibits the small folds into which all the basalt flows have been thrown. No other sections of the North Mountain basalt are exposed until Digby Gut is reached, because the sea-cliffs are low and expose only the upper flow or flows.

At Victoria Beach the best section is found. There is some doubt if the lower flow, as here estimated, is not composed of two separate flows, but the microscopic examination of slides made from the first exposures above and below the blank in the section indicates a coarseness of grain which characterizes the center of a thick flow. Erosion has probably removed several flows from the top of the section. The section consists of:

Top.	Six flows 2–45 feet in thickness	160± feet
Base.	Main flow	600+ "

The upper flows of the Victoria Beach section are absent from the exposures at the end of Digby Neck. They have either been removed by erosion or were never deposited there. The thicknesses of the portions of the flows remaining between the waters of St. Mary's Bay on one side and the Bay of Fundy on the other are estimated as:

	Sandy Cove	Tiverton
Upper flow	300± feet	150+ feet
Lower flow	150± "	75+ "

On Grand Manan the section is quite similar to those given above. The number of thin flows on the top of the series was not counted accurately. The section is:

Top.	Ten(?) thin flows averaging 10–15 feet in thickness..........................	100 feet
	Second flow	250 "
Base.	First flow	450 "

The number of flows exposed on Isle Haute is unknown. The section at Cape d'Or consists of 5 flows, of which the lower one (556 feet) is the thicker. At Cape Sharp and at Partridge Island two flows appear to be shown.

Only one petrographic description of the basalt of North Mountain has been published.[1] On account of the similarity of the basalts associated with the Newark group little attention has been paid to those of the Acadian area.

The basalt is a dark-gray or dark-greenish fine-grained rock composed of plagioclase feldspar and augite with accessory amounts of magnetite, olivine, and glass. The feldspar is a labradorite, varying slightly in composition. The texture of the rock is ophitic, laths of feldspar inclosing augites, or masses of augite inclosing small feldspar laths. Chlorite, magnetite, limonite, hematite, and serpentine are present as alteration products.

The proportion of glass to crystalline matter, of labradorite to augite, and the presence of olivine each depend on the proximity of the section to the top or bottom of the flow. The top of the flow is always quickly chilled in contact with the atmosphere, and solidifies with a large amount of glass and a large number of gas cavities. These cavities later become filled with quartz, calcite,

[1] V. F. Marsters, "Triassic Traps of Nova Scotia," *Am. Geol.*, V (1890), 140–43.

or some other mineral to form amygdules. At the base of the flow, rapid chilling also takes place; less glass is developed, but well-crystallized magnetite is found. Alteration, however, soon commences in the base of the flow because of the reaction of heated waters on the basalt.

The glass, characteristic of the top and the bottom of a flow, frequently contains most of the feldspar in laths already formed, showing that the feldspar had commenced to crystallize before the augite. In other cases the glass is accompanied by both augite and feldspar. The glass always has a cloudy appearance.

Gravitative adjustment takes place in all flows which are sufficiently thick, and which remain hot sufficiently long for a movement of the crystallizing magma to take place without being recorded in flow structure. As in the case of the Palisade sill, olivine tends to form near the base of the flow and in the quickly chilled top.

Gravitative differentiation is also shown in the relations of the labradorite to augite. The augite settles toward the base of a flow as in the case of a sill, and the feldspar rises.

The chemistry of the Cape d'Or flows will be treated in a separate paper, but it may be stated here that those basalts show a normal composition, averaging about 52.5 per cent silicia, 14.3 per cent alumina, 9.8 per cent lime, 2.5 per cent soda, and 1 per cent potash.

Rosiwal measurements on thin sections from the center of a 556-foot flow show a mineralogical composition of 40 per cent plagioclase feldspar, 56.5 per cent augite, and 3.5 per cent iron ores.

All the basalts show more or less alteration and disintegration except where rapid marine erosion exposes fresh rock. The amygdaloid, even where fresh, is always altered. In the drill-cores at Cape d'Or, the same character of alteration was shown in each amygdaloidal layer. A certain amount of hematite, with limonite, is developed, giving these rocks a reddish color.

Veins are very common in the dense basalts as well as in the amygdaloids. The veins are formed of jasper or quartz, with either reddish (hematite) or greenish (malachite or chlorite) walls.

ORIGIN

The basalt unconformity of the Acadian Triassic always shows upturned and beveled rocks overlain by Newark sandstones or conglomerates with bedding parallel to the underlying erosion surface. This fact indicates that the Newark sediments were deposited on a peneplain, as has been found the case in the Connecticut[1] and Richmond[2] areas.

On this peneplain, an orographic basin was formed, and into the geosynclinal area sediments were brought from all sides. An equilibrium between the rate of sedimentation and of subsidence of the geosyncline appears to have been reached when the Blomidon shales were deposited at the top of the Annapolis formation.

The Wolfville sandstone at the base of the Acadian Newark shows red sandstones and occasional conglomerates and shales, in general evenly bedded. The pebbles in the conglomerates are stream-worn, but are frequently subangular. The character of the Quaco conglomerate has been sufficiently treated. The Wolfville sandstone indicates stream transportation, with deposition in flood-plains, and perhaps in past in broad alluvial fans.

The Blomidon shales are generally evenly bedded, but show occasional ripple or current marks, and rarely mud cracks. The presence of *Estheria* indicates temporary bodies of water. Flood-plains of mature rivers would furnish the necessary conditions for the deposition of shales, with cut-off lakes in which the crustaceans could live.

The red color of the Annapolis formation evidences long oxidation of the iron during transportation and deposition.[3] The white or gray color indicates a lack of hematite, and the green color is caused by the presence of chlorite.

The climate during the deposition of the Annapolis formation was apparently hot and dry, with occasional floods. The presence of calcite in nearly all the sediments, and the scarcity of arkose,

[1] W. M. Davis, *U.S. Geol. Surv., 18th Ann. Rept.*, 1898, p. 20.

[2] N. S. Shaler and J. B. Woodworth, *U.S. Geol. Surv., 19th Ann. Rept.*, 1899, p. 408.

[3] J. Barrell, "Relation between Climatic and Terrestrial Deposits," *Jour. Geol.*, XVI (1908), 159–90, 255–95, 363–84.

and of plant and animal remains, all favor long oxidation of the sediments in a dry tropical climate.

The Scots Bay formation was deposited in part, at least, in a lake, because fish remains occur in the strata. This lake came into existence soon after the extrusion of the North Mountain basal flows, as is indicated by the lack of erosion in the upper amygdaloid.

The Five Islands volcanics are interpreted as representing a phase of igneous activity slightly earlier than that in which the North Mountain basalt flows were extruded. The volcanics may have come from central vents as well as from fissure eruptions.

The North Mountain basalt must have come from fissure eruptions, and spread out over a large portion of the Triassic geosyncline, as is indicated by the widely separated areas at North Mountain and at Grand Manan. The geographical extent of any individual flow is impossible to determine, but it appears that the earliest flow, or series of flows, was the thickest.

The physiographic conditions accompanying the formation of the Five Islands volcanics and the North Mountain basalts are poorly shown. The base of the North Mountain basalt is exposed only on Grand Manan, and there it is greatly weathered. No evidence of contemporaneous lakes over which the lava flowed has been found.

THE LOMBARD OVERTHRUST AND RELATED GEOLOGICAL FEATURES

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CONTENTS

TOPOGRAPHIC AND STRUCTURAL FEATURES

The region involved in this discussion lies near the head of the Missouri River in Montana. The chief topographic features are hilly dependencies of the Little Belt Mountains.

FIG. 1.—Geological map of the region about Three Forks, Montana

The principal structural features are shown on the map (Fig. 1) and in the structure sections (Fig. 2). The dynamic features consist of folds and faults.

FOLDS

There is no indication that any marked deformation took place in this region during the Paleozoic and Mesozoic eras. At the close of the Cretaceous period, probably, the great series of sediments which had been accumulating began to be deformed. In this region they were compressed into a series of closed folds with a general northeast-southwest trend. These folds are usually overturned to the southeast and pitch to the southwest. Two of these folds were named by Dr. Peale[1] the Horsehoe anticline and the Cottonwood isocline, both situated north of Logan, Montana.

East of Lombard, in the vicinity of Crane Station, there is a northward-pitching anticline. In the long ridge west of the Missouri River there is an elongate domal structure (Fig. 3) the western side of which is interrupted by a normal fault and obscured by an extensive overthrust. The southern part of this elongate dome is overturned to the east and pitches steeply to the south (Fig. 1; Fig. 2, section D-D; and Fig. 4).

FAULTS

The Lombard overthrust.—The most important feature of the structural geology of the region is an extensive overthrust fault which has its southern end in the ridge north of Three Forks, and extends a distance of at least 13 miles along the ridge to the northern border of the map. The writer proposes the name "Lombard overthrust" for this feature, because it is well exposed in the canyon of the Missouri River near Lombard. Here the fault plane dips about 40° to the west. This fault has brought strata of the Belt Series over strata of Cretaceous age in the north, near Lombard, and has brought the upper member of the Cambrian into contact with the Carboniferous Madison limestone in the southern end of the ridge (Figs. 2 and 5). The maximum displacement on the fault plane near Lombard cannot be very closely estimated,

[1] A. C. Peale, *Bull. U.S. Geol. Survey, No. 110,* 1893.

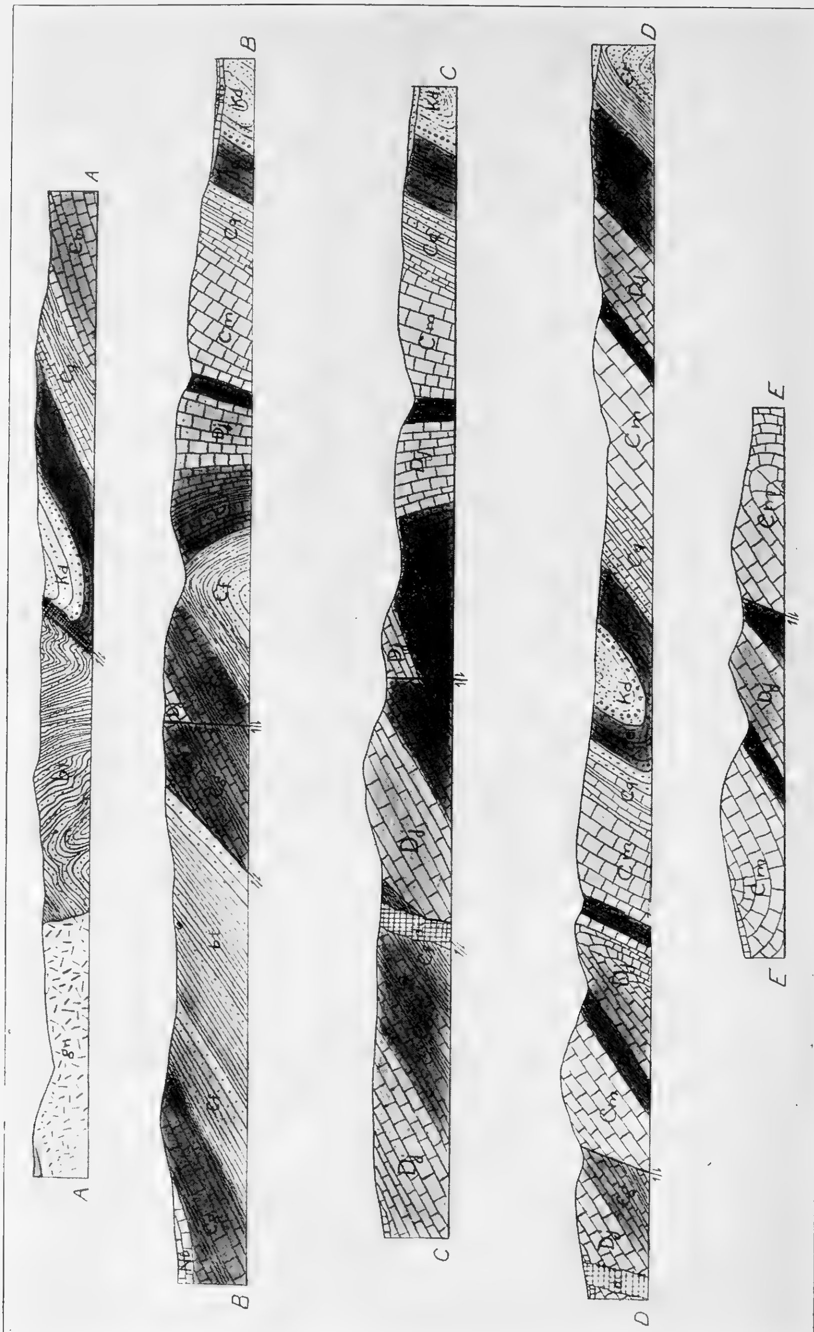

FIG. 2.—Geological sections

but it is approximately two miles, and strata which are stratigraphically about 6,800 feet apart are here in contact.

The age of the Lombard overthrust cannot be definitely determined, but it is certainly younger than the Cretaceous strata exposed near Lombard, and probably older than the Lower Oligocene deposits which occur near the southern end of the ridge and are apparently undisturbed. It may therefore be assigned with some uncertainty to very late Cretaceous or early Tertiary time.

A normal fault.—The only normal fault observed in this region appears in the highest part of the ridge north of Three Forks and west of the Missouri River. This fault cuts across the western limb of the elongate dome already noted, and has caused a repetition of the upper part of the Gallatin formation and the base of the Jefferson limestone (see Fig. 2, section C-C). This fault has a length of about two miles and a diminishing throw to the south. It could not be traced to its intersection with the overthrust fault, but the displacement apparently dies out in that direction also.

The age of the normal faulting is considered to be the same as that seen farther south in the Three Forks quadrangle, which is dated as probably Pliocene.

STRATIGRAPHIC GEOLOGY

PRE-CAMBRIAN

The oldest rocks exposed in this region are a series of somewhat altered sediments which occur below the base of the Cambrian, and are considered to be part of the Belt Series, which are typically exposed in the Little Belt Mountain region to the north and northeast. The exposures of the Belt formation occur along the Gallatin River east and northeast of Logan, and also north of Three Forks, in a widening strip which trends northeastward and crosses the Missouri River at the double horseshoe bend west of Lombard (Fig. 1).

The exposures north of the Gallatin River are of rather coarse micaceous sandstones and shales with thinly bedded siliceous limestones. They are not divisible on the basis of lithological characters into the various formations which characterize the Belt Series at the type localities.

The extensive exposure of the Belt Series north of Three Forks, which, so far as the writer was able to ascertain, has not been described before, consists of two fairly distinct formations which are considered to be equivalent to the Spokane and Empire formations of the Belt Series.

Spokane formation.—In the vicinity of the double horseshoe bend of the Missouri River there is a fine section through the

FIG. 3.—Domal structure in ridge west of the Missouri River

Spokane formation. The formation at this place consists of a thick series of well-stratified red and green slates with frequent layers of ripple-marked and mud-cracked sandstone. The finer beds are mostly very hard and siliceous and may be called argillites or even metargillites. At several places in the section distinct folds are visible, and also some faults. The minimum thickness of the formation in this section is 1,650 feet, but the average thickness is probably considerably greater than these figures.

Empire shale.—This formation, which overlies the Spokane formation, is exposed in a long strip west of the Missouri River, extending from near the southern border of the Fort Logan Quadrangle near latitude 46° to the double horseshoe bend. It consists of evenly bedded, pale greenish shales with a few bands of quartzite. The quartzite occurs in beds from 1 to 25 feet thick. The formation is in apparent conformity with the overlying Cambrian

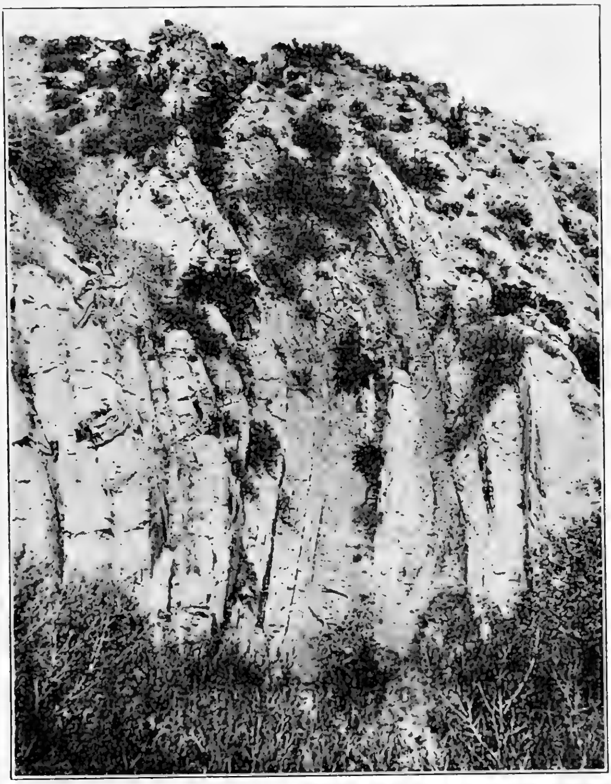

Fig. 4.—Folded Madison limestone near southern end of ridge, north of Three Forks.

quartzite near the southern end of the exposure, but inasmuch as the contact was traced for only a short distance an unconformity with very slight angular discordance may have been overlooked. Although the complete section of the Empire shale was not seen, it is probable that 800 feet is a conservative estimate for the thickness of the formation in this area.

There is still much disagreement among the various geologists who have worked in the parts of the Cordillera where the Belt Series is exposed, in regard to the age of the series and the correlation of the different formations in it. The writer is disposed to agree with the correlation in a recent report on the Philipsburg quadrangle in Montana,[1] in which strong evidence is shown for a rather long erosion period between the Belt Series and the overlying Cambrian quartzite. The two formations identified by the writer as the Empire and Spokane formations are therefore considered to be of Pre-Cambrian, Algonkian, or Proterozoic age.

PALEOZOIC

The Paleozoic formations recognized by the writer in this region are for the most part continuous with those described by Dr. Peale in his report on the "Paleozoic Section in the Vicinity of Three Forks, Montana,"[2] and later in the Three Forks Atlas Folio.[3] His descriptions of the formations are very good and apply equally well to the exposures in the region to the north, on the Fort Logan Sheet. There are some additional facts concerning the thicknesses and ages of the formations and a few changes in the nomenclature which will be discussed under the following headings:

Cambrian.—A comparison of sections made by different geologists in the neighboring quadrangles shows that the seven lithologic divisions noted by Dr. Peale in the Three Forks quadrangle are persistent throughout southwestern Montana and the neighboring part of Wyoming. It seems advisable to have but one name for each of these divisions, and since locality names are preferable to descriptive names the writer suggests that the nomenclature used by Dr. Weed[4] in the Little Belt Mountains Folio be adopted for the Cambrian throughout the whole region where these seven lithologic divisions are recognized.

For purposes of mapping it seems best to keep the broader divisions used by Dr. Peale, the two lower members forming the Flathead formation and the upper five the Gallatin formation.

[1] *Prof. Paper 78. U.S. Geol. Survey.* [2] *Bull. U.S. Geol. Survey, No. 110.*

[3] Atlas Folio, *U. S. Geol. Survey, No. 24.*

[4] Atlas Folio, *ibid., No. 56.*

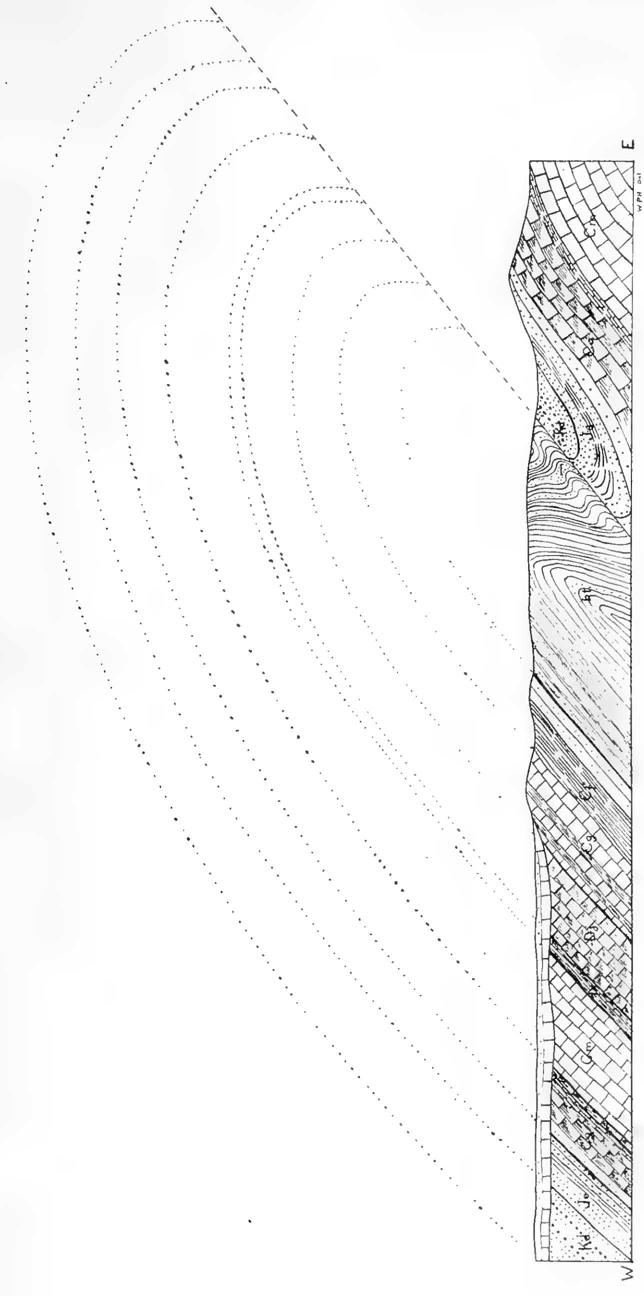

FIG. 5.—Diagrammatic section of the Lombard overthrust

The following section of the Cambrian northeast of Logan, Montana, was measured by the writer.

Dr. Peale's Nomenclature		Dr. Weed's Nomenclature	Thickness
1. Pebbly limestone	=	Yogo limestone	75 feet
2. Dry Creek shale	=	Dry Creek shale	20
3. Mottled limestone	=	Pilgrim limestone	300
4. Obolella shale	=	Park shale	280
5. Trilobite limestone	=	Meagher limestone	175
6. Flathead shale	=	Wolsey shale	450±
7. Flathead quartzite	=	Flathead quartzite	200
		Total	1,500± feet

Fossils from the Yogo limestone have been submitted by the writer to Dr. Walcott, who considers them of Upper Cambrian age, while those from the Meagher limestone are regarded by him as of Middle Cambrian age. Apparently Lower Cambrian strata are entirely absent in sections in this region. Although the boundary between the Middle and Upper Cambrian strata has not been definitely ascertained, it is likely that it comes between members 2 and 3.

Absence of Ordovician and Silurian strata.—In all of the sections studied by the writer in the Three Forks quadrangle and the neighboring district to the north, the Jefferson limestone lies in apparent conformity on the Yogo limestone without any intervening formations. The lower portion of the Jefferson limestone has been considered by Dr. Peale and others as probably of Ordovician and Silurian ages, although no fossils of those periods have been found in it. Dr. Kindle[1] has described the Jefferson limestone and its fauna and established its age as chiefly Middle Devonian with the lower part probably Lower Devonian.

In one or two good sections studied by the writer some rather poorly preserved corals were found within 25 feet of the base of the formation. These were identified as *Favosites* cf. *limitaris* Rom., which is rather common in much of the Jefferson limestone. The presence of these fossil corals is regarded as indicating the Devonian age of all of the Jefferson limestone, and since the gray Yogo lime-

[1] E. M. Kindle, *Bull. Amer. Pal. No. 20*, 1908.

stone immediately below the brown Jefferson dolomitic limestone contains Upper Cambrian fossils, the writer believes that at this contact there is a disconformity involving a hiatus in the sedimentary record of this region from the close of the Upper Cambrian to Lower Devonian time.

Further evidence in favor of this disconformity and stratigraphic overlap is brought out by the presence in sections in neigh-

FIG. 6.—Cliff of Jefferson limestone north of Crane Station

boring regions to the west and southwest of intervening strata of different lithologic character between the Yogo limestone and the Jefferson limestone, which in some cases contain fossils of Ordovician and Silurian ages. One very complete section from the Randolph quadrangle[1] in northeastern Utah, with 3,000 feet of Ordovician and Silurian strata between the Upper Cambrian limestone and the Jefferson limestone, shows very clearly the hiatus in the sections in the Three Forks quadrangle and the neighboring region to the north and northeast.

[1] G. B. Richardson, *Amer. Jour. Sci.*, XXXVI (1913), 406–416.

Devonian.—The strata of Devonian age in this region are divided into two distinct formations, the Jefferson limestone and the Three Forks formation.

Jefferson limestone: The Jefferson limestone is well described by Dr. Peale[1] as a massively bedded brown to dark-gray or black crystalline magnesian limestone with the composition of a dolomite. It is well exposed in the region under discussion in the form of brown cliffs 100 to 200 feet high (Fig. 6). In a few of the ridges

FIG. 7.—Valley in Three Forks formation, near Rekap Station

north of Three Forks the limestone is black in color, but shades of brown are the customary colors. In this region the Jefferson limestone has a thickness of about 500 feet, but it diminishes in thickness to the north and northeast, as noted in the sections in adjacent quadrangles.

Three Forks formation: Lying upon the Jefferson limestone is a series of shales and limestones which have been described by Dr. Peale[2] and named the Three Forks shales. The writer has made a careful study of this formation in all of this region, and has measured numerous sections and made extensive collections of

[1] A. C. Peale, *Bull. U.S. Geol. Survey, No. 110*, 1893, pp. 27–28.

[2] *Ibid.*, pp. 29–30.

fossils from certain of the members. A detailed account of the formation and a description of some of the fauna is in process of publication elsewhere,[1] so that only the more important points will be mentioned here.

In all of the region included in Fig. 1 the Three Forks formation shows seven fairly distinct lithologic divisions. These members are well shown in the following section of the formation made northeast of Logan near the Gallatin River.

Base of Gray Madison Limestone

1.	Yellow arenaceous limestone	30 feet
2.	Pale-yellow arenaceous shale	30
3.	Purple fissile shale	0.5
4.	Dark bluish-gray nodular limestone	9.5
5.	Fissile green shale	47
6.	Yellow crystalline limestone	15
	Gray limestone	12
7.	Yellow and orange shales	78
	Top of the Jefferson limestone. Total	222 feet

Another section farther north along the Missouri River at Rekap Station (Fig. 7), shows the variation in thickness of the different members.

1 and 2.	Yellow sandy limestone and shale	74 feet
3.	Black coaly shale	6
4.	Nodular gray limestone	7
5.	Fissile green shale and	120
6.	Gray and yellow limestone	
7.	Pebbly yellow and reddish limestones and shales	80
	Total	287 feet

It will be noted from these two sections that the members consist of limestones as well as shales, so that the term "Three Forks formation" is preferable to Dr. Peale's name "Three Forks shales."

In the region north of Three Forks and west of the Missouri River there are numerous good exposures of the Three Forks

[1] *Annals Carnegie Museum*, Pittsburgh.

formation, whose erosion has formed some rather prominent valleys, as shown on the map and in Figs. 7, 8, and 9. These valleys extend in a general north-south direction and are nearly parallel with one another. This repetition of the formation is due partly to folding and partly to faulting.

The easternmost valley eroded in the Three Forks formation is very narrow and shallow and extends northward along the eastern

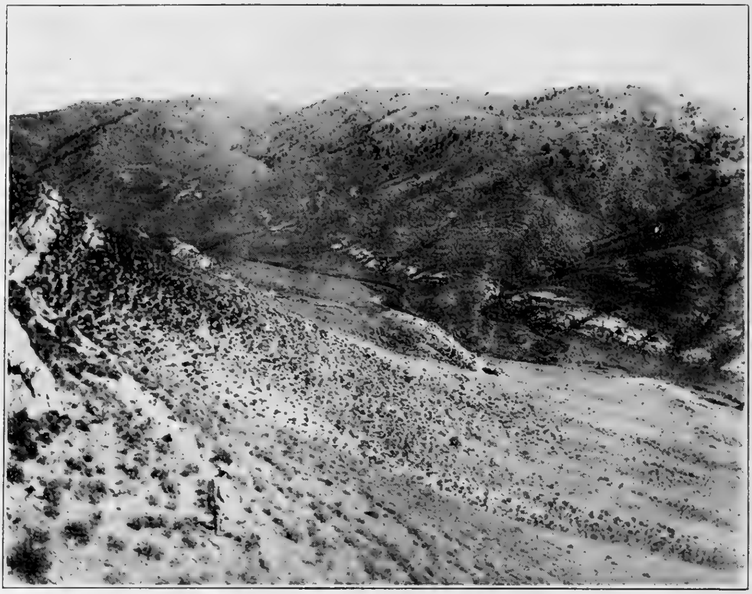

FIG. 8.—Great valley in Three Forks formation. Ridge north of Three Forks

slope of the range of hills for five or six miles. The exposures are poor because the strata are vertical or overturned and much crushed by close folding.

This valley, at its southern end, swings around to the west and opens into a much larger valley, which extends to the north for about two miles. The structure which is the cause of this curious arrangement of the valley is that of a southward-pitching anticlinal fold which is overturned to the east. The strata in this very large valley are in the western limb of the anticline (Figs. 8 and 9).

West of the overthrust fault there is another valley formed in the Three Forks formation. Numerous good sections of the formation were obtained in the small tributary gullies which cut across the dip of the strata on the western sides of these valleys.

The fossiliferous members of the formation are Nos. 1, 2, 4, and 5. The general conclusions from a study of the fauna are that the formation is very late Devonian in age, as reported by Dr.

FIG. 9.—View north from southern end of valley, at apex of southward pitching anticline.

Raymond in 1907,[1] and probably represents a transition into the Mississippian in its upper part in members 1 and 2.

Carboniferous.—Throughout the mountainous part of southwestern Montana the Carboniferous formations are very prominent and form conspicuous and precipitous cliffs. In the region about Three Forks the Carboniferous strata attain a thickness of from 1,500 to 2,000 feet.

[1] P. E. Raymond, *Amer. Jour. Sci.*, XXIII (1907).

Madison limestone: The lower formation has been named by Dr. Peale[1] the Madison formation and was subdivided by him into three members; (1) the Laminated limestones at the base; (2) Massive limestone in the middle, and (3) Jaspery limestone at the top. The thickness of the Madison formation near Logan is about 1,300 feet. Although it forms conspicuous gray cliffs along the ridge west of the Missouri River, its best exposures are seen where

FIG. 10.—Missouri River in canyon in Madison limestone

the river has cut a deep canyon through it near Lombard, and also in the smaller canyon along Sixteenmile Creek, east of Lombard (Figs. 10 and 11).

A large collection of fossils was made by the writer from the Madison formation in all parts of the region. These fossils all pointed to the general Lower Mississippian age of the Madison limestone.

Quadrant formation: Lying in apparent conformity upon the Madison limestone in this region is the Quadrant formation which

[1] A. C. Peale, *op. cit.*, p. 33.

forms the upper part of the Carboniferous system. The Quadrant formation consists of two members, as noted by Dr. Peale.[1] The lower is a red arenaceous limestone overlain by bands of shale and limestone. The upper member is thinly bedded cherty limestones alternating with quartzite layers. The top of the formation is somewhat arbitrarily placed by Dr. Peale at the base of a very massive and persistent quartzite layer which is

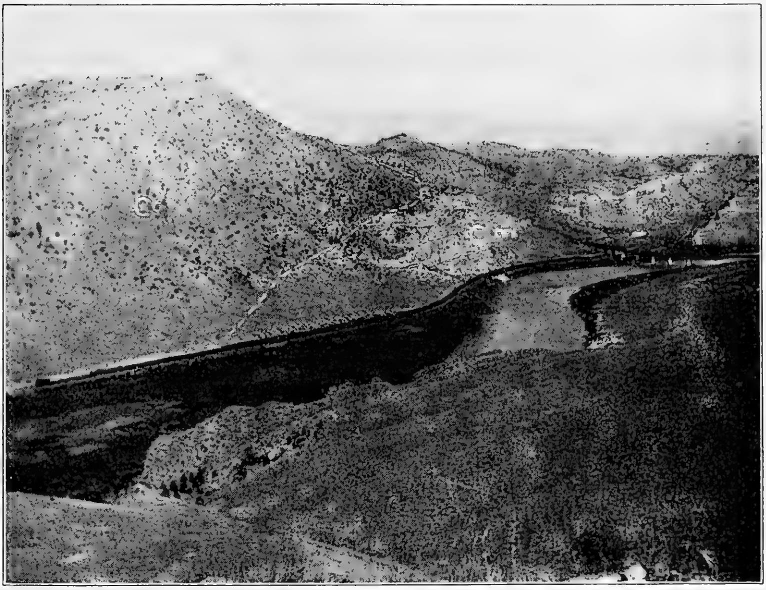

Fig. 11.—Double horseshoe canyon of the Missouri River. View east showing Lombard Station, and mouth of Sixteenmile Creek canyon.

considered to be the basal member of the overlying Ellis formation of Mesozoic age.

The writer obtained a thickness of about 400 feet for the Quadrant north of Logan and 674 feet near Lombard. The exposure of the Quadrant formation in the canyon near Lombard is excellent, and a section was measured straight up the side of the canyon from the top of the massive cliff of the gray Madison limestone to the

[1] A. C. Peale, *op. cit.*, p. 39.

top of the massive quartzite layer which forms the rim of the canyon. The strata here strike N. 40° E. and dip 30° west (Fig. 11).

Massive pink and yellow quartzite (base of Ellis formation?)	16 feet
Quartzite and arenaceous limestone in alternating layers	60
Massive white quartzite, limonite stains	9
Limestone breccia	2
Brown arenaceous limestone	62
Grayish-brown arenaceous limestone and talus	62
Pink arenaceous limestone in cliff	36
Yellowish-red arenaceous limestone	47
Gray limestone in cliffs, shaly at base	10
Reddish shale	30
Greenish shale	57
Buff shaly limestone and talus	100
Gray bituminous limestone in cliff, with black shale layers	45
Compact gray and yellowish-brown limestone	24
Black coaly shale with calcareous bands and gypsum veins	20
Brown crystalline limestone	4
Coaly black shale, very fossiliferous	50
Yellow arenaceous limestone in cliff, some quartzite bands	46
Red shaly limestone	10
Total	674 feet

The fossils collected from the Quadrant formation indicate that it is probably of Lower Pennsylvanian (Pottsville) age. The absence of any strata referable to the Tennesseic suggests the presence of a disconformity between the Madison and Quadrant formations, although no other evidence of such a hiatus was observed by the writer.

MESOZOIC

Mesozoic formations are rather poorly exposed in this region and were not studied in detail by the writer. They consist of shaly limestones and sandstones which are generally much less resistant than the Paleozoic limestones and therefore usually occupy lowland areas. These Mesozoic strata border the Missouri Valley on both sides, and the more resistant layers form low ridges which are parallel with the trend of the higher Paleozoic hills.

In this region the Ellis formation, consisting of sandy shales and limestones with numerous layers filled with pelecypod shells, lies on the Quadrant formation with no observed discordance of dip. In the region to the south there is a well-marked reddish sandstone formation of probable Triassic age intervening between the fossiliferous Ellis and the Quadrant. Since the Ellis fossils are considered to be Jurassic in age, it seems clear that there is a disconformity in this part of the sections of this region.

Above the Ellis formation is a series of sandstones and conglomerates which have been called the Dakota sandstone by Dr. Peale, but they have recently been shown to be more probably the equivalent of the Kootenai formation of the region to the north.[1] These sandstones are therefore of probable Lower Cretaceous age. Strata of Montana and Colorado age were identified by Dr. Peale in the hills north of Logan, but there is now some doubt as to whether they can be referred to a horizon as high as that.

TERTIARY

All of the Mesozoic and Paleozoic strata were involved in the extensive orogenic movements which began at the close of the Cretaceous in this region.

The type of folding and the associated overthrust faulting has already been described in this paper. Extensive erosion reduced the region to comparatively low relief in Tertiary times. The great lowland areas were filled in by sedimentary deposits of sandstone, limestone, and volcanic ash to a great depth. The major features of the present drainage were established on this late Tertiary surface and gradually, through uplift and erosion, they were brought into discordance with the underlying structure, as is well shown by the double horseshoe canyon of the Missouri River west of Lombard.

This whole series of Tertiary valley sediments has been grouped under the heading of the Bozeman formation for convenience in mapping. Dr. Peale's name "Bozeman Lake Beds" seems no

[1] W. R. Calvert, *Bull. U.S. Geol. Survey. No. 471–E*, 1912, p. 53.

longer applicable, since they have been shown to be due to subaerial and fluviatile deposition rather than to lakes.[1]

The Bozeman formation here is chiefly of Miocene age, but in some parts of the region strata of Oligocene (White River) age have been identified.

PLEISTOCENE

The hills in this region were evidently too low for local glaciation and no signs of regional glaciation have been observed as far south as this in Montana. Gravel terraces along the rivers indicate greatly increased stream action in Pleistocene times.

IGNEOUS ROCKS

The igneous rocks in the region north of Three Forks are relatively unimportant, and are in the form of rather small intrusions of three different rock types.

GRANITE

About two miles west of Lombard, in the double horseshoe bend, the Missouri River flows for a short distance through a gorge cut in an intrusive mass of granite. Only the eastern boundary of this granite could be accurately mapped, but the approximate western limits are noted on the map.

The granite is of a light-gray color, with a medium fine texture and a somewhat porphyritic structure. The minerals recognized in a megascopic examination are white and grayish feldspar somewhat kaolinized, quartz in small amounts, and hornblendes mostly altered to chlorite. Under the microscope the feldspars are seen to be deeply kaolinized, but are chiefly orthoclase with some albite. There is a considerable amount of hornblende which is altered in part to chlorite and epidote. Some biotite and magnetite are also present.

In places this rock is almost entirely without quartz and therefore grades into a syenite. It seems to correspond closely with the description of the syenite of Yogo Peak[2] and vicinity in the Little Belt Mountains, which is noted as grading into a granite-syenite-

[1] H. F. Osborne, *Bull. U.S. Geol. Survey, No. 361*, 1909, p. 28.

[2] Atlas Folio, *U.S. Geol. Survey No. 56*, 1899.

porphyry. The granite has a well-developed set of joints which strike northeast and dip 80° east, and are about parallel with the contact with the Belt Series.

The age of the granite cannot be definitely determined at this place, but it is probably about the same age as the granitic and syenitic intrusions of the Little Belt Mountains, which are post-Cretaceous and probably early Tertiary in age.

DIORITE

Small irregular intrusive masses of diorite and diorite porphyry occur in the vicinity of Dunbar's mine, north of Three Forks. These intrusions cut the white Tertiary limestones which at this locality are considered to be of Lower Oligocene age. The diorite was observed to have nearly vertical contacts with the limestone and to occupy a much smaller area than is indicated on the geologic map of the quadrangle. The diorite porphyry seems to be a local variation in the normal diorite and its distribution can be shown only on a detailed map of the district.

Specimens of fresh diorite were obtained from the dump at Dunbar's mine. The rock from the main shaft is of medium fine texture and evenly crystalline. It consists of an even mixture of black hornblende and gray feldspar. Under the microscope the rock is seen to consist of greenish-brown to dark-green pleochroic hornblende and labradorite feldspar. Apatite, olivine, and magnetite occur in small amounts as accessory minerals. Specimens of diorite from a shaft about a half-mile to the south show a small amount of pale-pink orthoclase feldspar scattered through the rock.

Some of the diorite from a small intrusion which cuts the Cambrian formations a few miles north of the mine is distinctly porphyritic and consists of hornblende phenocrysts in rather slender crystals about a half-inch long in a gray ground-mass of plagioclase feldspar and hornblende. Magnetite and apatite occur in small amounts scattered through the ground-mass and are visible under the microscope. The rock is deeply weathered at the surface and the hornblende is mostly altered to chlorite, and the feldspar is kaolinized.

There are zones of altered rock along the contacts of the diorite and the Tertiary limestone which are well exposed about Dunbar's mine. In this contact zone are many secondary minerals which include garnets, and several copper-bearing minerals, chiefly chrysocolla, with some malachite and azurite. It is the presence of these minerals which has caused the development of Dunbar's mine. This mine was not in operation during the summers of 1912 and 1913 when the writer visited the region.

DIABASE

A rather large intrusion of diabase was observed by the writer in the extreme northern part of the region, about a mile west of Lombard. This somewhat irregular dikelike intrusion follows the plane of the thrust fault across the double horseshoe bend of the Missouri River and varies in width from 100 to 500 feet. The intrusion has produced a noticeable contact effect on the country rocks, particularly on the Cretaceous rocks on the east side, which are indurated near the contact.

The diabase is deeply weathered near the surface and has a rusty brown color. It forms a very conspicuous massive wall on the north side of the Missouri canyon, northwest of Lombard. The rock shows the ophitic structure well and is composed of augite and labradorite with some olivine, magnetite, and apatite. The age of this intrusion cannot be very definitely placed but it is clearly post-overthrusting, and therefore of Tertiary age.

SUMMARY

The contributions of this article may be summarized as follows:

1. A new geologic map of a portion of the Fort Logan region, and a revised geologic map of a part of the Three Forks region.

2. The recognition of an extensive overthrust in the northwestern part of the region, "the Lombard overthrust."

3. New facts relative to the stratigraphy of the region mapped, including the identification of a portion of the Belt Series, and the recognition of a disconformity between the Yogo limestone and the Jefferson limestone.

4. Detailed sections of some of the Paleozoic formations.

5. The igneous rocks and their manner of occurrence.

THE SKELETON OF TRIMERORHACHIS

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A year ago, in a paper on the structure and habits of *Trimerorhachis*, I said, that "it will only be by the fortunate discovery of a connected skeleton that the tail, ribs, and feet will be made known."[1] Such a specimen has been discovered and skilfully worked out by Mr. Paul Miller, a photograph of which, as prepared, is shown in Fig. 1. The specimen came from the paleontologically famous Craddock Ranch, near the town of Seymour, Texas, from the same horizon as that of the skeleton of *Seymouria*, described by me a few years ago, and within a stone's throw of its locality. Its horizon seems to be nearly the same as that of the Craddock bone-bed, from which so many remarkable specimens have come. When found, the specimen was inclosed in a large, irregular nodule of bright red claystone; nothing was visible of it except the extreme tip of the nose and the base of the tail, as shown by a fracture. The under side of the nodule was smoothly convex both longitudinally and transversely; its upper side was irregular and gnarly. With this specimen, and in immediate relation with it as it lay upon the surface, were found a number of pieces, which, when fitted together, formed a block about one foot in length, which seemed to be a continuation of the tail end of the larger block. When fully prepared, however, the smaller block proved to belong to a second specimen of *Trimerorhachis*, including about twenty chiefly precaudal vertebrae, with their ribs and an imperfect femur.

The larger specimen, that figured herewith, is a nearly complete skeleton as far back as the sixth or seventh caudal vertebra. The

[1] Cope, *Proc. Amer. Phil. Soc.*, XVII (1878), 524; XIX (1880), 54; *Amer. Naturalist*, XVIII (1884), 32; Case, *Revision of Amphibia and Pisces of North America* (1911), 39, 106; Huene, *Bull. Amer. Mus. Nat. Hist.*, XXXII (1913), 372; Broom, *Anatom. Anzeiger*, XLV (1913), 73; *Bulletin Amer. Museum*, XLV (1913); Williston, *Journal of Geology*, XXI (1913), 625; XXII (1914), 160; XXIII (1915), 246.

bones, as usual in such nodules, are white and rather soft, rendering their preparation in the hard matrix difficult. It has been worked out so far as was possible without going below the surface of the bones.

FIG. 1.—*Trimerorhachis*. Specimen No. 1271, in original matrix. About one-fourth natural size.

The cadaver had come to rest in a prone position, apparently, with the head and tail directed obliquely upward, its vertebrae connected throughout in a sinuous curve, and the ribs nearly all in immediate connection with their articulating diapophyses. The right humerus had been dislocated, and lay near the posterior end of the right mandible, with its radius a little distance from its distal end. The right femur lay nearly in apposition with the acetabular part of the ilium; its distal part had been eroded away. Doubtless both the front and the hind legs of the left side are buried somewhere in the matrix.

The remarkable and wholly unexpected fact disclosed by these specimens is the presence of a thin bony skin or armor closely sheathing the whole body, with the exception of the skull and clavicular girdle. As the cadaver came to rest it was immersed in the soft mud to near its middle. The skin lining the cavity thus made retains its original position. On the decay of the body, the bones fell to the lower part, closely covered everywhere by the skin of the upper part of the body. On the right side the skin had bulged outward near the middle. When first uncovered the bones were concealed everywhere by the skin. It has been removed on one side or the other to expose the bones, and between them, in a few places, to show the skin of the under side of the body, which in some places lies in juxtaposition with that of the upper side, in others separated by a thin layer of the matrix.

A dermal covering of peculiar type in *Trimerorhachis* has been several times observed by Cope, Case, and myself, but it was assumed that it covered the ventral region only, and its nature was ill understood. The present specimens show very conspicuously that it covered the whole body, with the exceptions mentioned; in the preparation of the skull not a trace of it was seen, but it is closely connected with its hind margins. In no place in these specimens does it appear to have been more than a millimeter in thickness. It is composed of slender and delicate bony fibrillae, in short pieces, and apparently in several layers. In another specimen (Fig. 3, *B*, *C*,) transverse sections show that the bony rods were in numerous layers. As these fibrillae lie in this specimen they extend through a thickness of 6 or 8 mm., and are separated from each other by intervals greater than their own thickness. It seems hardly possible that postmortem causes could have separated them so uniformly, and one must conclude that they were imbedded in a considerable thickness of integument, at least a fourth of an inch. How long any of the rods were I cannot say; the longest connected piece that I trace is scarcely a fourth of an inch. It is still possible that the sections represent the ventral skin, since nothing of their character is visible in the connected skeleton.

Notwithstanding this thickness, the skin must have been flexible to have followed every inequality of the bones below it. It was doubtless covered by a smooth epidermis.

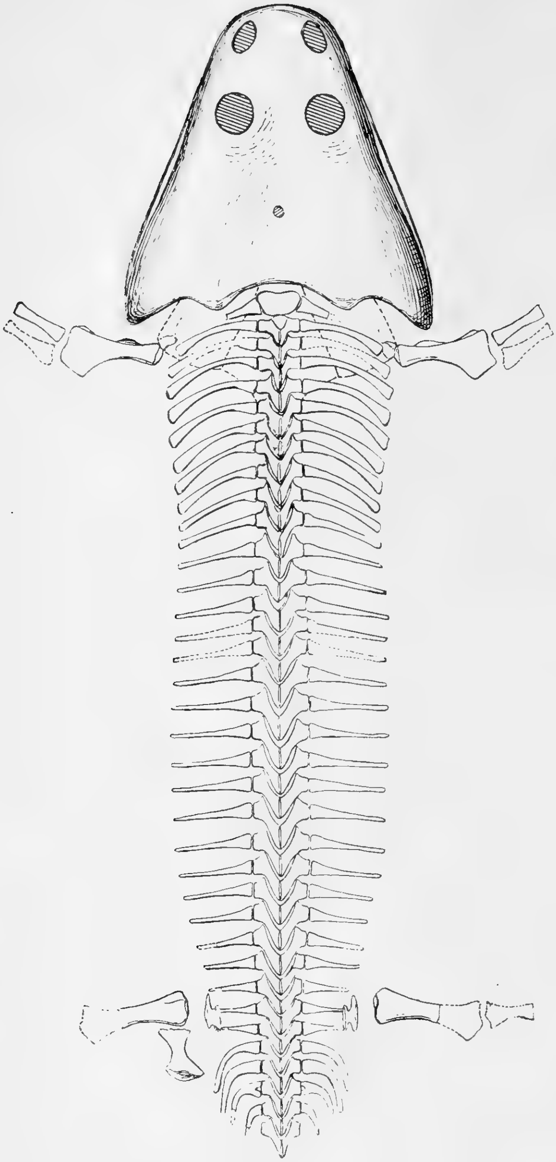

FIG. 2.—*Trimerorhachis*. Skeleton, from above, as restored from specimen shown in Fig. 1. One-fourth natural size.

Thirty-one precaudal vertebrae are visible, all in close articulation, the first one apparently with the condyle. That the vertebral column was very flexible is evident from its sinuosity as it lies in the matrix, without break. The general structure of the vertebrae is well known from isolated specimens. The pleurocentra are very small, and the intercentra are more or less U-shaped, indicating a large amount of cartilage. The spines are of nearly uniform height throughout the column, curving backward and upward, and slightly dilated at their extremities. Their height above the plane of the zygapophyses is nowhere more than 14 mm.; their width at the ends from 8 to 10 mm.

The ribs are preserved very completely in position; all have been exposed on one side or the other except two, near the middle. The first eight are the longest, measuring about 52 mm. They also have a considerable curvature and are more or less expanded at their extremities. With the tenth or eleventh they have decreased in length to 45 mm., are less curved, and not dilated at their distal ends. Thence to the tenth precaudal they are of uniform length, more slender, and pointed. When seen from above these are all slender and nearly straight, with a moderately expanded proximal end; when turned upon their sides they are broader, somewhat curved, and with a more dilated head. Apparently some of them at least have a capitular prolongation in articulation with the intercentra. The first two precaudal ribs are slender, pointed, and entirely free, and about one inch in length.

The right humerus lies near the angle of the right mandible, as will be seen in the photograph, with its head directed forward, and with the radius somewhat removed from its distal end. There are no remains of the skin either above or below these bones. Some half-dozen skulls of *Trimerorhachis* have now been obtained with the peculiar clavicular girdle in position or nearly so, lying more or less between the mandibles posteriorly. In the drawing (Fig. 2) I have outlined in interrupted lines a clavicular girdle of another skull of the same size as the present one, in position, placing it farthest back of any of the connected specimens. The angles of the clavicles with their ascending process must indicate the position of the scapula and articulation of the humerus. The scapula is hidden and not certainly determinable in this specimen, though the edge of a protruding bone at the inner side of the distal end of the humerus, as it lies in the matrix, is probably that of the scapula. The scapula, ilium, and limbs of the left side are doubtless preserved in this specimen covered by the skin and matrix, but it has not been thought wise to sacrifice so much of the specimen as might be necessary in the search for them. In all the material from the bone-beds so far examined not a trace has been found of hand or foot bones, so that nothing can be said of their structure.

The right ilium lies in place in the matrix, in a vertical position opposite the ends of the first two presacral ribs. The bone is relatively very small, as will be seen from the figure. Among the numerous ilia in the collections (I have seen about two score) there is no indication of roughening for attachment to sacral ribs. So far as was prudent the matrix has been removed about the ilium; there are no indications of ossified pubis or ischium. The proximal end of the right femur lies nearly in place opposite the

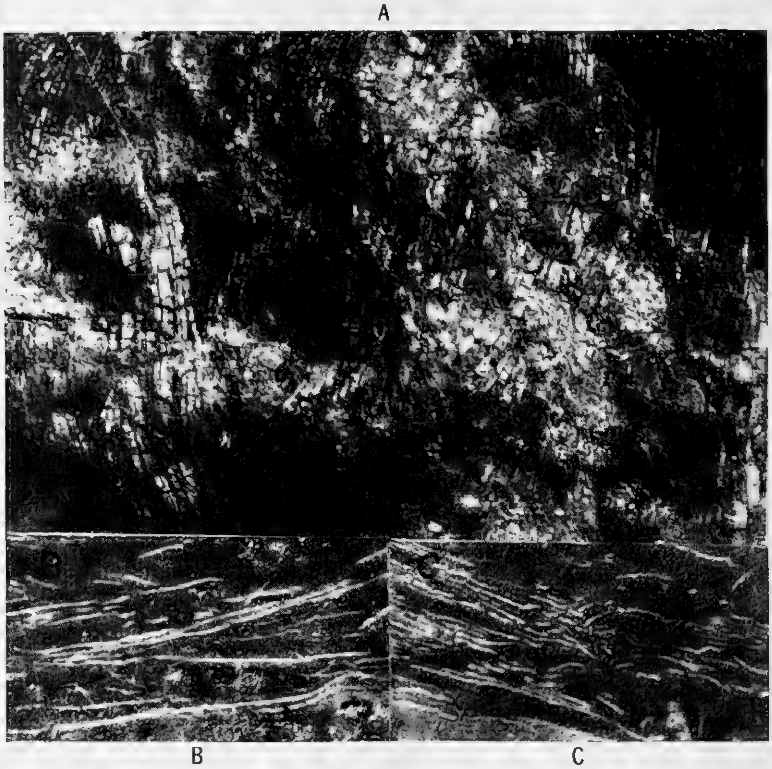

FIG. 3—*Trimerorhachis* Integument. *A*, surface view, No. 1271. *B, C*, cross-sections. No. 1208. All enlarged four times.

acetabular surface of the ilium, directed outward; its distal end has been lost from erosion of the matrix.

The looseness and small size of the ilium and the probable chondrification of the other pelvic bones are conclusive evidence, if more were needed, that *Trimerorhachis* was an exclusively aquatic animal, incapable of progression upon land. Are the undifferentiated "sacral" ribs and their lack of connection with the ilia a primitive or an acquired character? In such animals as the mosasaurs and ichthyosaurs, when the connection of the pelvis with the sacrum was lost, the ribs disappeared; they did not revert to their primitive forms. On the other hand, *Necturus* has its sacral ribs differing from the preceding ones only in their slightly larger size, and *Necturus* certainly has not had an exclusively aquatic ancestral line from the fishes. *Necturus* also has its lower pelvic bones, as well as the mesopodials, cartilaginous, and their ancestors at some time must have had them ossified.

Not only was *Trimerorhachis* a purely aquatic animal, but, in much probability, it was also, like *Necturus*, perennibranchiate. Lying just within the angle of the left mandible there is the end of a flat bone, 11 mm. in width, with a more slender anterior end directed forward and inward, that can only be an unusually large hyoid or epibranchial bone. Back of it there is the end of what appears to be a smaller one. On either side of the first vertebrae, directed forward and outward, there are the ends of three small, rib-like bones; I do not know what they are. The length of the skull in this specimen (No. 1,271) is 165 mm.; its width posteriorly the same. The length to the beginning of the tail, allowing for the sinuosities, is 550 mm. The length of the entire animal—and the specimen is one of the largest—must have been less than one meter.

REVIEWS

Geologia Elementar. Preparada com referencia especial aos Estudiantes Brazileiros e á Geologia do Brazil. Por JOHN C. BRANNER. Segunda Ediçaõ, pp. 396, figs. 174. Francisco Alves e Cia, Rio de Janeiro, 1915.

Previous to the appearance of the first edition of *Geologia Elementar* in 1906, about the only textbooks in geology available to Brazilian students were those written in foreign languages and the Portuguese translation of an abbreviated text of De Lapparent, published in Rio de Janeiro in 1898, and a much earlier translation from the French which appeared in 1846. Such works, however, are founded to a large extent upon the geology of Europe and North America and thus fall short of being the most appropriate subject-matter for South American students whose greatest interest naturally centers in the phenomena of their own continent. References to familiar scenes and places are not only more impressive and instructive than citations from remote regions, but they stimulate direct observations on local formations and lead on to practical studies of home phenomena.

Recognizing the urgent need of a Brazilian textbook of geology for Brazilian students, Dr. Branner prepared this *Geologia Elementar* by drawing on the geology of Brazil as largely as possible for illustrative and descriptive matter. He was singularly qualified to do this by virtue of his very extensive field studies in that country. Few countries offer a richer field for selecting material illustrative of geologic processes than Brazil, even though great portions of it, in spite of the activity of the Brazilian survey, yet remain unexplored geologically. Its illustrative resources are attested by the success of this endeavor.

The book is divided into three sections: Part I, Dynamic Geology; Part II, Structural Geology; Part III, Historical Geology.

Part III, both on the physical side and on the biological, is almost entirely a history of the geology of Brazil. The faunas represented and discussed are, with the exception of the Jurassic, almost exclusively Brazilian. The work thus gives, in convenient form, a summary of what is known of the geological history of Brazil.

The first edition, written originally in English and translated into Portuguese by Dr. Antonio de Barros Barreto, appeared in 1906. The many additions which appear in this second edition were written directly in Portuguese by Dr. Branner, who, to his other accomplishments, adds a sufficient mastery of the Portuguese language to have become also the author of a Portuguese-English grammar which, like the *Geologia Elementar*, is recognized as a standard.

R. T. C.

Geologische Beobachtungen in Spitzbergen. Ergebnisse der W. Filschnerschen Vorexpedition nach Spitzbergen 1910. By PROFESSOR H. PHILIPP. Ergänzungsheft Nr. 179 zu *Petermanns Mitteilungen.* Gotha: Justus Perthes, 1914. Pp. 46, figs. 4.

The rocks exposed are of Jurassic and Triassic age. The former contain coal and fossiliferous beds carrying cyathophylloid corals. The interior of the island is an arctic desert. As in deserts of more temperate zones, the changes of temperature due to insolation are so great that the accumulation of scree is excessive. So much rubble falls that in some cases the mountains are completely girdled with débris even to their tops; so much so that the speed of further destruction of the mountain is greatly decreased. Built in this manner there are everywhere great débris terraces.

The west coast is bordered by a mountain chain which precipitates the moisture from the sea breezes; this makes the interior a true desert, a *hamada.* Gravel floors and dreikanter are characteristically developed. Deflation is marked, but no sand dunes are formed because the rock dust is carried onto bordering glaciers and deported. Vegetation is practically wanting; only a few valley bottoms, in the rôle of oases, become green during the short summer. The author calls this region an "arctic" desert, in distinction from the usual polar desert.

Generally the island is ice covered. The covering is controlled by the physiography; the conformity of the glacial capping to the underlying land surface is the characteristic of the typical Spitzbergen ice field. In different regions the climatic control gives rise to valley, plateau, or cap ice and slope glaciers, or to combinations of these. Slope ice forms troughs and kars. The slopes bordering the valley glacier are ice covered to the divide top. This slope ice works down the sides at right angles to the axis of the valley and to the flow of the valley glacier. It works headward by bergschrund action, while the valley glacier deepens its bed by corrasion, until there is a decided reverse curve in the profile of the slope. The upper part is concave upward, the lower part is a convex ridge near the rim of the channel cut by the valley glacier. With decrease in abundance of snow, the slope glaciers may dwindle to bowls of snow (*wanner* and *mulden*), and by selective erosion they may become ridge-cutting cirques.

Glacial movement is essentially along shearing planes; these planes are parallel to the great friction of the glacier bed and are for that reason approximately trough-shaped. The glacier's whole movement is accomplished by means of a multitude of such planes. The planes show at the base and edges of the glaciers; on the average they are from one to two meters apart. Thus it results that, in proportion to the total amount of movement in a glacier, the shearing along each plane is very small. The blue bands are due to the regelation of the shear planes after they have been melted by the over-pressure or by friction.

Ice crystals are found in two types, those precipitated from the atmosphere and those formed by freezing waters. In one place a 20-cm. layer of névé consisted of vertical standing prisms; they were $\frac{1}{2}$–1 cm. in diameter and 10 cm. long arranged in two layers of 10-cm. crystals. In the higher parts of the snow fields, beautiful rosettes of crystals bedeck the snow surfaces. The diameter of the rosettes varies from 5 to 20 cm.

Most of the evidence of Pleistocene glaciation has been obliterated by the action of insolation and frost. From floral remains there seems to have been a climate warmer by 2.5–3° C. preceding a recent uplift of about 400 feet.

T. T. Q.

Kanawha County. By CHARLES E. KREBS. West Virginia Geological Survey, County Reports, 1914. Pp. 679, pls. 32, figs. 14.

County reports have been completed for about one-half the counties of this state. Kanawha County is the first to be treated in a separate volume and its importance is such as to justify a full report. It is among the leading counties of the state in production of coal, and is rich in petroleum and building-material.

This report follows the general plan adopted in previous reports. Part I treats of the historical and industrial development and physiography. Part II takes up the stratigraphy in detail. About forty general sections of Carboniferous outcrops are given with several times that number of partial sections.

Under mineral resources the oil and gas districts are described in detail with a number of well-records from each district. Statistics on coal production place Kanawha County third in rank of the counties of the state for 1912, with a total of 5,606,522 tons. This chapter treats also of the character and distribution of the coal beds with estimates on the total supply. Clays and road and building-materials are reported in less detail. A chapter on the soils of the county is copied from the report of the U.S. Bureau of Soils on Kanawha County.

Under separate cover three maps accompany this report, a topographic map, a general and economic geology map, and a soil map. A valuable feature of the economic geology sheet is found in the structure contours. The Pittsburg coal horizon is the key formation in the western part, and the Kanawha Black Flint in the eastern. This map shows several areas in which the geologic structure appears favorable for oil and gas, that have not been prospected.

W. B. W.

Geology and Geography of a Portion of Lincoln County, Wyoming. By Alfred Reginald Schultz. Bull. U.S. Geol. Survey, No. 543, 1914. Pp. 136.

The area described lies in the central part of Lincoln County in the extreme western part of Wyoming, east of the Salt River Range and west of Green River. Under the head of geography are discussed geographic positions, topography, altitudes, railroad and stage routes, geographic names, climate, arable land, and vegetation. The stratigraphic succession, beginning with the oldest rocks, is as follows: Cambrian, undivided (Ordovician, Silurian (?), and Devonian), undifferentiated Pennsylvanian and Mississippian, Pennsylvanian (Weber quartzite), Permian(?) (Park City formation), Lower Triassic (Woodside formation, Thaynes limestone, Ankareh shale), Jurassic or Triassic (Nugget sandstone), Jurassic (Twin Creek limestone, Beckwith formation), Upper Cretaceous (Bear River formation, Colorado group [Aspen formation, Frontier formation, Hilliard formation], Montana group [Adaville formation]), Cretaceous or Tertiary (Evanston formation), Eocene (Wasatch group [Almy formation, Knight formation, Green River formation]), Quaternary (Pleistocene and Recent).

Deposition was interrupted possibly at several times in the early Paleozoic. An unconformity based on fossil evidence, which shows the lower Cretaceous to be absent, occurs between the Beckwith formation (Jurassic) and the Bear River formation (Upper Cretaceous). Profound folding, faulting, and erosion occurred in post-Adaville (Upper Cretaceous) time. There was slight folding and faulting after the deposition of the Almy formation (Eocene). After the accumulation of the Green River beds (Eocene) there was a long erosion interval during which the present topographic features were developed. The Eocene, Knight and Green River formations are lake deposits. The Gros Ventre Mountains and probably the Wyoming and Salt River ranges had glaciers during a part of Quaternary time. The main disturbance that gave rise to the Gros Ventre Mountains, Hoback Range, Wyoming Range, Meridian Ridge, Salt River Range, and Absaroka Ridge occurred in post-Adaville (Upper Cretaceous) time.

Coal occurs in the Upper Cretaceous Bear River, Frontier, and Adaville formations and in the Cretaceous or Tertiary Evanston formation. Oil is found in the Upper Cretaceous Bear River and Aspen formations. Gold is present in the present stream and bench deposits. The latter only are worked. Phosphate occurs in the Park City formation (Permian [?]). The sandstone of the Frontier formation (Upper Cretaceous) and also the sandstones and limestones of the older formations would make excellent building-material. Salt springs and salt deposits, as well as rock salt, occur. Salt has been produced for many years.

V. O. T.

Geology of the Standing Rock and Cheyenne River Indian Reservations, North and South Dakota. By W. R. Calvert, A. L. Beekly, V. H. Barnett, and M. A. Pishel. Bull. U.S. Geol. Survey, No. 575, 1914. Pp. 49.

The Cheyenne River and Standing Rock Indian reservations, as here treated, include the area between the Missouri River and the one hundred and second meridian, and between Cannonball River on the north and Cheyenne River on the south. The object of the survey was the ascertainment of the coal value of the lands. The Pierre shale (Cretaceous-Montana group), which is the oldest formation exposed, covers about one-half of the area. The thickness exposed amounts to 650 feet. The Fox Hills sandstone conformably overlies the Pierre. It is the uppermost marine Cretaceous and the youngest formation of the Montana group; it is the most fossiliferous formation of the region. The Fox Hills ranges in thickness from 25 to 400 feet. The Cretaceous or Tertiary Lance formation, which consists of 700 feet of clay, sandstone, and lignitic shale, unconformably overlies the Fox Hills. Since "the broad geologic significance" of the unconformity at the base of the Lance is not known and since the other evidence is not conclusive, the authors designate the Lance as of Cretaceous or Tertiary age. The upper 200–300 feet of the Lance is of marine origin and contains a fauna very similar to that of the Fox Hills, if not identical with it. The remainder are fresh-water beds. Tertiary Fort Union sandstone and shale succeed the Lance conformably. The terraces along the Grand River are due to deposition in a lake formed by ice which extended down the Missouri Valley damming Grand River. Glacial bowlders (from a few inches to several feet in diameter), mostly of granite, are scattered over the whole northeastern half of the area. Most of the terrace gravel and scattered bowlders are early Pleistocene, while the gravels on the Missouri River are later Pleistocene. The strata of the region dip gently to the northwest. Lignite is contained as lenses a few inches thick in beds of carbonaceous shale in the Lance and Fort Union formations. The lignite beds are described as they occur in the various townships. The lignite will probably never be mined on a large scale but will continue to be worked for local consumption.

V. O. T.

The Geology of Long Island, New York. By MYRON L. FULLER. Prof. Paper, U.S. Geol. Survey, No. 82, 1914. Pp. 231, pls. 27, figs. 205, maps 2.

Long Island extends from the Narrows at the entrance of New York Harbor to a point nearly due south of the eastern boundary of Connecticut, a distance of 118 miles; its maximum width is 20 miles. The report deals chiefly with the Pleistocene geology. Long Island "may be considered as affording the type section of the earlier glacial deposits of the coastal zone"; the Iowan stage alone is absent. The literature on Long Island from 1750 to the present is summarized. Some forty pages are devoted to a thorough discussion of the physiography. It appears that Long Island Sound is a partly filled valley, cut in Cretaceous strata, produced by an eastward-draining river system. Its excavation began in post-Miocene time, was interrupted, and then completed in post-Mannetto (Aftonian?) time. The Hudson channels were formed in the Pleistocene.

The pre-Cretaceous rocks include the Fordham gneiss (pre-Cambrian), the Stockbridge dolomite (Cambrian and Ordovician), Ordovician and later granite dikes and pegmatite masses intruded into the gneiss. The beds are faulted and closely folded.

From the base up, the general sequence of the Cretaceous beds is as follows: basal clays (150 feet), Lloyd sand (85 feet), red clays (200 feet), white sand (100 feet), yellow clay (75 feet), dark clay (75 feet), undifferentiated (600 feet), buff clay (100 feet), yellow sand (150 feet), marl (10 feet). The basal clays and Lloyd sand are encountered only in wells. The surface Cretaceous beds are considerably folded (some overturned folds occur) and faulted, while at slight depths they have a gentle, even dip to the southeast. The lower beds are basal Upper Cretaceous.

There is a possibility that marls (here placed in the Cretaceous) may be Eocene, that the loose yellow quartz sand (here considered Cretaceous) overlying the marls may be Miocene; and that the white or yellow sands (here included in the Cretaceous) that succeed the Cretaceous clays may be of Lafayette age.

The Pleistocene deposits (with their probable time equivalents in parentheses) are: the glacial Mannetto gravel (pre-Kansan), the glacial Jameco gravel (Kansan), the interglacial Gardiners clay (Yarmouth), the transitional Jacob Sand and the glacial Manhasset formation (both included in the Illinoian), the interglacial Vineyard formation (Sangamon?, Iowan?, and Peorian?), the glacial Ronkonkoma and Harbor Hill moraines with associated till and outwash (all embraced in the early Wisconsin). Great periods of erosion occurred in post-Mannetto (Aftonian?) and Vineyard (Sangamon?, Iowan?, and Peorian?) times. Two ice erosion unconformities are present in the Manhasset formation, which separate the Montauk till from the Herod gravel below and the Hempstead gravel above. The various Pleistocene deposits are discussed in detail.

Stream, marine, wind, and marsh deposits constitute the Recent series.

A summary, in tabular form, is given of the principal points of geologic interest on Long Island. The geologic history is fully sketched. The remainder of the report is concerned with an estimate of the relative lengths of the Pleistocene stages and substages on Long Island, the Pleistocene and Recent orogenic movements of Long Island, the probable extension of the Pleistocene deposits (here discussed) along the New England coast (including a correlation table), the correlation of the Long Island Pleistocene deposits with the New Jersey non-glacial formations.

V. O. T.

Paleocene Deposits of the San Juan Basin, New Mexico. By W. J. Sinclair and Walter Granger. Bull. Am. Museum Nat. History, XXXIII, Art. XXII, June 3, 1914, pp. 297–316, Pls. XX–XXVII, figs. 2.

The Paleocene Puerco and Torrejon formations are exposed along the south and southwest margin of the San Juan Basin in northwestern New Mexico. There is an unconformity, shown both by erosion and by an abrupt faunal change, at the base of the Puerco (unconsolidated clays and channel sandstones) which appears "to be the dividing line between Cretaceous and Tertiary in this region." The Torrejon succeeds the Puerco without lithologic or stratigraphic break. The boundary between the two depends on fossil evidence, and is not exactly determined. Basal Wasatch sandstone and in some places seemingly younger sandstone unconformably overlies the Torrejon. A fluviatile origin is indicated for both the Puerco and Torrejon.

Two Puerco fossil levels, to the upper of which Polymastodon is confined, were accurately located. Fossil plants were found in the Puerco. Torrejon fossils were discovered much below previously located horizons. The sections measured by the authors are compared with Gardner's Rio Puerco and Arroyo Torrejon sections. The pre-Puerco beds are, beginning with the oldest exposed, clays, conglomerate, clays, conglomerate sandstone with silicified logs and pebbles of volcanic rocks. Dinosaur remains occur in both clay horizons. "More or less of this series of beds may be correlatable with the Animas formation."

V. O. T.

Cement Materials and Industry in the State of Washington. By Solon Shedd. Bull. No. 4, Washington Geol. Survey. Pp. 268, figs. 10, pls. 21. Olympia, 1913.

Increasing importations of cement from California and Europe have led to investigation of the state's possibilities in cement production. The results are given in this, the fourth of a series of bulletins on natural resources. The work was directed by Solon Shedd, assistant state geologist and professor of geology, Washington State College.

More than one-third of the report is taken up with chapters on the history of the cement industry, various kinds of cements, and origin and composition of raw materials. Manufacturing processes are described briefly and there is an excellent chapter on the factors to be considered in locating a plant. The remainder of the report takes up by counties the results of field work and contains maps of limestone and clay areas with analyses of samples from them.

In the eastern part of the states metamorphic limestones of doubtful age are found only as erosion remnants surrounded by basalts and granites. Deposits of economic importance are limited to four counties. Very little stone approaching natural cement rock is found in the state. The analyses show the limestones to be low in magnesia and silica. The latter probably averages less than 5 per cent. Analyses of adjacent clay and shale deposits are given in each case, and some estimate can be made of the possibility of proper mixtures for Portland ratios.

In western Washington sedimentary rocks predominate, but limestone is limited to a few localities in the north. Its quality is very similar to that farther east.

Taking the state as a whole, localities in which limestone and clay or shale outcrop in close proximity and favorably situated relative to transportation are few. At the time the report was published, five plants were in operation and two under construction.

W. B. W.

The Road and Concrete Materials of Iowa. By S. W. BEYER and H. F. WRIGHT. Iowa Geological Survey, Annual Report, 1913. Pp. 33–685, figs. 65, pls. 63, tables 8, maps 2.

Great development in road-building and concrete construction has led to widespread search for materials during the last decade, and justifies detailed examinations by the states of such resources. This report takes up by counties the character, amount, and availability of these materials over the entire state. Some reference is made to all the more important localities, but the records are more complete for the counties poorer in such materials than for those richly supplied.

Nearly three-fourths of the counties in the state have deposits of sand and gravel of economic importance. Gravels of two interglacial epochs are of considerable value. The Aftonian gravel is worked only in southwestern Iowa, because elsewhere it is too deeply buried. The type of locality for Aftonian is in Union County. The Buchanan gravel is available in the northeastern part of the state and is second only to the post-Wisconsin gravels as a source of road and concrete materials. It is found chiefly as a valley phase of outwash and the type locality is in Buchanan County.

Throughout the state the principal supplies are found in recent deposits in beds and terraces of the larger streams. Exceptions are found, but in general those counties crossed by drainage lines leading from the drift area have important deposits. The Mississippi River floodplain supplies the eastern tier of counties with much sand and some gravel, but similar deposits of the Missouri are more often charged with silt. In the area reached by the Wisconsin ice sheet, extensive deposits of sand and gravel are available in kames and eskers in addition to recent stream deposits.

Stone suitable for road and concrete work is limited to the eastern part of the state. In the west neither the argillaceous limestones of Pennsylvanian age nor the loosely cemented Cretaceous sandstones made good road materials. In the east and northeast, limestones are available, ranging in age from Ordovician to Mississippian. In many localities stone is not available on account of the heavy overburden of drift. Counties along the Mississippi River and its larger tributaries furnish the most favorable quarry sites.

A valuable feature of this report is found in the tables. They are compiled from data furnished by experiments on various properties important in road materials. Standard tests on cementing value, toughness, and hardness show a wide range of values. Good cementing properties may be associated with poor wearing properties or vice versa. Inferior hardness may decrease the value of materials excellent in other respects. These results show the necessity of thorough testing before final selection.

W. B. W.

Geology of the Pitchblende Ores of Colorado. By EDSON S. BASTIN. Prof. Paper, U.S. Geol. Survey, No. 90-A. Shorter Contributions to General Geology, March 17, 1914. Pp. 5, pls. 2.

The sources of uranium in the United States are given and the principal foreign occurrences of pitchblende (a complex uranate of variable composition) briefly described. Quartz Hill, which is near Central City, Gilpin County, Colorado, is "not only the one important locality in the United States where pitchblende occurs in mineral veins but one of the few in the world."

The oldest rocks of the area are included in the pre-Cambrian Idaho formation, which is mainly a quartz-mica schist. Pre-Cambrian granites of at least two ages intrude this formation. Tertiary (probably) dikes and stocks of monzonite porphyry and bostonite porphyry cut all of the pre-Cambrian rocks.

The mineral veins, which are the products of combined fissure filling and replacement along a series of east to northeast striking fractures, traverse both the pre-Cambrian and Tertiary rocks; they are believed to be related to the monzonite intrusions. Pyritic and lead-zinc veins are represented.

A number of the specimens of the vein material show the contemporaneous origin of pitchblende, chalcopyrite, and probably minor amounts of pyrite and quartz. In other specimens the pitchblende is cut by veinlets of sulphides.

"It is believed that the pitchblende was deposited during the earlier or pyritic mineralization, that it was afterward fractured, and that the fractures thus formed were filled by sulphides of the later or lead-zinc mineralization."

The pitchblende ores apparently represent a local variation in the general sulphide mineralization of the area. They were formed under conditions of low temperature and pressure; this is true also of the Cornwall and Erzgebirge deposits. The European pitchblende occurs with cobalt and nickel minerals. No such association was observed in the case of the Quartz Hill pitchblende.

V. O. T.

Reconnaissance of the Grandfield District, Oklahoma. By MALCOLM J. MUNN. Bull. U.S. Geol. Survey, No. 547, 1914. Pp. 83.

The Grandfield district includes the southeastern part of Tillman County and the southwestern part of Cotton County in southern Oklahoma. The purpose of the report is to discuss the geology with special reference to possible oil and gas accumulations. The oldest beds exposed represent the lower portion of the Wichita formation (lower Permian). They consist of sandstone, shale, clay, and a clay-limestone conglomerate (the Auger conglomerate lentil) which is absent in places. The Grandfield conglomerate unconformably overlies the Wichita formation. It is composed of well-rounded pebbles, up to three inches in diameter, of quartz, quartzite, a few of granite, and fragments of chert, limestone, and silicified wood imbedded in a red clay-limestone matrix. It is exceedingly uniform in composition, appearance, hardness, and thickness (average 3–4 feet), is widely exposed, and "displays a structure that is surprisingly conformable to the present topography, being high on the divides and low near the valleys." It probably will be correlated with some portion of the Seymour formation in Wichita County, Texas which is referred to the Pleistocene. The suggestion is made that the Grandfield conglomerate may not be a stream deposit.

Quaternary gravels, alluvium, dune sand, and soil mantle the older consolidated deposits.

The general structure of the Permian strata is based on the exposures of the Augur conglomerate. The most important structure is the southeast-northwest trending Devol anticline which crosses the district. To the north and parallel to this lies the Deep Red syncline. Minor anticlines and synclines are present. About one-half of the report is devoted to "detailed stratigraphy and structure of the exposed rocks by townships."

In the adjacent portion of northern Texas are located the Petrolia, Burkburnett, and Electra oil and gas fields. The "sands" are of Pennsylvanian age. Since similar beds evidently underlie the Permian in the Grandfield district, and since the structure of both places is comparable, the existence of commercial pools in the Grandfield district is very probable. Suggestions as to the location of test wells are given. The opinion is expressed that "accumulations of oil and gas in pools is due to the action of large bodies of water moving under both hydraulic and capillary pressure."

V. O. T.

Relation of the Wissahickon Mica-Gneiss to the Shenandoah Limestone and to the Octoraro Mica-Schist, of the Doe Run-Avondale District, Coatesville Quadrangle, Pennsylvania. By ELEANORA F. BLISS and ANNA I. JONAS. A dissertation (Bryn Mawr College). Pp. 64, pls. 5.

The authors conclude "that the Wissahickon mica-gneiss [pre-Cambrian] is separated from the Shenandoah limestone [Cambro-Ordovician] and from the Octoraro mica-schist [Ordovician] by a thrust fault, which has been obscured by post-Ordovician metamorphism."

V. O. T.

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NOTE ON THE LINEAR FORCE OF GROWING CRYSTALS

GEORGE F. BECKER AND ARTHUR L. DAY
Geophysical Laboratory, Carnegie Institution of Washington

In 1905 we published a short paper,[1] qualitative in character, with the purpose of demonstrating from simple laboratory measurements the existence of a linear force, apart from the volume expansion, exerted by growing crystals. We sought to show (1) that when a crystal, fed with appropriate saturated solution, grows in an open crack between walls with which it comes into contact on both sides, pressure is exerted to separate the walls, notwithstanding unrestricted opportunity for growth in other directions; (2) that the linear force thus exerted is of the order of magnitude of the breaking strength of the crystal and therefore a geologic force of considerable magnitude and importance.

The crucial experiment offered in support of this conclusion was prepared in an ordinary crystallizing dish upon the bottom of which was cemented a block of plate glass having a plane upper surface. A well-formed crystal of alum was laid upon this plane surface, and upon it a second plane glass plate carrying a weight. A saturated solution of alum was poured into the crystallizing dish in sufficient quantity to cover the crystal, and then left to evaporate quietly under conditions reasonably free from temperature change and from

[1] "The Linear Force of Growing Crystals," *Proc. Wash. Acad. Sci.*, VII (1905), 283.

dust. The original drawing of the experimental arrangements is reproduced here for the sake of definiteness (Fig. 1). Saturated solution was added from time to time if needed, so that throughout the experiment the crystal remained submerged in its saturated solution. The thickness of the crystal was measured at intervals with an appropriate instrument.

The experiment was repeated many times with a single crystal of alum and various weights, and also with a crystal of copper sulphate, of potassium ferrocyanide, and of lead nitrate, in appropriate solutions. In no single instance during this series of observations did the crystal fail to lift (1) its own weight; (2) the weight of the superimposed glass plate; (3) the weight of the load upon the glass plate. The distance through which the load was lifted varied in different experiments from a few hundredths to 0.5 mm.[1]

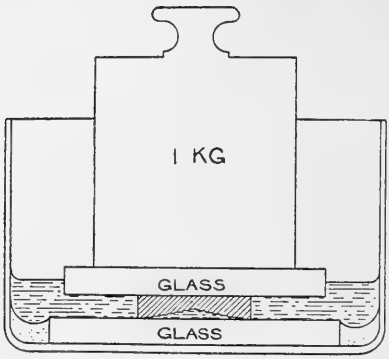

FIG. 1.—A crystal shown growing between two glass plates and lifting a heavy load. Reprinted from the paper of 1905 (*op. cit.*).

In 1913 Bruhns and Mecklenburg[2] published a series of experiments upon the same subject which purported to repeat those which we had made and to disprove them. They announced their inability to obtain the experimental results which we have described, and categorically denied, in the face of much corroborative evidence contained in their own paper, the existence of such a linear force exerted during the growth of crystals.

To this paper we did not at once reply because it seemed impossible that other investigators would long allow the crucial experi-

[1] The data upon which this preliminary account is based were obtained during the winter of 1902–3, but the records were burned in the Geological Survey fire in the following year, which may serve to explain the absence of complete data in the publication of 1905.

[2] W. Bruhns and Werner Mecklenburg (Clausthal), "Über die sogenannte Kristallisationskraft," *Jahresbericht des Niedersächsischen geologischen Vereins zu Hannover*, VI (1913), 92.

ment in a question of fact to remain unverified where a principle of such far-reaching importance to geologists was at stake. The issue could have been put to the test by anyone in a few hours without special facilities of any kind.

When, however, a distinguished physical chemist (Boeke, in his admirable book, *Grundlage der physikalisch-chemischen Petrographie*, 1915, p. 328) accepts their conclusion without test, and casts out the "linear force of growing crystals" from geological calculation entirely, a form of protest appears necessary. This outcome is the more unfortunate because it must be patent to a physical chemist that Bruhns and Mecklenburg did not in fact repeat our simple experiment at all, but substituted one which is not, by itself, conclusive upon the point at issue; and, further, because all of their recorded experimental evidence is entirely in accord with our experience and conclusions. There appears to be no contradiction of fact, but only one of appropriate interpretation; the conditions which govern the behavior of a single loaded crystal are modified when an unloaded crystal is introduced into the same solution, as was done by Bruhns and Mecklenburg.

Now upon the main question of fact as to whether a crystal of alum or other substance will or will not lift a load when immersed in its saturated solution in an open vessel, nothing is simpler than to repeat the experiment which we described. An ordinary open crystallizing dish, an alum crystal placed on the bottom of it and covered with a saturated solution of the same liquid, and an ordinary brass weight of one or two hundred grams upon the crystal, together with a simple apparatus to be found in any laboratory for measuring the thickness of the crystal before and after the experiment, provide all the equipment necessary to establish or disestablish the fact of growth in the direction of the load. Two fairly typical cases follow:

These experiments are so straightforward, and withal so conclusive in their results, that it would hardly seem possible to go astray; nevertheless, Bruhns and Mecklenburg, in the paper above referred to, have denied their validity. A series of measurements taken from the paper of Bruhns and Mecklenburg is quoted in Table II.[1]

[1] *Op. cit.*, p. 100.

This is not a simple repetition of our experiment, although it has been made to appear so. Bruhns and Mecklenburg have placed in the same vessel a loaded crystal *and an unloaded crystal,* and have observed, as might have been anticipated, that the unloaded crystal increased in thickness while the loaded crystal did not. This result was confirmed in other measurements of the same kind which need not be reprinted here.

TABLE I*

Conditions as Above Described; Room Temperature about 20°; Load 95 Gm. No Other Crystal Present

Time (Hours)	Thickness of Crystal	Increase of Thickness
0	8.3260 mm.	0 mm.
22	8.4400	0.114
98	8.4569	0.131

A Very Small Crystal, Conditions as Before, Load 0.7 Gm.

Time (Hours)	Thickness of Crystal	Increase of Thickness
0	3.7649 mm.	0 mm.
20	3.7803	0.015
50	3.8027	0.038
68	3.8029	0.038
145	3.8262	0.061

*The experimental results contained in the present paper were courteously placed at our disposal by Mr. J. C. Hostetter, of the Geophysical Laboratory, who will report in greater detail upon this problem in the near future.

Let us consider for a moment the conditions of crystal growth in a saturated solution. Suppose a single isometric crystal to be immersed in a solution saturated with respect to it; and suppose further that the water is gradually removed from the solution by evaporation, thus inducing potential supersaturation and the continued growth of the crystal in consequence. If the supersaturation is greater than can be balanced by the growth of this crystal under the prevailing conditions, other nuclei will tend to form upon which deposition may take place. Now, what will happen when two crystals of the same substance are present, one of them being less stable than the other owing to its inferior size, or because it is strained, or because it is an inherently instable form, or for any other reason? In the first place, it is plain that a solution to be in equilibrium with a less stable crystal will require to be more concentrated than that in equilibrium with the more stable one; consequently in the foregoing case the solution will become supersaturated with respect to the more stable crystal before it is supersaturated with respect to the other, and the former will begin to grow before the latter, which, indeed, will not grow at all (it may even dissolve) unless the degree of supersaturation is greater than the growth of the more stable crystal can keep balanced.

TABLE II

A LOADED (1 GM.) AND AN UNLOADED CRYSTAL IN THE SAME SOLUTION. TEMPERATURE = 10° C.

Date	Unloaded Crystal		Loaded Crystal	
	Thickness of Crystal	Increment of Thickness	Thickness of Crystal	Increment of Thickness
May 5, 1913	9.68 mm.	....	10.00 mm.	....
June 5, 1913	10.22	+0.54 mm.	10.06	+0.06 mm.
July 5, 1913	10.86	+0.64	10.04	−0.02
September 5, 1913	11.42	+0.56	10.06	+0.02

Analogous cases also arise when the crystals are of equal stability but the solution is inhomogeneous, and there results from the action of outside forces (imperfect stirring, thermal convection, gravitative adjustments) a distribution of concentration such that one crystal is in contact with solution of higher concentration and grows while the other cannot.

A familiar instance may be cited. If in an unstirred saturated solution in a closed vessel two identical crystals are placed, of which one is suspended a few millimeters above the other, the lower crystal will grow while the upper one dissolves slowly. And similarly under like conditions the bottom of a very large crystal will grow at the expense of the top, and the prismatic lateral faces gradually acquire the contour of a flight of steps; the reason in either case is that under the action of gravity the solution tends to become more concentrated in its lower layers, and hence, since it is kept saturated at the level of the upper crystal, it will be potentially supersaturated at the level of the lower. In short, the rate of growth of an isometric crystal depends altogether upon whether the concentration of the layer of solution in contact with it is or is not potentially supersaturated with respect to that particular crystal. One serious result of this is that if diffusion toward a certain face is obstructed (e.g., when that face lies against a glass plate), that face will be unable to grow like the other faces. To this we shall revert.

Now it is the importance of this principle to the question under consideration which has been overlooked by Bruhns and Mecklenburg. As soon as it is appropriately applied, their observations correlate perfectly with ours.

The effect upon the saturation concentration of differently oriented faces of the same crystal in non-isometric systems is a matter less well understood and is beyond the scope of this inquiry. We may therefore omit further consideration of it in this connection.

In plain terms and without taking account of unnecessary complications, the situation in a saturated solution, under the conditions now under consideration, may be described somewhat in this way. Given a body of saturated solution of a salt in an open vessel, the amount of the dissolved substance which can remain in solution for a given temperature is limited, and it may begin to separate out either when the temperature is changed or when continued evaporation from the free surface of the liquid has sufficiently increased the concentration. Differences in the concentration due to the slowness of diffusion will cause gravitative readjustments, bringing the portions containing the maximum amount of dissolved matter to the bottom. A single crystal of the salt exposed in the bottom of the vessel will now grow upon its exposed faces, and if the rate of evaporation is not too great, this growth may take care of all of the excess of solute resulting from the evaporation process. If the evaporation proceeds at a greater rate, other nuclei will form, and if two or more crystals are feeding upon the product of the evaporation their relative rate of growth (+ or −) may depend upon relative stability, position, size, or the amount and distribution of load.

Inasmuch as a crystal lying upon the bottom of an evaporating dish must rest upon one of its faces, this face will support a load represented by the weight of the crystal less the buoyancy correction, and this load will impose limiting conditions upon the rate of growth upon this face when compared with the neighboring faces, as was pointed out in our paper in 1905, and by Bruhns and Mecklenburg in 1913. A weight placed upon the crystal merely adds something to the total load supported by this face (and perhaps covers an additional portion of the crystal surface), *but contributes no new factor to the problem.* If this superimposed weight is very large, the distribution of the resulting strain may become important, but these are questions of degree only. Limitations of circulation or diffusion in the capillary liquid layer below the crystal are affected by the amount and distribution of the aggregate load, and not at all by its character (whether crystal substance or foreign matter). This fact would hardly appear to require demonstration, but has certainly caused some confusion, nevertheless.

It is then clear that the exposed top and side faces (or the side faces alone if the top is covered) may grow freely while the bottom remains more or less undernourished, depending upon the load which is supported there and the consequent impairment of circulation. Nevertheless, if the degree of supersaturation and the amount of material which is being furnished to the crystal through evaporation and diffusion is sufficient in quantity and properly circulated, the saturation concentration opposite that face also, that is, in the thin layer of liquid upon which the crystal rests, may be reached and the crystal may grow upon the bottom as well as upon the sides. Failure of the circulation in this supporting layer may, and in fact usually will, restrict the growth here to the periphery of the supporting face, causing it eventually to rest upon a thin outer rim[1] of new growth rather than upon its initial flat surface, but growth will nevertheless take place here as elsewhere. The

[1] As was pointed out in our paper in 1905, these supporting rims are often so thin as to debar the usual methods of area measurement. At that time an approximate measurement was obtained by inking the crystal with an insoluble ink and printing its impression upon a plane glass plate coated with white celluloid. The impressions thus secured contain lines so fine as to defy reproduction by the usual means and probably yield but a rough approximation of the surface area which supports the load.

greater the crystal, the greater the weight supported upon its contact surface (or rim), and the greater, a fortiori, the difficulty of reaching the saturation concentration in any portion of the supporting liquid layer and providing for further growth from the bottom.[1]

To make specific application of this analysis to our case, namely, a single alum crystal resting upon a thin liquid layer in its own saturated solution and supporting an outside load, the most favorable surfaces for growth will be the lateral faces, and there the

[1] That the description of these phenomena as observed by Bruhns and Mecklenburg differs in no essential particular from our own may be seen from the following extracts from their paper (*op. cit*):

P. 97: "The common view of crystal growth has hitherto been that a crystal grows exclusively through additions of new matter from without. A crystal can therefore grow only where there is surface in contact with the solution, which offers room for new material to be added, and where expansion can occur. A great deal of experience and many observations are in accord with this view."

P. 100: "Unloaded crystals show continuous growth and the increase in weight, which diminishes in the case of loaded crystals approximately in proportion to the decrease in exposed area, proceeds normally; that is, where new material can find a foothold there is growth, where it cannot there is none."

P. 102: "A further circumstance which requires to be considered in connection with the formation of the cup-shaped base [see Fig. 1] is this, that in a laboratory experiment in a glass vessel the base of the crystal is not in contact with the vessel but rests upon a layer of water or of solution which adheres both to the glass and to the crystal. The occurrence of such adhesion or adsorption layers is sufficiently familiar; they are lacking only when the crystal grows fast to its support. By reason of this liquid layer between the crystal and its support, the supersaturated solution is enabled to diffuse under the crystal, even though the rate of diffusion in the capillary layer is smaller than elsewhere. It will not advance far, however, for the molecules in excess of the quantity needed to saturate the solution, when they attempt to pass close under the crystal, will be quickly caught, that is, a rim [*Wulst*] will grow beneath the periphery of the crystal, as observation in fact shows."

P. 103: "Crystals which form on the bottom of the vessel, without exception show cup-shaped bases."

P. 103: "If a large alum crystal is laid upon a smooth surface in a saturated solution which is evaporating, its lower surface becomes cupped, but not in regular steps like rock salt or bismuth. Instead of this the central portion remains practically flat while a narrow supporting rim grows about it. Neither does long-continued growth result in a stepped formation; the narrow rim moves outward while the inclosed area continues nearly or quite flat."

P. 105: "The explanation of the phenomenon may perhaps be that the supporting rim—which must of course bear the weight of the crystal—possesses a higher solubility than the remainder of the crystal. Possibly also there is a difference in solubility in different crystallographic directions."

potential supersaturation will first be reached. If the rate of evaporation is sufficiently great, the saturation concentration in the liquid layer below the crystal will also be reached, in whole or in part, and growth from below will go on, albeit at an appropriately diminished rate compared with the sides because of the load and the deficiency of circulation. If the upper surface is covered by the load, it will share the limitation of circulation of the bottom surface. If the load upon the crystal is too great, or the rate of evaporation slow, the saturation pressure may not be reached anywhere in the supporting liquid layer, and growth here may be stopped. A still further increase in the load may even cause resolution of the bottom surface, while the side surfaces continue to grow.

In support of this analysis, the accompanying photograph (Fig. 2) of a crystal grown under a heavy load and the measurements made upon it (Table III) will be found interesting. A single crystal of potash alum was immersed in a solution saturated with both potash and chrome alum under a load of 190 gm. Other conditions were as heretofore described. The dark areas are fresh deposit, colored of course by the chrome alum and thus distinguishable from the original crystal. It is plain that there is no

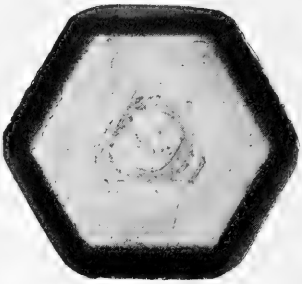

Fig. 2.—A crystal grown under load. Dark portions are new growth (under load). (View from above.)

TABLE III

Conditions as Before. Load 190 Gm.

Time (Hours)	Thickness of Crystal	Increase in Thickness
0	3.5090 mm.	0 mm.
17	3.5239	0.015
65	3.5859	0.077
113	3.5926	0.084

fresh deposit (colored matter) on the central portions of the original crystal above or below. The accessions of fresh matter are found exclusively on (and beneath) the new lateral faces. Nevertheless, this crystal lifted its load (Table III), and we are concerned at the moment less with the form than with the fact of linear growth in the direction of the load. Bruhns and Mecklenburg have recognized and pictured this peripheral rim (*Wulst*) and admit its lifting action for increasing loads of crystal substance,[1] but deny lifting power when crystal substance is replaced by foreign substance.

The distribution of growth about an unloaded crystal is rather well shown by the same device. Fig. 3 is a vertical section through an unloaded crystal of potash alum grown in a solution saturated with both chrome and potash alum. The color plainly reveals the distribution of new crystal substance and shows the original crystal, together with the mass of new matter deposited upon its upper surface, to have been lifted bodily 0.4 mm. by the new growth. It may be noted also that the original crystal was inverted from its position of original growth (its cup is still distinguishable facing upward) in order that subsequent growth might suffer no modification through special limitations of circulation imposed by the original supporting rim.

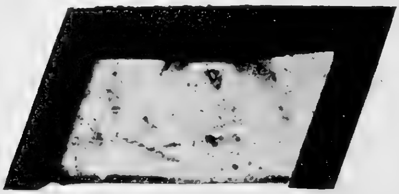

Fig. 3.—Distribution of new growth about an unloaded crystal

By the same reasoning, the case offered by Bruhns and Mecklenburg (Table II) is capable of equally definite analysis. Here we have in the same solution two crystals, one loaded and the other not. The saturation concentration will ordinarily be first reached upon the top and side surfaces of the unloaded crystal; secondly, in the exposed (and strained) side surfaces of the loaded crystal; thirdly, in the supporting liquid layer beneath the unloaded crystal; and last of all, in the liquid layer beneath the loaded crystal. Whether this last concentration can be reached in the presence of the three lower saturation concentrations, all of which are exacting their toll of the solution, will depend upon fortuitous relations of

[1] See Bruhns and Mecklenburg's paper, p. 105; also the quotations therefrom, footnote, p. 320.

temperature, rate of evaporation, and load. It is also possible that steps 2 and 3 in this process may have a different order from that assumed. This is, however, of small consequence here. The principle to be recognized is that potential supersaturation will be reached in the liquid layer adjacent to the unloaded crystal first, and in the layer adjacent to the loaded crystal later, if at all. If no supersaturation occured, obviously no growth of the loaded crystal would be possible. Growth at the bottom of the loaded crystal may therefore be positive, zero, or negative, and is much more likely to be zero or negative than positive in the conditions described by Bruhns and Mecklenburg. The rate of evaporation and the amount of the load are governing conditions here, supposing always that no other nuclei develop.

Two sets of measurements are submitted in support of this analysis. Table IV contains the record of two crystals, a loaded (74 gm.) and an unloaded one, placed in a saturated solution together, after the manner of Bruhns and Mecklenburg, and the results confirm their observations (Table II) perfectly. The unloaded crystal grows at the top, sides, and in the supporting rim below, while the loaded crystal shows no growth in the direction of the load.

TABLE IV

CONDITIONS AS BEFORE

TIME (HOURS)	CRYSTAL 1 (LOAD 74 GM.)		CRYSTAL 2 (UNLOADED)	
	Thickness of Crystal	Increase of Thickness	Thickness of Crystal	Increase of Thickness
0	4.5988 mm.	0 mm.	3.9852 mm.	0 mm.
20	4.5988	−0.003	4.2588	0.274
43	4.6001	−0.001	4.6636	0.678

The results of Table V may perhaps serve to illustrate wherein Bruhns and Mecklenburg were hasty in generalizing from such an observation to the sweeping conclusion that no growth can take place in a loaded crystal in the direction in which the load is applied. This experiment (Table V) also shows two crystals, a loaded and an unloaded one, in the same saturated solution, and differs in no detail from the previous case (Table IV) save that the load has been lightened (74 gm. to 0.7 gm.) and differs in no detail from Bruhns and Mecklenburg's series (Table II) save that our rate of evaporation from the solution was probably faster than theirs. The measurements leave nothing to be desired in the simplicity and directness of the proof offered that a loaded crystal may also lift its load in a solution containing an unloaded one (as unsuccessfully attempted by Bruhns and Mecklenburg), though in the light of the foregoing analysis it must be clear that the conditions there are least favorable for such growth. Nevertheless, growth will occur there also if the rate of evaporation is sufficiently high. It may not be inferred, however, that the supporting rim of the unloaded crystal carries no weight ("Er muss ja vornehmlich den Kristall

TABLE V

CONDITIONS AS BEFORE

Time (Hours)	Crystal 1 (Load 0.7 Gm.)		Crystal 2 (No Load)	
	Thickness of Crystal	Increase of Thickness	Thickness of Crystal	Increase of Thickness
0	4.0307 mm.	0 mm.	3.4617 mm.	0 mm.
18	4.0357	0.005	3.5516	0.090
43	4.0492	0.019	3.9907	0.529

tragen," Bruhns and Mecklenburg, p. 105);[1] it merely carries less weight than the corresponding portion of the loaded crystal. The conditions in the liquid layers adjacent to the two crystals therefore differ in degree only, and one crystal may grow, or both may grow, according to the degree of supersaturation developed by the conditions of evaporation. Since the process of distribution of the crystalline molecules depends upon diffusion, a small difference of load means but a small difference in concentration at unit distance, and consequently a sluggish molecular flow. Diffusion would be similarly delayed by increasing the horizontal distance between a heavily weighted crystal and an unweighted one, but we have not put this evident inference to the test of experiment.

Had Bruhns and Mecklenburg chanced to place their unloaded crystal beneath the overhanging load upon its neighbor, it would

[1] See footnote, p. 320.

have grown alone until it shared the load, after which both crystals would have grown at rates approximately in inverse relation to their individual shares.

The effect of distributing a load over three crystals is shown by a simple case (Table VI).

TABLE VI

EXPOSURE 3 DAYS. TEMPERATURE ABOUT 20°. LOAD 200 GM.

	Thickness of Crystal		Increase of Thickness
	Initial	Final	
Crystal 1.....	3.416 mm.	3.527 mm.	0.111 mm.
Crystal 2.....	2.841	2.970	0.129
Crystal 3.....	3.033	3.108	0.075

Nor is it necessary that the measurements given in this table should stand alone in support of so important a conclusion. Bruhns and Mecklenburg succeeded in raising disks of porcelain loaded with weighted beaker-glasses, by the help of the crystallization of chrome alum, to elevations of a millimeter and more under certain conditions. These conditions were that the solution in contact with the disks and their load should be allowed to evaporate to dryness, the maximum elevations resulting when fresh portions of saturated solution were added and evaporated successively. These observations were not measured in detail, but are sufficiently well described in the following paragraphs (Bruhns and Mecklenburg, *op. cit.* pp., 107 and 108):

"Greater or less loading of the little beaker-glasses made no difference in the crystal development. All the six beakers—and this is the important point—no longer rested upon the porcelain disk but rather upon chrome alum crystals. After breaking the glasses loose, it was possible to establish beyond doubt that the crystals which supported the loaded beaker-glasses were at least 1 mm. thick, in many places even thicker, and the glass was no longer anywhere in contact with the porcelain supports" [p. 107].

"After a fragment of the crystallizing dish was broken away, in order to obtain a vertical section through the system, it could also be plainly seen that the porcelain disks no longer touched the bottom of the dish at any point, but were separated from it by a crystal layer the measured thickness of which was from 1 to 2 mm. Through the crystallization of the chrome alum, therefore, both the porcelain support and the beaker-glasses were actually separated from the bottom and lifted up" [p. 108].

This elevation, they assert, has nothing to do with any force of crystallization, and is to be accounted for by "forces of capillarity and adsorption," but just how these forces produce this result they do not explain.

If two parallel plane surfaces are separated by a drop of liquid which wets them both, it is well known that the effect of capillarity is to urge them together with a force $2TV/d^2$, where T is the surface tension, V the volume of the drop, and d the distance between the plates, and this force may be great enough to change the melting-point of blocks of ice or to break sheets of heavy plate glass. Thus a flat disk of porcelain moistened with alum solution and resting on a flat glass plate experiences a downward pressure as if it were heavily loaded.

If a solution has a greater or smaller surface tension than the solvent, the solute tends respectively to desert the surface of the solution, or to seek it, and in the physics of colloids the concentration of solute at such a surface is known by analogy as adsorption. As E. Dorsey[1] and others have shown, aqueous solutions of salts such as chlorides and carbonates of the alkalies and zinc sulphate have a surface tension greater than that of water, and according to Poynting and Thomson,[2] the surface tension of salt solutions generally exceeds that of water. The adsorption in this case, considered as a possible lifting force, is therefore negative. Adsorption films in their relation to crystal growth have been investigated experimentally with great thoroughness by Marc in a series of four papers, "On Crystallization from Aqueous Solutions" (1908–10);[3] and

[1] *Phil. Mag.*, XLIV (1897), 369.

[2] *Properties of Matter*, 1902, p. 181.

[3] The chief conclusions reached by Marc are contained in the following brief citations (*Zeitschr. f. phys. Chem.*):

"It was found that the rate of crystallization, so far as it could be determined, of all the substances investigated was proportional to the square of the supersaturation" (*op. cit.*, LXVII [1909], 500).

". . . . that a very rapid change precedes the crystallization proper, which is interpreted to be an adsorption phenomenon. Support is given to this view by the again, "On Adsorption and Saturated Surfaces" (1913),[1] without developing any single fact in support of the hypothesis advanced by Bruhns and Mecklenburg.

Neither capillarity nor adsorption exerts any upward pressure on the loaded disks of porcelain in the experiments under discussion, while adsorption does not prevent the exercise of the very great downward pressure due to the surface tension of water. Yet the alum crystallized and the disks were raised.

In the opinion of the observers it was essential to the elevation of the disks that evaporation should be complete.[1] Was the elevation, then, produced after the crystallization was complete and the mass solidified? The observers make no such statement, which, indeed, would seem absurd. But if the raising was not effected after solidification, it must have been produced before solidification, or while the underlying film was liquid and while crystallization was in progress, in opposition to capillary force as well as to the weight of the disks and their load.

Liesegang appears to have appreciated this anomaly in Bruhns and Mecklenburg's statement, though accepting their conclusion, for he sought to relieve it by the following explanation (referring to the experiments of Bruhns and Mecklenburg): "Nicht ein Wachstumsdruck der Krystalle sondern Capillar- und Adsorptionskräfte bewirkten hier also die Hebung. Das heisst die Leistung war schon volbracht ehe Kristalle auftraten."[2] "The lifting was done before the crystals formed." This is not claimed by Bruhns and Mecklenburg, nor supported by any experimental evidence which they

fact that this preliminary phenomenon is particularly sensitive to slight impurities upon the crystal surface" (*ibid.*, LXXIII [1910], 718).

"No relation could be established between concentration and the quantity of adsorbed material" (*ibid.*, LXXIII [1910], 686).

"In all cases the rate of crystallization is diminished by the addition of substances which are adsorbed by the crystal, eventually even to the point of becoming practically zero" (*ibid.*, LXXIII [1910], 718).

"It was shown that the substances chiefly adsorbed by crystals are colloids, while the crystalloids are adsorbed only very slightly" (*ibid.*, LXXXI [1913], 692).

[1] Bruhns and Mecklenburg, *op. cit.*, p. 106: "Es sei aber ausdrücklich betont dass der Versuch nicht gelang, wenn wir nicht die Masse bis zum Grunde trocken werden liessen."

[2] R. E. Liesegang, "Kristallisationskraft," *Naturw. Rundschau der Chem. Ztg.*, Zweite Jahrg. 1913, p. 183.

offer, and indeed would seem to be without any foundation whatsoever.

We fail to see any reason for connecting the rise of the porcelain disks with capillarity or with adsorption. These could only obstruct the elevation, and must have been overcome by a linear force attending the crystallization of the alum, as in our own experiments.

It is not expedient, however, to rely on reasoning alone in matters of physics if experimentation is practicable, and we accordingly made the effort to separate the forces to which Bruhns and Mecklenburg appeal, through evaporation of solution of a colloid (gum arabic) in which was immersed a block of glass replacing the alum crystal between the two plates of glass (Table VII). Evaporation to dryness caused no rise of the upper glass plate as it

TABLE VII

BLOCK OF GLASS REPLACING THE ALUM CRYSTAL (FIG. 1). LOAD (GLASS PLATE) = 24 GM. GLASS BLOCK AND LOAD COMPLETELY IMMERSED IN 2 PER CENT SOLUTION OF GUM ARABIC IN WATER. ROOM TEMPERATURE

Time (Hours)	Spherometer Readings	Increase in Thickness	Notes
0	37.2609	0 mm.	
3.1	37.2649	+0.004	
28.1	37.2654	+0.0045	
45.1	37.2621	+0.001	
50.2	37.2615	+0.001	Evaporated to dryness
Refilled with 2 per cent gum arabic solution; all conditions unchanged			
58.8	37.2669	+0.006	
68.8	37.2670	+0.006	
76.1	37.2670	+0.006	
116.9	37.2653	+0.004	Evaporated to dryness

should have done were capillarity and adsorption the source of energy. A saturated solution of alum added to the colloid (Table VIII) starts crystal formation and growth at once, but at a rate much slower than in the cases where no colloid was present. This is in full accord with the experiments of Marc.[1]

In addition to confirming the results of Marc, Table VIII offers independent and explicit experimental proof that the "linear force" appears here also in spite of the action of the colloid in retarding

[1] See footnote, p. 326.

diffusion through increased viscosity and in interposing an adsorption film at the crystal surface.

Conditions in ore deposits appear to correspond very well with those in the laboratory, for crystallization may be found accompanied by local evidence of linear thrust or not, according to the magnitude and distribution of the opposing forces. Its failure is most often manifest in comb structure, found in crevices whose walls are each lined with tightly adhering crystals which either interlock and extend quite across the crevice or grow together near the central plane and mutually exclude further development. Such comb structure is common in veins, but far from universal.

TABLE VIII

SAME PLATES, BLOCK OF GLASS, AND CONDITIONS, EXCEPT THAT THE 2 PER CENT GUM ARABIC SOLUTION HAS BEEN SATURATED WITH POTASSIUM ALUMINIUM SULPHATE

Time (Hours)	Spherometer Readings	Increase in Thickness
0	37.2653	0 mm.
4.2	37.2694	0.004
24	37.2721	0.007
29	37.2812	0.016
46	37.2818	0.017
71	37.2842	0.019
95	37.2857	0.020
148	37.2873	0.022
173	37.2916	0.026
214	37.3079	0.043
287	37.3178	0.053
366	37.3170	0.052
409	37.3185	0.053

It may be inferred, further, that linear pressure plays a subordinate part in much more complex occurrences.

Messrs. Bruhns and Mecklenburg seem to have misunderstood the last paragraph of our paper in which we called attention to the fact that the linear force of growing crystals can*not* be disposed of as a mystery comparable to the growth of plant roots. It is a sharply defined physical process open to quantitative experimental investigation. It may not be fully understood, but it is no mystery.

. The conclusion of these authors seems to be that during growth, material is added only to the upper and lateral faces of the crystal, so that a molecule once added remains at its original level. This was Kopp's contention in opposition to Lavalle, whose conclusions, however, were confirmed by Lehmann and others, including ourselves. This is in fact the root of the matter. If a given increment of the mass after deposition remains at its original level throughout the subsequent growth of the crystal, this exerts no linear force; while if the motion of the particle has a vertical component in consequence of the vertical extension of the lateral faces of the crystal, linear force is exerted.

On the other hand, if several crystals are immersed, one or more of them being loaded while others are not loaded, the loaded crystals grow only when the concentration of the solution in contact with them exceeds the saturation concentration for each crystal. Pressure, of course, increases solubility or raises the point of saturation for most salts.[1] Hence in such circumstances the unloaded crystals, or, more strictly, the less loaded crystals, usually are the only ones to exert lifting power, but in this case, also, growth raises the weight of each crystal.

Thus Bruhns and Mecklenburg's results with loaded porcelain disks are readily explicable. They experimented with solutions containing many small crystals, some of them weighted, others free. The disks did not rise measurably until the liquid was low and its surface (and consequent rate of evaporation) greatly increased by protruding solid matter, or until the crystals reached from the bottom of the dish to the disks, after which the disks were lifted.

Repetitions of this operation, extending over a few days, produced aggregate displacements of 5.0 mm. If to this be added our original measurement, twice confirmed in the course of the present control tests, that this linear force, because of the narrow rim

[1] As is well known, if the solution of a solid at constant temperature is attended by a diminution in total volume and a liberation of heat, pressure increases solubility. Such is the case for most crystalline solids including the alums. If the change in volume accompanying solutions is an increase, as in ammonium chloride, pressure decreases solubility.

through which it acts, actually exerts a pressure of the same order of magnitude as the breaking load of the solid crystals, need there be further hesitation in assuming that this is a force to be reckoned with in engineering[1] or in geology?[2]

SUMMARY

In 1905 we showed by appropriate experimental evidence that a single crystal immersed in its own saturated solution, and growing by reason of the potential supersaturation of the solution resulting from evaporation will lift a weight placed upon it. This observation has been confirmed in the present paper.

In 1913 Bruhns and Mecklenburg placed two crystals in a similar saturated solution, one loaded and the other free, and noted that the load upon the one crystal was not raised, although the free crystal grew rapidly. From this experiment they were led to deny the power of a crystal to lift a weight of foreign substance, although admitting the power of the unloaded crystal to lift its own substance. They appear to have overlooked in this conclusion the fact that the solubility of the loaded crystal is for most substances greater than that of an unloaded one, and also that this is a difference in degree only, for the unloaded crystal also supports weight (its own).

In consequence of this greater solubility, with an unloaded and a loaded crystal in the same solution, the necessary condition of potential supersaturation will be reached in the liquid adjacent to the unloaded crystal before it is reached in the other, and the growth of the unloaded crystal thereafter may keep the concentration below that necessary for the growth of the loaded crystal. This appears to be the condition reached in Bruhns and Mecklenburg's experiment. If it happens, however, that the rate of growth

[1] Cf. the investigations of Dr. Hans Kühle, "Die Ursache des Treibens der Zemente," *Tonindustrie Ztg.*, XXXVI (1912), 1331–34; and of Klein and Phillips, "Hydration of Portland Cement," *Technologic Papers of the Bureau of Standards No. 43* (1914), pp. 50, 56, 57.

[2] Cf. the recent observations of Stephen Taber, *Virginia Geol. Survey Bull.*, No. VII (1913), p. 222; also G. D. Harris, "Rock Salt, Its Origin, Geological Occurrences and Economic Importance in the State of Louisiana," *Geol. Survey of Louisiana, Bulletin No. 7* (1907), p. 75.

of the unloaded crystal is insufficient to take up all of the excess concentration provided by the continued evaporation, then supersaturation will increase. It is entirely possible under these conditions that the potential supersaturation necessary for the growth of the loaded crystal may then be attained or even exceeded, and that the loaded crystal will also grow and lift its load. This condition was attained experimentally without difficulty in the observations recorded in this paper. If concentration increases still more rapidly, and exceeds the ability of both unloaded and loaded crystals to take up, through their continued growth, all the matter in excess of the saturation concentration, then additional nuclei may form upon which excess matter may be deposited. This appears to have been the condition attained in the last series of Bruhns and Mecklenburg's observations in which the solution was evaporated to dryness.

Here six disks of porcelain loaded with weights were all raised a millimeter or more in the same solution, but Bruhns and Mecklenburg attribute this result to the action of capillarity and adsorption, and deny the competence of the "linear force of growing crystals" to effect such mechanical displacements.

A simple analysis suffices to show that capillarity in a solution evaporating to dryness can have no other effect than to press the crystal down upon its base with a force equal to $2TV/d^2$, where T is the surface tension, V the volume of the drop of liquid between the crystal and its base, and d the distance separating the two, and that the lifting action observed by Bruhns and Mecklenburg has occurred in spite of this opposing force and not because of it. Adsorption delays diffusion and diminishes the rate of growth, but does nothing to promote it. These forces therefore cannot be appealed to in explanation of the lifting observed by Bruhns and Mecklenburg and by us.

We therefore return to the original thesis that the growth of crystals in saturated solution develops a linear force in the direction of the load, and that neither the magnitude of the load (up to the breaking load) nor its character (whether exclusively crystal substance or partly foreign substance) has any other effect than to increase solubility and so to raise the concentration necessary for potential supersaturation and growth upon the loaded crystals. This degree of supersaturation is readily attainable through evaporation or otherwise, and when attained the loads are lifted. With this thesis established, there is no conflict between the observations of Bruhns and Mecklenburg and our own, and all the experimental evidence offered is perfectly correlated.

Carnegie Institution of Washington
Geophysical Laboratory
February, 1916

THE CLASSIFICATION OF THE NIAGARAN FORMATIONS OF WESTERN OHIO[1]

CHARLES S. PROSSER
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CONTENTS

INTRODUCTION

There has been more or less uncertainty concerning the names which ought to be used for the Niagaran formations of the Silurian system in western Ohio together with their correlation with the formations of the same series in eastern Indiana. Field work in the summer of 1914 in this area has cleared up some of this uncertainty and part of the results are deemed of sufficient importance to warrant their early publication.

[1] Presented at the Ohio Academy of Science meeting in Columbus on November 28, 1914, and at the American Association for the Advancement of Science meeting in Columbus on December 28, 1915. Published by permission of the State Geologist of Ohio.

A series of sections at Piqua, along the Stillwater River between Covington and West Milton, and along Ludlow Creek in Miami County, and in the vicinity of Lewisburg, Eaton, and New Paris in Preble County, has furnished the writer the complete section from the Ordovician to the highest Silurian rocks of this area.

DESCRIPTION OF SECTIONS

The contact of the Ordovician and Silurian systems is clearly shown at Ludlow Falls, and the succeeding rocks as high as they extend in this region are admirably exposed at the falls and in the series of quarries which border the creek for some distance above the falls. Sections at other localities agree with the ones along this creek and show that the general order of succession is essentially the same for these counties.

LUDLOW CREEK SECTIONS

Four of the series of sections measured along Ludlow Creek will be given, which were checked by several other sections along the same stream. From these a general section of the rocks shown along this creek can be compiled.

The following section is based on the outcrops in the northeastern corner of the Colonel Samuel B. Smith quarry and the bank at the northern end of Ludlow Falls:

SECTION OF LUDLOW FALLS AND THE SMITH QUARRY

	Thickness		Total Thickness	
No.	Feet	Inches	Feet	Inches
6. *Dayton limestone.*—Northeast corner of the Colonel Samuel B. Smith quarry. The rock varies from light gray to somewhat darker gray on fresh fracture and some as weathered is bluish-gray. Other layers on the weathered faces are buff to brownish or rusty color from disintegrated iron pyrite. The rock splits into even-bedded layers; but the surfaces of the bedding planes are frequently rather rough and show stylolites structure. The majority of the layers vary in thickness from 2 to 10 inches, most of them ranging from 4 to 6 inches. The lowest layer is from 3 to 4 inches thick, and the				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	next one above 10 inches, which in places splits into 2 layers with hackletooth structure at contact. The lower layers contain iron pyrite, which stains them on weathering. There are also calcite crystals, but no fossils were noted	8	2	41	5
5.	*Brassfield limestone.*—Crystalline and crinoidal light-gray to pinkish limestone, with very irregular bedding planes. Specimens of corals and Stromatopora are rather common, and there is an occasional Brachiopod shell. In places there are irregular masses of blue shale which contain a good many corals. This is the bottom of the quarry at this corner, and the barometer with an interval of only 7 minutes read the same at the highest outcrop of the Brassfield limestone on the northern bank of Ludlow Creek, just above the Dayton, Covington, and Piqua traction bridge and Ludlow Falls	5	1	33	3
4.	The upper 5 feet of the bank at the northern end of Ludlow Falls varies in color from light gray to pinkish and greenish, while some of it when weathered is brownish. Most of it is coarsely crystalline, part of it is very crinoidal, and it contains large numbers of Bryozoa, corals, and Stromatopora	5	0	28	2
3.	Rather massive, more or less crystalline, limestone, which is of light-gray color, somewhat brownish as weathered; and some of it is very light gray, almost white, and is locally called a "marble." It contains very few fossils, if any. At the center of the falls there are 11 feet of the Brassfield limestone undercut by the water of the stream	16	6	23	2
2.	*Belfast bed.*[1]—Blue rock, which is probably argillaceous and rather sandy, with layers from 2 to 6 inches thick and the average about 3 inches. This zone was thought by Dr. Foerste				

[1] The writer understands Dr. Foerste to now refer the Belfast bed to the Richmond, which is also the opinion of Dr. E. R. Cumings, based on a study of its Bryozoa. Dr. W. H. Shideler, however, has found certain Brachiopods in the Belfast which he thinks allies it with the Brassfield.

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	to represent the Belfast, since he wrote, "If they [the layers] represent the Belfast bed of more eastern sections, as is believed to be the case, they certainly have changed considerably from the typical form of the rock."[1]	2	8	6	8
1.	*Richmond formation.*—Rather thin-bedded blue rock to shaly layers, perhaps with sandy to calcareous composition. This zone extends to water level and blue shale is washed out of a pit that has been dug still deeper by the water. About 5 feet of this zone are shown in the bank on the southern side	4	0	4	0

The foregoing section gives 26 feet 7 inches for the thickness of the Brassfield limestone. This agrees fairly well with the estimate based upon the thickness of the Brassfield on the northern bank at the falls and the section in the Big Four Railway cut west of the station on the southern side of the creek. Mr. W. Z. Miller, my assistant, made the top of the Brassfield limestone in the railway cut about 7 feet higher than the top of the ledge on the northern bank of the creek, which gave $28\frac{1}{2}$ feet for the total thickness of the Brassfield limestone on Ludlow Creek.

The general section of Ludlow Creek is continued by the section of the western wall of the Colonel Samuel B. Smith quarry and the bank above it, below the house of Patrick Gallagher.

Section of Western Wall of the Smith Quarry

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
26.	*Laurel limestone.*—Top of bank just below house of Mr. Patrick Gallagher. Light- to bluish-gray rock in fairly even layers varying from 2 to 5 inches in thickness. The upper weathered ones are rather buff and finely porous	3	5	24	10
25.	Partly covered interval. Light- to brownish-gray, rather thin-bedded, dolomite	2	8	21	5
24.	*Osgood beds.*—Partly covered zone; but at top bluish-gray shale to shaly limestone	1	3	18	9

[1] *Journal of the Cincinnati Society of Natural History,* XVIII (1896), 182.

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
23.	Brownish- to bluish-gray, thin layer, from 1 to 2 inches thick		1½ ±	17	6
22.	Bluish-gray shaly limestone to shale, from 6 to 7 inches thick. A specimen of *Leptaena rhomboidalis* (Wilckens) was noted		6½ ±	17	4½
21.	*Dayton limestone.*—Top layer of western bank of the Colonel Samuel B. Smith quarry. Light gray, with rusty spots due to iron pyrite, from 3 to 4 inches thick		3½ ±	16	10
20.	Layer 2 ± inches thick		2 ±	16	6½
19.	Layer from 3 to 4 inches thick with dark-gray blotches in its upper part		3½ ±	16	4½
18.	Dark-gray irregular bands in the lighter colored rock. It contains iron pyrite and varies from 4 to 5 inches in thickness		4½ ±	16	1
17.	Light-gray rock without much dark color, which contains some iron pyrite and varies from 5 to 6 inches in thickness		5½ ±	15	8½
16.	Three-inch layer at bottom of more or less massive zone (Nos. 16 to 21, inclusive), with average thickness of 1 foot 10 inches at top of quarry wall on the western and northern sides		3	15	3
15.	Two rather compact layers, the upper one 4 inches and the lower, 6 inches thick		10	15	0
14.	This layer will split up into thinner ones and it contains iron pyrite		9	14	2
13.	Compact layer		4	13	5
12.	This layer may split up to some extent on weathering		9	13	1
11.	This layer on weathering splits into various layers from 2 to 5 inches thick	1	2	12	4
10.	This layer on weathering tends to split into layers from 2½ to 4 inches thick		9	11	2
9.	Layer with dark-gray blotches or banding due to iron pyrite		6	10	5
8.	Layer from 5 to 6 inches thick, which tends to split to some extent and contains masses of calcite		5½ ±	9	11
7.	Six-inch layer with stylolites structure in the basal portion		6	9	5½
6.	The limestone of this layer and the underlying Dayton layers is, in general, compact, probably				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	somewhat impure, and in part of rather light-gray color. This layer varies in thickness from 12 to 13 inches	1	½±	8	11½
5.	Eleven-inch layer		11	7	11
4.	Four-inch layer		4	7	0
3.	Layer from 7 to 8 inches thick		7½±	6	8
2.	Layer from 3 to 4 inches thick and the base of the Dayton limestone. The average thickness of layers Nos. 2 to 15, inclusive, is 9 feet 3 inches The Dayton limestone is correlated by the writer with the compact, even-bedded limestone below the soft, blue shale or clay of the Osgood beds of Indiana, as defined by Dr. Foerste. Therefore in this and the following sections of this paper the Dayton limestone is regarded as the lower member of the Osgood beds.		3½±	6	½
1.	*Brassfield limestone.*—The bottom layer of the extreme western wall of this quarry is the upper part of the Brassfield limestone. Farther to the southeast on this western side of the quarry 5¾ feet of the upper Brassfield limestone, from its contact with the Dayton limestone to the bottom of the quarry, is shown. It is a crystalline limestone of light-gray to pinkish color, the bedding surfaces frequently of greenish color. The upper part is fairly fossiliferous, the common forms being corals, Bryozoa, Stromatopora, and crinoid segments. Some of the rock contains so many crinoid segments that it is a crinoidal limestone. Bottom of this part of the quarry	5	9	5	9

In the foregoing section, Nos. 2 to 21, inclusive, are referred to the Dayton limestone, which then has an average thickness of 11 feet 1 inch in the western part of the Smith quarry. Samples of the Dayton limestone from this quarry were analyzed by Professor D. J. Demorest with the following result:

Siliceous Residue	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
9.97	1.35	55.37	31.18
10.10	1.40	55.37	31.23

Nos. 2 to 24, inclusive, are referred to the Osgood beds, which gives this formation in this section an average thickness of 13 feet.

Farther west in the series of quarries on the northern side of Ludlow Creek is the one of Otto Ehlers, which in the Miami County report is called the Ellis quarry.[1] The section of this quarry is important in determining the stratigraphy of this region due to the excellent exposure of the shale zone (No. 7 of section) which separates the Dayton and Laurel limestones.

SECTION OF THE OTTO EHLERS QUARRY

No.		Thickness		Total Thickness	
		Fee	Inches	Feet	Inches
21.	*Laurel limestone.*—Three layers at the top of the quarry wall which in descending order are respectively 4, 7, and 6 inches thick. As weathered, these layers are buff-colored and fairly compact. The upper part of this zone is perhaps above the Laurel limestone	1	5	20	4
20.	Compact layer which is more massive than the two immediately below it		10	18	11
19.	More compact layer than that immediately underlying it		8	18	1
18.	It splits into 2 or more layers which are similar to underlying ones		6	17	5
17.	Compact, light-gray dolomite, weathering to buff color and varying from 6 to 7 inches in thickness		6½±	16	11
16.	It tends to split at the bottom into 3 layers		6	16	4½
15.	Light-gray dolomite which weathers to buff color		3	15	10½
14.	Shale containing calcareous nodules to shaly limestone		3	15	7½
13.	Light-gray, weathering to buff color, compact dolomite		10	15	4½
12.	Shaly, light-gray dolomite, weathering to buff color, from 3 to 5 inches thick		4 ±	14	6½
11.	Light-gray, argillaceous shale		2	14	2½
10.	Light-gray, fine-grained dolomite, which splits into 3 layers	1	8	14	½
9.	Light-gray, argillaceous shale		3	12	4½

[1] *Report of the Geological Survey of Ohio*, III (1878), 479.

No.	Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
8. Zone of rather thin layers of light-gray to bluish-gray dolomite, with shaly to shale partings	1	4	12	1½
7. *Osgood beds.*—Zone of rather dark-gray shale which weathers to a bluish-gray color and is rather calcareous. Conspicuous zone on quarry wall	3	2	10	9½
6. *Dayton limestone.*—Massive zone at top of Dayton limestone which splits into at least 3 layers, which, in descending order, are respectively 9 to 10, 3, and 11 to 12 inches thick. It is a light- to bluish-gray, compact limestone	2±	0	7	7½
5. Light- to bluish-gray limestone forming massive zone on northern wall. It splits, however, into 3 layers, which, in descending order, are respectively 11, 7, and 8 inches thick	2	2	5	7½
4. Light-gray layer on weathered face from 12 to 14 inches thick, which will split into 2 or 3 layers	1	1 ±	3	5½
3. Layer similar to those below it		10	2	4½
2. Bluish-gray, compact layer, 7 to 8 inches thick		7½±	1	6½
1. Bluish-gray, compact rock, containing large masses of calcite. Bottom of exposed rock in quarry		11		11

In the foregoing section the shale zone (No. 7) which separates the Dayton limestone from the Laurel limestone is beautifully shown on the quarry wall. This layer of shale was recognized in various sections in Miami and Preble counties and is a very important aid in identifying the formations of these counties and correlating them with those of southeastern Indiana.

At the western end of the almost continuous line of quarries on the northern side of Ludlow Creek is the Maxwell quarry, the upper part of which carries the general section along Ludlow Creek stratigraphically higher than those already described. The following section of this quarry was measured at its western end to the west of the J. J. Wagner brick house:

SECTION OF THE MAXWELL QUARRY

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
19.	*Springfield dolomite.*—Light gray, weathering to whitish color on surface, and splitting into layers varying from 2 to 6 inches. Impression of *Calymene niagarensis* Hall about 1 foot below the top of this zone	2	6	25	8
18.	Light-gray layer with *Pentamerus oblongus* Sowerby common in its lower 3 inches		5	23	2
17.	*Mottled zone.*—Massive zone of mottled-colored dolomite, gray with light-colored blotches and spots, which splits into 2 conspicuous layers on part of the quarry wall and more where much weathered. Surface rather rough and pitted when weathered. This zone has been correlated with the West Union limestone; but there is some uncertainty whether that limestone extends as far to the northwest as this locality and consequently for the present it is not referred to any definite formation	5	6	22	9
16.	*Laurel limestone.*—Thin-bedded with uneven bedding planes. As weathered, rusty to brownish color on surface, which extends for some distance into the rock	1	10	17	3
15.	Light-gray to bluish-gray, compact layer		5	15	5
14.	Thin-bedded, light- to bluish-gray zone, with irregular bedding planes		10	15	0
13.	Compact, light- to bluish-gray layer		5	14	2
12.	Rather shaly layer		5	13	9
11.	Two compact, light-gray layers, the upper 9 and the lower 8 inches thick	1	5	13	4
10.	Light-gray, shaly dolomite and blue shale		6	11	11
9.	Thin-bedded dolomite splitting into 3 or 4 layers	1	4	11	5
8.	*Osgood beds.*—Fine blue, argillaceous shale to clay	1	8	10	1
7.	Rather coarse, blocky blue shale which forms the lower part of the shale zone. Nos. 7 and 8 constitute the shale zone in the upper part of the Osgood beds with a thickness of 2 feet 2 inches		6	8	5

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
6.	*Dayton limestone.*—Massive zone at top of Dayton limestone with a thickness of 2 feet 3 inches, which splits into 5 layers and the first three in descending order are from 4 to 5 inches each in thickness, while the fourth from the top is 8 inches and the fifth 4 inches thick. Light-gray with blotches and spots of dark-gray, compact rock with stylolites or hackletooth structure at the bedding planes	2	3	7	11
5.	Layer of shaly, greenish limestone		10	5	8
4.	Compact layer of light-gray color with some dark-gray blotches containing iron pyrite and calcite	1	0	4	10
3.	Shale to shaly limestone parting		2	3	10
2.	Dark- to light-gray limestone which splits into several layers	3	2	3	8
1.	To water level in old quarry pit		6		6

In the foregoing section, Nos. 7 and 8 correspond to the shale zone (No. 7) of the Ehlers quarry and form the upper member of the Osgood beds. The Laurel limestone comprises Nos. 9 to 16, inclusive, with a total thickness of 7 feet 2 inches. The extreme upper part of this quarry wall shows nearly 3 feet of light-gray fossiliferous rock which is referred to the Springfield dolomite.

Professor Bownocker has recently published a bulletin on the "Building Stones of Ohio" which contains a section of this quarry.[1] In this bulletin the zone called the "West Union limestone" corresponds to the "Mottled zone," No. 17 of the foregoing section, and the upper limestone of the "Osgood beds" is what the writer is correlating with the Laurel limestone of Indiana, and includes Nos. 9 to 16, inclusive, of the foregoing section. The blue shales overlying the Dayton limestone of Professor Bownocker's section correspond to Nos. 7 and 8 of the writer's section, the top of which he regards as corresponding to the top of the Osgood beds of Indiana.

GENERAL SECTION ALONG LUDLOW CREEK

A general section of the formations exposed at Ludlow Falls and in the series of quarries on the northern bank of the stream has been

[1] *Geological Survey of Ohio, 4th Ser., Bull. 18* (1915), p. 37.

compiled from the separate sections described above, which shows the formations from the upper part of the Richmond in the Ordovician system to the lower part of the Springfield dolomite in the Silurian system. Some of the zones or formations vary in thickness in different outcrops, in which case the variation in thickness has been given. This necessarily causes a variation in the entries in the column of total thickness.

GENERAL SECTION ALONG LUDLOW CREEK

Total Thickness	Thickness of Zone or Formation	Names of Series and Formations
		Niagaran Series
$57\frac{3}{4}'$ to $61'$		
	$2\frac{11}{12}'$	*Springfield dolomite* (only lower part shown)
$54\frac{5}{8}'$ to $58\frac{1}{12}'$		
	$5\frac{1}{2}'$	Mottled zone
$40\frac{1}{3}'$ to $52\frac{7}{12}'$		
	$7\frac{1}{6}'$	*Laurel limestone*
$42\frac{1}{6}'$ to $45\frac{5}{12}'$		Top of *Osgood beds*
	$1\frac{11}{12}'$ to $3\frac{1}{6}'$	Shale zone
$40\frac{1}{4}'$ to $42\frac{1}{4}'$		*Dayton limestone*
	$11\frac{1}{12}'$	Base of *Osgood beds*
$20\frac{1}{6}'$ to $31\frac{1}{6}'$		
		Oswegan Series
	$26\frac{1}{2}'$ to $28\frac{1}{2}'$	*Brassfield limestone*
$2\frac{2}{3}'$		
		Cincinnatian Series
	$2\frac{2}{3}'$	*Belfast bed* at top of *Richmond formation*
$0'$		

A mere outline of the classification of the formations of the Niagaran series along the Ohio-Indiana state line was published by the writer on April 20, 1915,[1] and the Brassfield limestone was given in the Oswegan series.[2]

Correlation of the Brassfield limestone.—The limestone in the foregoing sections, which is called the Brassfield, is the one which in Ohio has generally been called the Clinton and correlated with the well-known New York formation of that name, which forms the

[1] *Outlines of Field Trips in Geology for Central Ohio,* The College Book Store, Columbus, Ohio, p. 18.

[2] *Ibid.*

basal part of the Niagaran series of that state. As early as 1896 Dr. Foerste stated that—

> The identity between the Clinton faunae of the two states [Ohio and New York] on closer examination is not found to be so close as at first supposed. Whether this is due to geographical causes, the Clinton of New York being more litoral, or whether it is due to moderate differences of horizon, can not be told until the Clinton of New York is much more closely studied. Although I have been accustomed to call the Ohio formation the Clinton, yet I should be willing to recognize the fact that the identity is not very marked, by giving it a name of its own, for instance, the *Montgomery formation*, on account of its typical development in Montgomery County, in Ohio.[1]

In 1906 Dr. Foerste proposed the name Brassfield formation for this limestone from outcrops "along the Louisville and Atlantic Railroad, between Brassfield and Panola, in Madison County," Kentucky.[2] It was stated that "for the . . . . limestone section at the base of the Niagaran division of the Silurian, hitherto identified with the Clinton of New York, the name Brassfield limestone is proposed."[3]

After listing the fauna of the Brassfield limestone in Kentucky, Ohio, and Indiana, and noting the absence in it of certain characteristic Brachiopods of the New York Clinton, Dr. Foerste wrote as follows:

> The identification of the Brassfield limestone of Kentucky, and of its northern extension in Ohio and Indiana, in former years, with the Clinton limestone of New York, rests rather upon a somewhat similar facies of the two faunas, and upon the general absence of the more typical species of the Rochester shale fauna of New York in these limestones at the base of the Silurian in Ohio, Indiana, and Kentucky, than upon the presence of any considerable number of species common to both areas. On closer inspection, the fauna of the Brassfield limestone of Ohio, Indiana, and Kentucky appears to differ sufficiently from the fauna of the Clinton limestone of New York to warrant the assumption of the presence of some sort of barrier between these two areas.[4]

Dr. Foerste has also stated in a later publication that "the Brassfield limestone is the southern continuation of the strata which were identified in Ohio, by Professor Orton, as Clinton."[5]

[1] *Journal of the Cincinnati Society of Natural History*, XVIII, 189.

[2] *Kentucky Geological Survey, Bull. 7*, p. 27. [3] *Ibid.*, p. 18. [4] *Ibid.*, p. 35.

[5] *Journal of the Cincinnati Society of Natural History*, XXI (September, 1909), 1.

At the 1912 meeting of the Geological Society of America, Professor Charles Schuchert proposed the Cataract formation: "a new formation at the base of the Siluric in Ontario and New York," from a locality called the Cataract in the Credit River region of Ontario, 48 miles northwest of Toronto.[1] In August of the same year Professor William A. Parks in describing "The Palaeozoic section at Hamilton, Ontario," stated that "a new formation—the Cataract— . . . . represents an invasion from the north and west at the commencement of Silurian time. The upper limestones and shales of this formation are highly fossiliferous and present a fauna comparable with that of the Brassfield formation of Ohio and Kentucky."[2]

Dr. Merton Y. Williams described a series of sections in the Niagara escarpment of Ontario in a paper before the Geological Society of America in December, 1913, in which he reported that "the Medina sandstones of Niagara gorge (125 feet thick) are represented farther north by dolomite and shales (Cataract formation)."[3]

An article by Dr. Kindle on "What Does the Medina Sandstone of the Niagara Section Include?" contains the following sentence: "The examination by the writer of a number of sections holding this fauna [Cataract] in connection with a review of the Niagara section has convinced him that all of the terranes associated with the Cataract fauna are represented in the Medina of the Niagara section."[4]

In a later and exhaustive paper on the "Medina and Cataract Formations of the Siluric of New York and Ontario," Professor Schuchert shows the close relationship of the Brassfield fauna to that of the Cataract formation of Ontario and also "that the Cataract is a close correlate with the Medina" formation of New York.[5] In another place is the statement that "in other words, the

[1] *Bulletin of the Geological Society of America*, XXIV (March, 1913), 107.

[2] *Guide Book No. 4* (Twelfth International Congress of Geologists), "Excursions in Southwestern Ontario," B_3, p. 128.

[3] *Bulletin of the Geological Society of America*, XXV (March, 1914), 40.

[4] *Science*, N.S., XXXIX (June 19, 1914), 918.

[5] *Bulletin of the Geological Society of America*, XXV, (September, 1914) 291.

typical Medina formation shades through lateral alteration into the typical Cataract."[1]

This apparently agrees with the idea expressed by Professor R. Zuber, of the University of Lemberg, on the escarpment at Hamilton, Ontario, in August, 1913, when he said that the Medina and Cataract appeared to him to be different facies of the same formation. Concerning the relation to the Brassfield, Professor Schuchert wrote:

> The Cataract may also be compared with the Brassfield formation of Ohio and Indiana, as the two are clearly related, and also both are of a limestone facies. The former has 76 species and the latter 140. Between the two there are 24 forms in common. . . . . When the two biotas are finally carefully compared with each other, there will undoubtedly be added more significant forms strengthening the view that the Cataract and Brassfield are fairly close correlates in time. However, as these two faunas are not of the same epicontinental basin, one cannot expect a large percentage of the forms to be common to both; the Brassfield element came in from the Gulf of Mexico region, while the Cataract migrated into Ontario through the Gulf of St. Lawrence embayment across the Province of Quebec or came in from the Arctic.[2]

A little later Dr. M. Y. Williams, in his article on the "Stratigraphy of the Niagara Escarpment of Southwestern Ontario," has stated that "Medina is used in the sense in which Grabau has redefined the term, that is, to include the beds above the Queenstown shale and below the Clinton formation. It is extended, however, laterally to include the Cataract formation as defined by Schuchert."[3]

The Medina sandstone underlies the Clinton beds of New York and is not included in the Niagaran series, but is the upper formation of the Oswegan series as classified by the New York Geological Survey. Therefore, if the correlation reviewed above be accepted, then the Brassfield limestone (formerly called Clinton) of Kentucky, Ohio, and Indiana is to be transferred from the Niagaran to the Oswegan series of the Silurian system.

Furthermore, Professor T. E. Savage believes that in the Mississippi Valley the Sexton Creek limestone "represents about the

[1] *Ibid.*, p. 294. [2] *Ibid.*, p. 291.

[3] *Summary Report of the Geological Survey* [Canada] *for the Calendar Year 1913* (1914), p. 182.

same general period of deposition as the Brassfield limestone."[1] The Sexton Creek limestone is the upper formation of the Alexandrian series, named and described by Professor Savage,[2] a series that in Illinois and Missouri contains all the formations between the Richmond-Maquoketa formation, at the top of the Cincinnatian series, and the base of the Niagaran series.

Since the above was written, advance pages of a work on *Historical Geology* by Professor Schuchert have been received in which the following correlation appears:

Lower Silurian or Oswegan	Medina, Cataract, and Brassfield formations. Becsie limestone.[3]

OTHER SECTIONS OF WESTERN OHIO

Sections farther up the Stillwater River toward Covington show the middle and upper parts of the section exposed along Ludlow Creek, while those in Covington carry the general section still higher. Sections farther west, near Lewisburg and New Paris, agree essentially with those of the Stillwater Valley.

Sections in and near Covington.—About two miles south of Covington is the Jackson Stone Co. quarry, near the Stillwater River, on the Charles H. Jackson farm. It is easily reached by the Piqua, Covington, and Dayton trolley line, leaving the car at stop 45, which has the name of Sugar Grove. The section given below is of the eastern wall of the quarry, the top of it near the engine house, a short distance southwest of the crusher.

SECTION OF THE JACKSON STONE CO. QUARRY

No.	Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
22. *Cedarville dolomite.*—Buff, mostly porous, crystalline dolomite, with *Pentamerus oblongus* Sowerby common all through the outcrop. Zone at base with large number of specimens of *Pentamerus oblongus* Sowerby as well as *Favosites niagarensis* Hall..................	3	8	109	9

[1] *Illinois State Geological Survey, Bull. 23* (1913), p. 33.

[2] *American Journal of Science,* 4th Ser., XXV (1908), 434, 443; *Illinois State Geological Survey, Bull. 23,* pp. 14, 15.

[3] *A Text-book of Geology,* Part II, *Historical Geology* (1915), p. 661.

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
21.	*Springfield dolomite.*—Buff-colored, rather thin, layers of even-bedded dolomite. The layers vary in thickness from 2 to 8 inches and the majority of the layers are probably from 4 to 6 inches thick. No one of the exposed layers is blue. Fossils, as *Pentamerus oblongus* Sowerby, and corals are common and certain layers contain numerous specimens of *Pentamerus oblongus.* This zone, with its thin even beds of buff color, has clearly the lithologic appearance of the Springfield dolomite	10	6	106	1
20.	Bluish-gray, weathering to a buff color, rather compact, slightly porous, dolomite which generally splits into two layers	1	½	95	7
19.	Bluish-gray, somewhat mottled, layer which contains but few fossils		10½	94	6½
18.	Bluish-gray layer, fairly compact, in part subcrystalline, with some small holes and containing large numbers of *Pentamerus oblongus* Sowerby. On account of the large number of fossils this zone may be called a *Pentamerus* layer and clearly belongs in the Springfield dolomite		10	93	8
17.	*Mottled zone.*—Massive layer of bluish-gray dolomite marked with large, irregular-shaped spots of light-gray color, so that the entire surface has a coarsely mottled color. It has a porous structure with medium-sized cavities. It contains some fossils, as, for example, cup corals and crinoids, with an occasional specimen of *Pentamerus.* At the base is a stylolites parting	7	2	92	10
16.	*Laurel limestone.*—Lithologically like lower layers, thickness varying from 9 to 10 inches, more porous in upper 4 inches, with small and larger holes. Some fossils, as a cup coral and *Pentamerus?*		9½ ±	85	8
15.	Bluish-gray, somewhat porous, limestone. A cup coral was noted		10	84	10½
14.	Layer of light-gray mottled with dark-gray, fairly compact, limestone, varying in thickness from 12 to 13 inches	1	½ ±	84	½

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
13.	Light-gray limestone in 4 layers, with shaly partings, varying in thickness from 19 to 21 inches. Lithologically similar to subjacent layers	1	8 ±	83	0
12.	Light-gray, with dark-gray spots and blotches, compact limestone, which is harder than lower layers and varying in thickness from 12½ to 13 inches	1	¾ ±	81	3¾
11.	Gray, weathering to a brownish color, gritty shale, about 1 inch thick		1 ±	80	3
10.	Layer lithologically about the same as the subjacent one		5	80	2
9.	Light to slightly brownish-gray with dark-gray blotches and spots of hard limestone, varying in thickness from 14 to 16 inches. Mr. Harry H. Brandon of the Jackson Stone Co. stated that the Laurel limestone worked in this quarry, Nos. 9 to 16, inclusive, with a thickness of 7 feet 1 inch, is a superior rock for macadamizing roads and in respect to its binding quality is one of the best in the state	1	3 ±	79	9
8.	Light-gray limestone blotched with dark-gray spots and streaks from pyrite. Calcite crystals are also present. It is a hard layer which forms the present floor of the quarry (August, 1914), and its upper surface is undulating, forming sort of dome-shaped elevations		5	78	6
7.	Gray, gritty shale and perhaps rather calcareous		3 ±	78	1
6.	Light-gray limestone blotched with spots and streaks of darker-gray color, which are due to pyrite in small grains that has discolored the rock; when weathered it changes to a brown or rather rusty color. The zone varies in thickness from 16 to 17 inches and is the base of the Laurel limestone, which in this quarry has a thickness of 9 feet 1 inch	1	4½	77	10
5.	*Osgood beds.*—Dark-gray shale, very gritty to the teeth, which is exposed in upper part of pit in floor of quarry. The measurements and characters of the zones below the floor of the				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	quarry to and including No. 5 were obtained from the outcrops in the upper part of the pit in the floor of the quarry	1	8	76	5½
4.	*Dayton limestone.*—This zone was not exposed at the time the quarry was studied on August 29, 1914. Mr. Brandon, however, stated that it is 12 feet in the pit from the bottom of the quarry to the white "Clinton" limestone. If the statement that it is 12 feet from the floor of the quarry down to the top of the white "Clinton" is correct, then the Dayton limestone has a thickness of about 8 feet 3½ inches. Mr. Brandon described it as a hard, blue stone	8	3½	74	9½
3.	*Brassfield limestone.*—Mr. Brandon stated that in the well drilled at the engine house in this quarry the white "Clinton" is between 18 and 20 feet thick	19	0	66	6
2.	*Richmond formation.*—Mr. Brandon stated that below the white "Clinton" the well passed through 45½± feet of blue stone, and the base of this zone he reported as 110 feet below the mouth of the well in the engine house	45	6	47	6
1.	The well penetrated 2 feet of rock, which is described by Mr. Brandon as reddish "granite." Bottom of well	2	0	2	0

A halftone of the eastern wall of this quarry, the one described in the foregoing section, is given in Fig. 1. The lower part of the wall shows the Laurel limestone. Mr. Cottingham's foot is on top of the "mottled zone," his hand marks the base of the 10½-foot zone of Springfield dolomite, while the extreme top of the bank below the building is the basal part of the Cedarville dolomite.

The foregoing record is an important one in the series of sections in this part of the state, since there is a continuous exposure from the Osgood shale up and into the lower part of the Cedarville dolomite. The Laurel limestone is well shown and has a thickness of about $9\frac{1}{6}$ feet, which is 2 feet more than its thickness in the Maxwell quarry of Ludlow Creek. Samples of the Laurel limestone from this quarry were analyzed by Professor D. J. Demorest with the following result:

Silicious Residue	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
14.35	1.40	52.68	29.53

The "mottled zone" is also thicker, since in this quarry it is 7 feet 2 inches, while it is only 5 feet 6 inches in the Maxwell quarry. The Springfield has a thickness of 13 feet 3 inches, overlying which is the lower 3 feet 8 inches of the Cedarville dolomite. The northern wall of this quarry extends higher stratigraphically than the eastern wall below the crusher, and on this wall the "mottled zone" is 6 feet 10 inches thick, above which is 13 feet of Springfield dolomite, capped by 9 feet 5 inches of Cedarville dolomite. At the northern end of the eastern wall almost 10 feet of the Cedarville dolomite is shown.

An illustration of this quarry has been published[1] under which appear the names "West Union, Springfield, and Cedarville limestones." The West Union probably refers to what is listed as the "mottled layer" in the foregoing section.

The recent bulletin by Professor Bownocker contains a section of this quarry[2] in which the "West Union limestone" corresponds to the "mottled zone," No. 17 of the foregoing section, and the upper limestone of the "Osgood beds" corresponds to what the writer correlates with the Laurel limestone of Indiana, Nos. 6–16 of his section. The 2 feet of "dark-blue shale" of Professor Bownocker's section corresponds to No. 5 of the writer's section, and he considers the top of this shale as corresponding to the top of the Osgood beds in Indiana.

[1] *Eighth Annual Report of the State Highway Department of Ohio* (1913), Fig. 9, p. 257. The geological part of the report is probably to be credited to Mr. W. C. Morse, judging from the statement on p. 17.

[2] *Geological Survey of Ohio, 4th Ser., Bull. 18* (1915), p. 36, and Pl. III opposite this page apparently gives a view of this quarry or one in its vicinity.

The upper Niagaran dolomites were formerly extensively quarried in Covington, but in recent years they have not been worked to any extent. Just south of the town is the J. W. Ruhl

FIG. 1.—Eastern wall of the Jackson Stone Co. quarry, two miles south of Covington, Ohio. The lower part is the Laurel limestone. Mr. Cottingham's foot is on top of the "mottled zone," above which is all of the Springfield dolomite, while the top of the wall is the base of the Cedarville dolomite.

quarry, the long wall of which is visible from the traction cars to the west of the track. The following section of the eastern wall, near its upper end and a short distance south of Bridge Street, was made:

SECTION OF THE J. W. RUHL QUARRY AT COVINGTON

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
11.	*Cedarville dolomite.*—Fairly massive, gray to buff, porous dolomite, with the characteristic lithologic appearance of the Cedarville. Certain layers contain abundant impressions of crinoid segments and parts of stems with an occasional cup coral. Rather infrequently more or less of the calcareous material of a crinoid stem is preserved. In the weathered wall are rather large holes in addition to the smaller ones which give it the porous structure. Near the base, *Spirifer* and other Brachicpod shells were noticed in association with crinoids. The upper 11 feet of this part of the quarry wall belong in the Cedarville, but on a wall farther south some 15 feet of Cedarville are shown...	11	0	26	5
10.	*Springfield dolomite.*—When weathered, buff, compact rock containing small holes, due to solution of crinoid fragments. Layers vary from 2 to 6½ inches in thickness; but the majority are 3, 4, or 5 inches thick. All of the zone is somewhat porous..................	2	6	15	5
9.	Chert zone containing 4 layers of chert. The rock is harder than in the zone above, denser, not so porous, and of slightly greenish-gray color. *Pentamerus oblongus* Sowerby occurs in the second chert above the base as well as in the lowest one..............................	2	10	12	11
8.	Ten-inch layer in which *Pentamerus oblongus* Sowerby is common......................		10	10	1
7.	Compact, hard rock, somewhat rough on the broken surface. Color gray; but of different shades, so that it is not uniform............	1	8	9	3
6.	Hard, compact, light-gray rock in which holes are infrequent. Stylolites are frequent in the bedding planes of this part of the quarry wall	1	1	7	7
5.	Lithology of layer similar to overlying one...	1	1	6	6
4.	Similar, but with a more conspicuous bedding plane at the base........................	1	3	5	5
3.	Massive gray layer near bottom of quarry, which has pretty compact structure, but is not so hard as the three layers which immediately				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	overlie it. It contains some calcite crystals and a Brachiopod shell similar to a small *Pentamerus*	1	10	4	2
2.	Layer similar in lithologic characters to the superjacent one		6½	2	4
1.	*Mottled zone.*—Massive layer of drab color, mottled with light-gray spots and blotches. Compact rock and harder than layers above. This was the lowest exposed layer near the northern end at the time the quarry was studied in July, 1914	1	9	1	9

The Springfield dolomite in this quarry is believed to comprise the zones numbered 2 to 10, inclusive, which have a total thickness of 13 feet 7½ inches. The same formation in the Jackson quarry is 13 feet 3 inches thick, which shows a close agreement in these two sections, since there is a difference of but 4½ inches in the thickness of the Springfield formation in the two quarries.

Section near Lewisburg.—About 20 miles southwest of Covington is the large quarry of the Lewisburg Stone Co., which is rather more than a mile northwest of the station at Lewisburg, Preble County, and located on the southern bank of Twin Creek. This quarry and the bank of Twin Creek below the crusher furnish an important section, since almost the complete series of rocks from the upper part of the Brassfield limestone into the lower part of the Cedarville dolomite are admirably shown. The western wall of the quarry extends higher stratigraphically than the southern wall, but with the exception of the extreme top of the section it was the southern wall of the quarry toward the western end that was measured.

Section at the Lewisburg Stone Co. Quarry

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
20.	*Cedarville dolomite.*—Light-gray, weathering to a dark-gray, porous rock with the lithologic appearance of typical Cedarville. At the time the quarry was studied, on account of the shattered condition of the wall, due to extensive blasting, it was difficult to decide where the line				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	between the Cedarville and Springfield dolomites ought to be drawn. This zone appears certainly to belong in the Cedarville and possibly it may be the base....................	4	7	53	11
19.	Zone on southern wall with abundant specimens of *Pentamerus oblongus* Sowerby; but on the western wall the fossils are not common......		3	49	4
18.	Rather compact, light-gray rock containing abundant crinoid stems and an occasional specimen of *Pentamerus oblongus* Sowerby. Some chert in more or less definite layers. On the western wall a zone corresponding to this and including the superjacent 3 inches is rather clearly marked. It contains chert in layers and has a thickness of 4 feet 10 inches...........	3	3	49	1
17.	"First cap rock" of the quarrymen. Gray and very porous rock, the cavities to a large extent apparently due to the solution of fossils. This zone has the lithologic appearance of the Cedarville dolomite, and it is not improbable that it belongs in that formation. According to Mr. E. T. Paul, manager of the Lewisburg Stone Co., the thickness of this zone is variable and "runs from 2 feet up to about 5 feet; the average, however, being about $3\frac{1}{2}$ feet."......	3	6	45	10
16.	*Springfield dolomite.*—The four following layers are composed of light-gray to perhaps buff-colored rock, which has rather compact texture. It is now used for cut stone............. Feet Inches 2 2 1 4 8 1 5	5	7	42	4
15.	Buff, massive zone which splits into 2 or 3 layers and contains *Calymmene niagarensis* Hall. This zone and the superjacent 4 layers are called "buff rock" by the quarrymen........	3	0	36	9
14.	*Mottled zone.*—"Second cap rock" of the quarrymen. Light-gray, porous rock with dark-gray spots and blotches. It contains crinoid segments and fragments of other fossils. The lithologic appearance of the zone is very similar to that of the mottled zone in the Jackson and Maxwell quarries and the interval between the				

No.				Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	base of the mottled zone and the top of the Osgood shale is about the same in all three sections			4	1	33	9
13.	*Laurel limestone.*—The following courses all have a bluish-gray color when seen on fresh surface:		Inches	6±	0	29	8
	Light-gray, compact course		6–7				
	Light-gray, compact course		4–5				
	Light-gray course, the upper part blotched with dark-gray spots, but not many in lower part		8				
	Shaly limestone parting		$\frac{1}{4}$–1				
	Light-gray, compact layer		8				
	Light-gray course, with dark-gray spots and bands which tend to split into 2 layers		8				
	Light-gray layer		9–9$\frac{1}{2}$				
	Very mottled light- and dark-gray, thin layer		3$\frac{1}{2}$				
	Light-gray layer		10				
	Similar to above layer with a broken parting at base		8				
	Bluish-gray layer with dark-gray streaks and spots		6				
	The total thickness of the above layers varies from 5 feet 10$\frac{3}{4}$ inches to 6 feet 2 inches.						
12.	The three following layers are of light-gray color with dark-gray spots, blotches, and streaks and have about the same lithologic appearance:	Feet	Inches	4	2	23	8
	First layer	1	3				
	Second layer		10				
	Compact, massive layer containing calcite crystals	2	1				
11.	*Osgood beds.*—Bluish-gray, soft shale which forms the floor of the quarry. Six inches or more are shown in the quarry. Mr. Robert Mollett, foreman of the quarry, stated that at the time of the March flood of 1913 the shale was shown by the side of the railroad track						

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	below the crusher and varies in thickness from 2 feet 6 inches to 3 feet	2	9 ±	19	6
	Dayton limestone.—Mr. Mollett stated that the upper surface is somewhat uneven and that the limestone extends about 1 foot higher than the top of the exposed ledge on the south bank of Twin Creek below the Lewisburg Stone Co. crusher.				
10.	Upper foot, according to Mr. Mollett, not exposed	1 ±	0	16	9
9.	Light-gray layer, very rusty colored from weathered iron pyrite. Varies in thickness from 1 to 2½ inches		1¾ ±	15	9+
8.	Mostly light-gray, thin-bedded to shaly, limestone	1	0	15	7½
7.	Thin layer of more or less crystalline structure, which contains fossils		2 ±	14	7½
6.	Bluish-gray, thin-bedded layers, weathering to a very light-gray or whitish color. Rarely thin, somewhat irregular, finely crystalline layers in which is an occasional fossil	2	4	14	5½
5.	This zone will split into 3 layers. The upper one contains much pyrite and has weathered in spots to a very rusty color. The middle and lower parts of light-gray color with spots and irregular layers of dark-gray color from iron pyrite		10	12	1½
4.	Light-gray to bluish-gray, rather thin-bedded layers on bank of creek, with slightly glistening surface. Upper part of zone contains imperfect Brachiopods	2	4	11	3½
3.	Light-gray, compact layer which is harder than rock above. Base at creek level on September 5, 1914		7	8	11½
2.	Two thin layers of compact, bluish-gray rock, the upper one 2 inches and the lower one 2½ inches thick		4½	8	4½
1.	*Brassfield limestone.*—The upper surface rough. Mottled pink and gray crystalline limestone in bed of creek, just below the bank of Dayton limestone. In the bed of the creek 13 inches				

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
	of Brassfield limestone was measured; but it extends on down the creek and a quarryman stated that about 8 feet is shown along the creek	8±	0	8	0

A view of the southern wall of the Lewisburg Stone Co. quarry is shown in Fig. 2. The lower part of the wall is the Laurel even-bedded limestone, the top of which Mr. Cottingham is indicating by the hammer, above which is the conspicuous "mottled zone," and above this zone is the Springfield dolomite.

In the foregoing section the Laurel limestone is called the "blue building stone" by the quarrymen and comprises Zones 12 and 13 with a thickness of about 10 feet 2 inches. A section at a different part of the southern quarry wall gave a thickness of 9 feet 10 inches. It is well shown in the picture of the southern wall of this quarry (Fig. 2) where Mr. Cottingham is marking its top with the hammer. Samples of the Laurel limestone from the southern wall of this quarry were analyzed by Professor Demorest with the following result:

Silicious Residue	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
8.85	1.20	56.00	32.21

The massive "mottled zone," with a thickness of 4 feet 1 inch, immediately above the Laurel limestone, is also well shown in Fig. 2. Samples from this zone in the southern wall of the quarry were also analyzed by Professor Demorest with the following result:

Silicious Residue	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
2.54	0.75	54.12	42.13
2.55	0.80	54.12	42.31

The following analysis by Professor Demorest of samples of the West Union limestone from Sproull Ravine, about 1½ miles northeast of Duncanville and 7½ miles northeast of West Union, Adams County, is given for comparison with that of the "mottled zone:"

SiO_2	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
20.24	4.05	44.67	29.14

It will be seen from these analyses that the West Union is a much more silicious rock than the "mottled zone" and that the latter is a dolomite. It is to be noted that the chemical composition and lithologic character of the "mottled zone" differ considerably from those of the West Union limestone in its typical region.

The rock between the first and second cap rocks of the quarrymen is called by them the "buff building stone" and corresponds to Zones 15 and 16 of the last-given section, all of which evidently belongs in the Springfield dolomite.

All the rock above the shale zone (No. 11) of the Osgood beds is quarried and crushed for concrete and road material. The fine rock, which the men call "sand," binds well on the roads, and it was stated that the entire product of the quarry for 1914 was used on the Ohio roads by the State Highway Commissioner.

Dr. Foerste some years ago published a brief description of the Weaver quarries, located on the northern side of Twin Creek, opposite the eastern part of the Lewisburg Stone Co. quarry.[1] Recently Professor Bownocker has published a section of the Lewisburg quarry in which the upper limestone of the Osgood beds with a thickness of 9 feet 11 inches corresponds to the Laurel limestone of the last-given section.[2] The 3 feet of blue clay beneath is the Osgood shale and the subjacent 10 feet of "blue-gray limestone" the Dayton. The "West Union limestone," 4½ feet thick,[3] corresponds to the "mottled zone" of the last-given section, overlying which is the Springfield with a thickness of 8 feet and then the Cedarville which forms the highest part of the quarry. Apparently the line of division between the Springfield and Cedarville dolomites

[1] *Journal of the Cincinnati Society of Natural History*, XVIII (1896), 183, 184.

[2] *Geological Survey of Ohio, 4th Ser., Bull. 18* (1915), p. 40.

[3] *Ibid.*, p. 39.

FIG. 2.—Southern wall of the Lewisburg Stone Co. quarry, one mile northwest of Lewisburg, Ohio. The lower part is the Laurel limestone, the top of which is marked by the hammer. Above the Laurel limestone is the conspicuous "mottled zone," overlying which is the Springfield dolomite.

is drawn at the same horizon as the top of Zone 16 in the writer's section, which gives a thickness of 8 feet 7 inches for the Springfield or 8 feet as measured by Professor Bownocker.

SECTION NEAR LAUREL, INDIANA

In the foregoing sections the correlation of the terranes referred to the Osgood beds and the Laurel limestone, both of which were named by Dr. Foerste,[1] was decided upon after visiting Laurel, Indiana, and studying some of his sections in that typical region. A section at one of these localities, in a somewhat condensed form, is given below. The section is on the bank of a stream at a locality known as Derbyshire Falls, on the C. J. Valkenburg farm, nearly 3 miles southwest of Laurel and some 47 miles southwest of the Lewisburg Stone Co. quarry. A section of the Laurel limestone, Osgood beds, and Clinton limestone measured at this locality and the Lower Derbyshire Falls was published by Dr. Foerste in 1898.[2] The measurements in the following section are those of the writer and his assistant, Mr. Kenneth Cottingham; but the classification is in accordance with that of Dr. Foerste, except where differences are noted:

DERBYSHIRE FALLS SECTION

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
18.	*Laurel limestone.*—This limestone is shown in the old quarry just across the quarry road to the south of Derbyshire Falls and this zone extends to the top of the quarry wall. It is light gray, as weathered, rather thin-bedded, the layers varying from 2 to 8 inches in thickness. There are also at least 3 chert layers ranging from 1 to 3 inches in thickness.......	4	7	52	0

[1] Osgood beds: *Indiana Department of Geology and Natural Resources, 21st Annual Report* (1897), pp. 217, 227–29.

Laurel limestone: *Journal of the Cincinnati Society of Natural History,* XVIII (February, 1896), pp. 190, 191, and *Indiana Department of Geology and Natural Resources, 21st Annual Report* (1897), pp. 217, 230, 231.

[2] *Indiana Department of Geology and Natural Resources, 22d Annual Report* (1898), pp. 244, 245. An illustration of Derbyshire Falls is given on Pl. XVI, which faces p. 244.

No.		Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
17.	Thicker layers of compact limestone, light gray to buff, when weathered, with shaly partings. The majority of the layers are perhaps 3 to 5 inches in thickness; but there are thicker ones which apparently range from 8 to 14 inches. No chert was noticed in this zone...........	5	3	47	5
16.	*?Top of Osgood beds.*—Buff, compact, 8-inch layer at top of ledge on south side of falls, which is apparently the one across the quarry road in the base of the old quarry at the spring. The top of this layer is apparently the horizon where Dr. Foerste has drawn the line of separation between the Osgood beds and Laurel limestone. Lithologic characters, however, in the vicinity of Laurel would apparently favor classing it with the Laurel limestone..................		8	42	2
15.	Blue, argillaceous, soft shale or clay. This is the blue-clay stratum of Dr. Foerste..........	1	6	41	6
14.	Shaly, light-gray limestone................		4	40	0
13.	Light-gray, compact, even-bedded limestone; some of the bedding planes rather rough. The layers vary in thickness from 5 to 9 inches, and perhaps the majority of them average about 8 inches. This is the Lower Quarry or Osgood rock of Dr. Foerste, and is apparently the continuation of the Dayton limestone in Indiana	6	4	39	8
12.	*Brassfield limestone.*—Light-gray, crystalline limestone. Apparently the upper foot and 3 inches of this zone was regarded by Dr. Foerste as a "doubtful horizon: White Clinton or base of Niagara rock".........................	2	3	33	4
11.	Crystalline gray to pinkish limestone. It is very irregularly bedded and contains pyrite, so that it is frequently rusty colored on the weathered surface. Dr. Foerste's section reports "Clinton; 7 feet 6 inches; reddish"....	6	7	31	1
10.	*Richmond formation.*—Light-gray, impure limestone with portions that are darker colored...	1	6	24	6
9.	Gray, impure limestone, the upper layer a foot thick separated by a shaly parting from a lower layer of similar limestone, 1 foot 3 inches thick	2	3	23	0

No.	Thickness Feet	Thickness Inches	Total Thickness Feet	Total Thickness Inches
8. One layer of gray, massive, impure limestone. No fossils seen	4	0	20	9
7. Layer similar to one above	2	2	16	9
6. Massive, light-gray layer with dark-gray spots. No fossils noted	3	0	14	7
5. Shale parting		1	11	7
4. Grayish, somewhat crystalline, limestone which tends to split into thinner layers		9	11	6
3. Bluish shales alternating with gray, fossiliferous limestone	2	3	10	9
2. Grayish, somewhat crystalline, limestone, hard and very fossiliferous	5	4	8	6
1. Grayish to bluish shales which are not very fossiliferous. Foot of falls	3	2	3	2

In the foregoing section Zones 11 and 12, with a thickness of 8 feet 10 inches, have been classed together and considered the western continuation of the Brassfield limestone of Ohio. Zones 13 and 14 of light-gray limestone with a thickness of 6 feet 8 inches are considered the western continuation of the Dayton limestone of Ohio. Dr. Foerste has stated that "in Ohio *Pentamerus oblongus* occurs in the Dayton limestone, equivalent to the base of the Osgood bed."[1] The soft blue shale or clay of Zone 15 is believed to correspond to the blue shale of Zone 11 in the Lewisburg Stone Co. quarry and the shale at the same horizon in the various quarries along the Stillwater River. As stated above in the description of the section, the lithologic break occurs at the top of this shale, which appears to the writer from the sections which he has studied to be the horizon where he would draw the line of division between the Osgood beds and Laurel limestone. If the 8-inch layer of compact, buff limestone (No. 16) immediately above the soft blue shale zone be classed with the Laurel limestone, then 10½ feet of it are shown in the wall of the old quarry on the bank above and south of the falls. It is believed to be the eastern continuation of this limestone which makes Zones 12 and 13 with a thickness of 10 feet 2 inches in the Lewisburg Stone Co. quarry and the

[1] *American Journal of Science, 4th Ser.*, XVIII (1904), 341.

limestone which has been called the Laurel in the sections farther east along the Stillwater River.

Samples of the Laurel limestone were collected at the quarry above Derbyshire Falls and analyzed by Professor Demorest with the following result:

SiO_2	Fe_2O_3 and Al_2O_3	$CaCO_3$	$MgCO_3$
17.84	1.00	47.89	31.54

This analysis shows that the Laurel limestone at Derbyshire Falls is a more silicious one than that at the Lewisburg Stone Co. quarry, which contains but 8.85 of silicious residue. On the other hand, the Lewisburg stone contains a larger percentage of $CaCO_3$, where it amounts to 56 per cent of the rock; the other constituents at the two localities do not differ to any marked degree.

ORIGIN OF THE LYMAN SCHISTS OF NEW HAMPSHIRE

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INTRODUCTION

During the summers of 1911 and 1912, through the generosity of Mr. R. W. Sayles, I made a geological investigation of part of the townships of Littleton, Lisbon, Lyman, Bethlehem, Bath, and Landaff, in New Hampshire. In the fifteen weeks devoted to this work about 250 square miles were examined. The results that have been published[1] have reference to an area of only eight or nine square miles (Fig. 1), in the study of which three of the fifteen

[1] F. H. Lahee, "Geology of the New Fossiliferous Horizon and the Underlying Rocks, in Littleton, New Hampshire," *Am. Jour. Sci.* (4), XXXVI (1913), 231–50.

weeks were consumed. The survey of the rest of the area amounted to a reconnaissance of intricately metamorphosed schists, regarding which final conclusions were deferred until more could be learned. Having had opportunity to revisit some parts of the field where the "Lyman schists" are exposed and having examined a suite of thin sections of these schists, I submit the present paper as a second chapter on the geology of the "Ammonoosuc District."

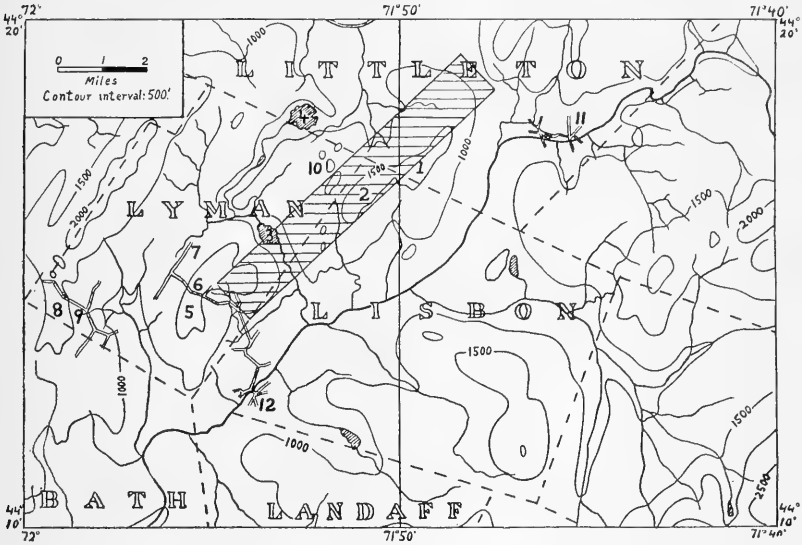

FIG. 1.—Index map of the localities mentioned in the text. The shaded rectangular area is the strip of country described in the article on the Littleton fossiliferous horizon. 1, Blueberry Mountain. 2, Bald Hill. 3, Young's Pond. 4, Partridge Lake. 5, Parker Hill. 6, the "Parker Hill locality." 7, Lyman village. 8, Black Mountain. 9, the "Black Mountain locality." 10, Mormon Hill. 11, Littleton. 12, Lisbon. Only a few roads are drawn.

I am happy to express my gratitude to Mr. W. L. Whitehead, a candidate for the doctorate of science in geology at the Institute, for making the accompanying microphotographs, and to Mr. Sayles for the use of Figs. 2 and 15.

SUMMARY

1. The term "Lyman schists" was applied by Hitchcock to a group of schists many of which are characteristically whitish on their weathered surfaces.

2. These Lyman schists are broadly exposed in the area northwest of the Blueberry Mountain–Bald Hill range and its southwestward extension.

3. Hitherto the Lyman series has been regarded as a group of metamorphosed sedimentary rocks.

4. Field evidence, megascopic examination of hand specimens, and microscopic examination of thin sections indicate that the Lyman series contains interbedded members which appear to be of volcanic origin.

5. These metamorphosed volcanic rocks include, among others, species related to the quartz keratophyres and the keratophyres, and probably also tuffs and agglomerates of similar composition.

6. It seems more reasonable to attribute the origin of the coarse conglomerate schist near Young's Pond, Lyman, to vulcanism than to glaciation.

7. The association of acidic effusives with the Paleozoic rocks east of the main Appalachian protaxis is not exceptional for New Hampshire. Such effusives are found in Maine, in the Maritime Provinces of Canada, and in the Piedmont Plateau of our middle and southern Atlantic border states.

THE LISBON AND LYMAN SERIES

On the northwestern side of the Blueberry Mountain formation[1] are highly metamorphosed greenish and whitish schists which outcrop over many square miles. The greenish varieties are often chloritic. They and certain other associated rocks were called by Hitchcock the "Lisbon group." The whitish schists belong to his "Lyman group." In his earlier reports he relegated these two formations to the Huronian,[2] the Lyman group being considered the younger member; but subsequently he referred them to the Cambrian or to the Ordovician,[3] and concluded that "the Lyman schists . . . . do not represent a stratigraphical terrane"; the term "is a petrographical designation."[4]

[1] F. H. Lahee, *op. cit.*

[2] C. H. Hitchcock, *Geology of New Hampshire* (1877), II, 277.

[3] *Ibid.; Geology of Littleton, New Hampshire*, reprint from the *History of Littleton* (1905), pp. 11, 29.

[4] *Ibid.*, p. 31.

GENERAL DISTRIBUTION OF THE LYMAN SERIES

No attempt will be made here to mark out the exact distribution of this series. It is exposed over broad areas west of the Blueberry Mountain Siluro-Devonian belt and it may be related to schists on the east of this belt. The principal localities (Fig. 1) to which reference will be made in the sequel are Mormon Hill, the valley just northwest of Young's Pond, and Parker Hill. Lyman schists are also exposed on the hill southwest of Young's Pond, on the lower eastern slope of Black Mountain, near Partridge Lake, and elsewhere in the broad valley between Gardner Mountain and the Mormon Hill–Parker Hill range. In all these places the group has a breadth of outcrop of several hundred feet, the rocks are schistose, the strikes are roughly northeast-southwest, and the cleavage and the bedding (where visible) have steep dips.

FIELD RELATIONS AND MEGASCOPIC DESCRIPTIONS OF THE LYMAN SERIES

The Young's Pond locality.—Near a small schoolhouse about one-third of a mile northwest of Young's Pond is a large outcrop of a conglomeratic schist which we used to speak of as the "schoolhouse conglomerate" (Fig. 2). It is the rock which Mr. Sayles has recently described as possibly being a tillite.[1] This conglomerate schist appears to rest unconformably upon a whitish or light-grayish porphyritic sericite schist. The contact, which is very irregular, runs northeast-southwest and may be seen not only near the schoolhouse, but also, a few hundred feet southwest, near the brook that flows into Young's Pond. The conglomerate schist is on the northwest, the porphyry schist on the southeast, of this contact. The conglomerate schist is between 300 and 400 feet wide across the strike, and the porphyry schist is between 150 and 250 feet wide. This statement should not be understood to imply that these rocks have no variation across their outcrop belts. There is evidence that the porphyry is interrupted at least at one horizon by a bed of fine conglomerate schist.

West of the "schoolhouse conglomerate" is a series of whitish rocks including fine, non-porphyritic schists, fine porphyritic

[1] R. W. Sayles, "Tillite in New Hampshire," *Science*, N.S., XLI (1915), 220.

schists, fine conglomerate schists in which the pebbles and paste are of similar whitish materials and the pebbles are much sheared, and schists of the texture of medium sandstones. The last-mentioned material and some of the finer conglomerate schists looked so much like altered pyroclastics that they were called tuffs in the field. (See description of the Parker Hill white schist, below.) All these rocks are exposed more than once across the strike.

The porphyry schist that underlies the "schoolhouse conglomerate" has an exceedingly fine groundmass, which is sericitic and in places rich in chlorite. The phenocrysts, ranging up to nearly $\frac{1}{2}$ inch in diameter, but averaging $\frac{1}{8}$–$\frac{3}{16}$ inch, are of quartz and plagioclase. They are uniformly distributed and constitute about half of the rock. The quartz has a very high luster, is somewhat bluish and very transparent, and has tendency to break with a rude cleavage. The plagioclase is so fresh that the striations are distinct and the fracture surfaces are brightly reflecting. The shearing of the rock seems to have been localized in the groundmass. Within its own mass this schist has no bedding.

FIG. 2.—Lyman ("schoolhouse") conglomerate, showing obscure outlines of pebbles. The dark masses, edged with black enamel, are of the fine drab schist. Photograph by Mr. Sayles.

The conglomerate schist ("schoolhouse conglomerate"), also, is quite devoid of bedding. It contains many large and small fragments of the porphyry schist, together with pieces of other whitish rocks of the Lyman series, and masses of rust-brown, smooth-looking schist, which are conspicuously darker than the Lyman varieties. All the pebbles have been more or less sheared and in such a way that their longest axes are parallel with the dip of the cleavage. Some seem to have been roundish, but more often they were obviously angular. Naturally the shearing has increased the irregularity of their shapes.

The quartz-plagioclase porphyry pebbles have been deformed less than the other varieties. Their average dimensions may be expressed by the ratio 2:1.25:1. They range up to two feet in length.

The dark fragments, mentioned above, are often drab-colored on the weathered surface, but dark-greenish when fresh. As will be explained presently, they are chlorite and actinolite schists. They are of medium fine grain and of uniform texture, they are markedly sheared, and their shape is very irregular, even jagged. Some were found to be 10 or 12 feet long and only 1 or 2 feet wide. Others are less elongate (Fig. 2).

As compared with the pebbles, the paste of this conglomerate schist is in relatively small amount. Nor does it seem to have been derived from an argillitic substance. It looks rather as if it had been fine clastic débris, of texture ranging from fine sandstone to fine conglomerate, derived from the same sources whence came the larger pebbles. Its appearance is that of metamorphosed tufaceous material. Partly on account of the metamorphism and partly because of similarity of character, the paste is not sharply defined from the pebbles. On fresh surfaces of the rock the pebbles are distinguished with difficulty, and even on weathered exposures, where the psephitic structure is best brought out, the details are blurred.

The Mormon Hill locality.—On a traverse across the strikes on Mormon Hill, one passes over a series of schists much like those near Young's Pond. They are porphyries, tuff-like clastic rocks, and fine and coarse psephites, all sheared. They dip steeply northwest. In one place obscure cross-bedding indicated that the stratigraphic sequence was younger westward; and in another locality the same fact was shown by an unconformable contact between tuff-like schist on the southeast and conglomerate schist on the northwest. The series was roughly measured as having a breadth of outcrop of 800 feet.

The porphyry schist of this region differs from that near Young's Pond in lacking quartz phenocrysts. Its phenocrysts are all of plagioclase. Otherwise, in respect to size, abundance, and arrangement of phenocrysts and characters of the groundmass, it is megascopically like the type above described.

The coarse psephitic rocks here contain fragments of whitish and drab schists, as at Young's Pond.

FIG. 3.—Rounded plagioclase phenocryst surrounded by groundmass. Enlarged 16 diameters. The large white areas are due to imperfections on the negative.

The Parker Hill locality.—Porphyry schists, tuff-like schists, and psephite schists are here exposed in a belt several hundred feet wide. The porphyry schists are finer than the Young's Pond type. Along the road that crosses Parker Hill between Lisbon and Lyman villages exposures near the top of the hill exhibit curious relations. A dark-gray schist (called hereafter the Parker Hill dark schist) is associated with a whitish rock of the Lyman series. The latter, which will be called the Parker Hill white schist, in several outcrops, constitutes a matrix in which are scattered large and small irregular blocks and strips of the dark schist, many being greatly contorted. The phenomenon resembles intraformational pebbles in clastic material. The white schist is of the texture of a medium sandstone. Quartz and feldspar are both abundant and the interstices between the larger grains are filled with finer particles of quartz and feldspar, together with secondary mica. The dark schist is phyllitic. Some specimens of it have minute phenocrysts in a still finer groundmass.

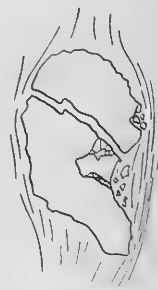

FIG. 4.—Broken quartz phenocryst. The curving lines indicate the arrangement of mica laths. Enlarged 16 diameters.

MICROSCOPIC DESCRIPTIONS

Porphyry schist of the Young's Pond locality.—Thin sections of the porphyry schist from near the schoolhouse northwest of Young's Pond show a nearly uniform groundmass. The diameters of the smaller phenocrysts are thirty or forty times those of the larger groundmass grains and there is no gradation between the two (Fig. 3).

Clear, but with a few vacuoles, the quartz phenocrysts display only slight crushing, and this is mostly peripheral (Figs. 4–7). Their corners have been rounded. Several individuals are invaded by long narrow bays of the groundmass (Figs. 5 and 8). It is worth while noting that, although the outer borders of these phenocrysts are jagged on account of granulation and penetration by mica laths, the edges of the embayments are clean-cut and smoothly curving.

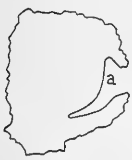

FIG. 5

FIG. 6

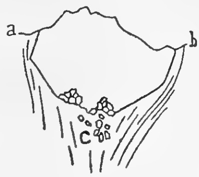

FIG. 7

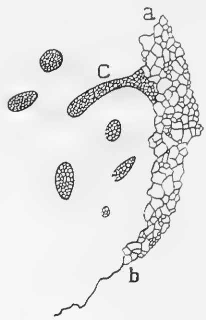

FIG. 8

FIG. 5.—Quartz phenocryst with edges serrate on account of marginal granulation and penetration by mica laths. Note smooth outline of the embayment (*a*). Enlarged 26 diameters.

FIG. 6.—Detail of outer edge of the quartz phenocryst represented in Fig. 5. The shaded area is quartz (*Q*). The small laths are mica (*M*).

FIG. 7.—Quartz phenocryst showing terminal granulation at pole of minimum compression (*c*). *a–b* is the edge of the thin section. Enlarged 20 diameters.

FIG. 8.—Part of a large quartz phenocryst. The border zone, *a–b*, is a granulated portion of the phenocryst. Outside this zone is the much finer, uniform groundmass (not figured). Several embayments of the groundmass are shown, one cut longitudinally (*c*), and the others intersected transversely at various angles. Note regular outlines of these embayments as compared with the jagged border of the grain as a whole. The figure is drawn from a microphotograph, but not with absolute precision in the finer details. Enlarged 16 diameters.

Like the quartz, the plagioclase phenocrysts are not severely crushed (Fig. 9). The angle of extinction on sections approximately perpendicular to the albite twinning varied between 13° and 17°. This and the fact that the index of refraction was always lower than that of balsam indicate that the mineral is albite. Some grains have very good crystal outlines (Fig. 10), but as a rule they have had their corners more or less rounded (Fig. 3).

As for the groundmass, it consists of abundant quartz and chlorite, with some sericite and feldspar. It is so fine that microscopic discrimination between quartz and feldspar is almost impossible. Both chlorite and sericite show some tendency to parallel arrangement. The chlorite is likely to occur in larger flakes in the lee of the phenocrysts and in the quartz embayments—in other words, where there was some protection from the shearing stress, such as it was. Neither quartz nor feldspar phenocrysts contain scattered inclusions of the groundmass.

FIG. 9.—A plagioclase phenocryst showing the bundles of sericite laths that wrap round it at the poles of maximum compression. Enlarged 11 diameters.

The porphyry from the channel of the brook running into Young's Pond is somewhat more sheared than that from the schoolhouse ledge. The quartz and feldspar phenocrysts are more strained and granulated, and in some places the broken fragments are separated by a strip having cataclastic structure (Fig. 11). Sericite is more abundant and has better orientation. It is often thickly plastered against the phenocrysts about which it wraps at the poles of maximum compression (Fig. 9). In other respects this schist is similar to the less metamorphosed specimens.

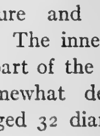

FIG. 10.—Plagioclase phenocryst with zonal structure and crystal form. The inner, stippled part of the crystal is somewhat decayed. Enlarged 32 diameters.

Pebbles of the conglomerate schist of the Young's Pond locality.—Pebbles of the porphyry schist are identical with the bedrock of the same. They need no further description here.

The dark masses which have been mentioned as greenish when fresh, but drab when weathered, are of peculiar interest, since they have been regarded as highly metamorphosed blocks of argillite. They have been compared with the slate blocks in the Squantum tillite.[1] Thin sections were prepared from several fragments

[1] R. W. Sayles, *op. cit.*

taken from different outcrops of the "schoolhouse conglomerate." Microscopic examination revealed two distinct varieties. One is composed largely of zoisite and bundles of parallel actinolite needles, with some chlorite and titanite and a little plagioclase. The other is rich in chlorite, plagioclase, and zoisite, and contains titanite and a little epidote and sericite. This schist is finely porphyritic, the phenocrysts being of plagioclase (Fig. 12). Many have been bent, sliced, or granulated by the shearing. The white mica is fairly well oriented and, together with the other minerals, is inclosed in an irregular background or network of chlorite. There are some chlorite aggregates which look as if they had formed from a mineral that was once present as phenocrysts. No quartz is recognizable in either rock.

FIG. 11.—"Torn" plagioclase phenocryst. The large dark area in the middle of the photograph is about one-third of the entire crystal, the other two-thirds being below the picture. The irregular lower edge is the "torn" end. Enlarged 20 diameters.

With reference to the origin of these rocks, it would seem as if their source was most probably igneous. Some of them might have been derived from sedimentary products of incomplete decomposition, but they can hardly have come from normal argillitic material.

FIG. 12.—Section of a pebble of fine porphyry schist from the "schoolhouse conglomerate" at the Black Mountain locality. Enlarged 16 diameters.

Parker Hill white schist.—The whitish schist that contains the dark phyllitic fragments is composed principally of quartz and orthoclase in nearly equal proportions, somewhat less plagioclase, and some chlorite and sericite. The particles of quartz and feldspar have every gradation in size from the largest to the smallest (Fig. 13). There is relatively little matrix, the larger grains being so numerous that they nearly, if they do not quite, touch one another. Many of the grains are angular; none is conspicuously rounded, and they do not seem to have been rounded before metamorphism. Of the two minerals, sericite and chlorite, the latter is most plentiful. The chlorite is least likely

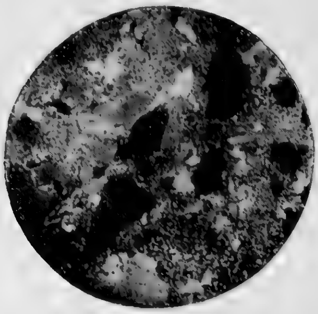

FIG. 13.—Section of a typical psammitic member of the Lyman series. Enlarged 12 diameters.

FIG. 14.—Section of a porphyritic pebble of the "Parker Hill dark schist." Enlarged 15 diameters.

to have parallel orientation. Another specimen from farther northeast near this horizon exhibited similar characters in thin section.

Parker Hill dark schist.—The specimen from which the section was cut was obtained northeast of Parker Hill along the strike of the rock exposed in the Lisbon-Lyman road, and it is thought to belong to the same horizon. The phyllite is a small angular fragment in a whitish clastic matrix of the kind just described. It is porphyritic (Fig. 14), having small phenocrysts (0.13–1.0 mm.) of plagioclase, often with well-preserved crystal form, distributed in a very fine groundmass of plagioclase and chlorite. The phenocrysts do not

FIG. 15.—Part of the "egg conglomerate" where the majority of the pebbles are angular and subangular. Photograph by R. W. Sayles.

contain inclusions of the groundmass. This rock is remarkably like a pebble taken from a conglomerate which Hitchcock[1] called the "egg conglomerate" (see Fig. 15), a pebble which would be called a felsitic rock without hesitation.

GENERAL CONCLUSIONS ON THE ORIGIN OF THE LYMAN SCHISTS

Among the characters described in the foregoing paragraphs many are of such a nature as to suggest that at least some members of the Lyman schist group are igneous rocks—probably volcanic—more or less modified by dynamic metamorphism. For the sake of clearness and emphasis, the significant facts which lead to this conclusion are reviewed below in summary form for three typical rocks.

Porphyry schist of the Young's Pond locality.—The quartz-plagioclase porphyry schist which has been described from the Young's Pond locality is assumed to have been an effusive rock for the following reasons:

1. It has a strong resemblance to the quartz porphyry type of igneous rock.
2. It is massive, without bedding.
3. Locally it has faint indications of flow structure.
4. The phenocrysts are rather uniformly distributed through the groundmass.
5. The quartz phenocrysts have high luster and high transparency, a faint bluish opalescence, and a tendency toward cleavage, all these being features not uncommon in true quartz porphyries.
6. Some of the feldspar phenocrysts have crystal form.
7. There is a great difference between the size of the smaller phenocrysts and that of the larger groundmass particles.
8. Many quartz phenocrysts and some feldspar phenocrysts contain embayments of the groundmass, these embayments having

[1] C. H. Hitchcock, *Geology of New Hampshire* (1877), II, 333. This "egg conglomerate" is exposed on the northwest slope of Blueberry Mountain and may grade laterally into the Fitch Hill arkose. Most of its pebbles are of quartz porphyry, quartz keratophyre, granophyre, devitrified rhyolite, and other felsitic types. The great preponderance of effusive rocks among the pebbles is to be noted for comparison with the Lyman series.

regular curving edges evidently due to magmatic corrosion and not to subsequent localized granulation or recrystallization.

9. Some feldspar phenocrysts have zonal structure parallel to the outlines of the corrosion inserts of the groundmass (Fig. 10).

10. Both quartz and feldspar phenocrysts, and even those feldspar crystals which have zonal structure, are quite free from the type of inclusion of the groundmass which is so common in many metacrysts.

11. Although two or three feldspar crystals are sometimes attached as if they had grown so (Fig. 16), quartz and feldspar never occur thus together. If the materials of the schist were derived from the breaking up of a granitoid rock, small pebbles composed of both quartz and feldspar would be expected.

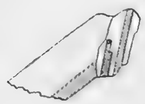

Fig. 16.—Two attached plagioclase individuals which occur as a phenocryst. Enlarged 7 diameters.

12. All, or nearly all, of the feldspar phenocrysts are albite. A clastic rock would be likely to contain several species of fragmental feldspar, for there are plenty of rocks in this region which have orthoclase, microcline, microperthite, micropegmatite, etc., among their constituents.

13. The abundance of albite in this rock suggests that the content of Na may be abnormally high for an argillitic sediment. However, I have not analyzed the rock chemically, and the Rosiwal method would be unsatisfactory on account of the difficulty of determining the particles of the groundmass.

14. The preponderance of easily recognized pebbles of felsitic rocks in the "egg conglomerate" proves that acidic effusive rocks may be expected in the region.

If, then, we grant that the quartz-plagioclase porphyry schist is effusive, its composition places it in the class of quartz keratophyres, and the similar quartzless rock of Mormon Hill belongs to the keratophyres.

Parker Hill white schist.—This is taken as representative of the "tuff-like schists" of the Lyman group. It is undoubtedly a metamorphosed clastic as is demonstrated by the following facts:

1. Megascopically and microscopically it has a distinctly fragmental aspect.

2. Locally it contains angular blocks and sometimes isolated pebbles.

3. It grades into the fine variety of Lyman conglomerate schist.

4. It has obscure bedding (layers differing in texture) in some places.

5. There are all gradations in size between its largest and smallest particles.

6. There is a relatively small proportion of small grains as compared with the porphyry schist.

This Parker Hill white schist certainly was never a normal clastic in the ordinary sense of the term. It might be called an arkose schist on account of its having abundant clastic feldspar. However, its more or less intimate association with effusive rocks, the presence in it of the constitutents of the porphyry schists, both as small particles (quartz and albite grains, etc.) and as larger fragments (some whitish like the Lyman schists and some dark like the Parker Hill dark schist), and the observed gradations between it and the fine Lyman conglomerate schist which is composed chiefly of sheared pebbles of felsitic nature—these facts induce me to classify the rock as a metamorphosed tuff.

Conglomerate schist of the Young's Pond locality.—There is no doubt that this "schoolhouse conglomerate" looks very much like a glacial deposit, as stated by Hitchcock[1] and recently by Sayles; but if the accepted criteria for till ever did exist here, they have been entirely destroyed by metamorphism. For this reason it is futile to look for signs of glacial abrasion on an underlying rock pavement. The weakness of the evidence for glacial origin was fully appreciated by Mr. Sayles, and I may add that evidence against such glacial origin is almost, if not quite, as inconclusive. However, one should bear in mind that great variation in size of constituent fragments and absence of bedding are characters shared by talus, landslide débris, pyroclastic materials, and not infrequently even by river-laid alluvial cone deposits. Is it not more probable that the "schoolhouse conglomerate," being closely associated with an effusive rock (quartz-plagioclase porphyry schist),

[1] C. H. Hitchcock, "New Studies in the Ammonoosuc District of New Hampshire," *Bull. Geol. Soc. Am.*, XV (1904), 472, and *Geology of New Hampshire* (1877), II, 302.

having a large proportion of its pebbles and bowlders consisting of effusive rocks, and having a paste which resembles the Parker Hill white schist (cf. above), is a coarse pyroclastic, an agglomerate, rather than a tillite?

It is important to note that both Hitchcock and Hawes[1] maintained that rocks of the Lyman group were the outcome of the metamorphism of sediments. Neither of these geologists held the view that these schists were of volcanic origin, yet both were struck by the resemblance between some members of the series and ordinary felsite.

STRUCTURAL RELATIONS OF THE LYMAN SERIES

The structural relations, and therefore the age, of the Lyman schists still remain obscure. These rocks are surely not younger than Devonian, and they may be older, as has been stated by Hitchcock. In several places on the Parker Hill–Mormon Hill range stratigraphic structures point to an anticlinal axis eastward. If this is so, since the Blueberry Mountain–Bald Hill range is regarded as synclinal, the intervening valley is anticlinal. Again, if this is so, it becomes necessary to explain the lack of correlation between the Lyman schists on the western range and the marine argillites and sandstones of the eastern range. Unconformity or extensive faulting may be the cause. At present I do not feel justified in discussing this subject further. More time should be given to field investigation. The region offers ample opportunity for research in petrology and in structural geology.

ACIDIC EFFUSIVE ROCKS EAST OF THE APPALACHIAN PROTAXIS

South of the latitude of New York City the Appalachian Mountains are flanked on the east by the Piedmont Plateau. North of the same latitude, the New England Province corresponds to the Plateau. Both regions are underlain by plutonic rocks and folded, sheared, sedimentary rocks, chiefly of Paleozoic and pre-Cambrian age. With extended study of these complex rocks two results stand out conspicuously: an increasing number of meta-

[1] C. H. Hitchcock, *Bull. Geol. Soc. Am.*, XV (1904), 468, 469; and G. W. Hawes, "Mineralogy and Lithology of New Hampshire," p. 176, in Hitchcock's *Geology of New Hampshire*, III (1878).

morphosed rocks is being transferred from the pre-Cambrain to the Paleozoic, and the origin of the schists is found to be more diverse than was at first conceded. It is in line with these results that the variety and distribution of effusive rocks, both flows and pyroclastics, interbedded with the schistose Paleozoic sediments, are being expanded as investigation proceeds. In a paper written in 1894, G. H. Williams called attention to this fact.[1] He briefly described the following localities in eastern North America, where volcanic rocks were known at that time: Newfoundland, Nova Scotia, New Brunswick, that part of the province of Quebec lying west of Maine and north of Vermont and New Hampshire, Maine, Massachusetts, Pennsylvania, Maryland, Virginia, and the Carolinas. To this list it is probable that Rhode Island and New Hampshire may now be added. Williams mentioned New Hampshire in his text, but did not show any volcanic rocks in this state on his map. He observed that "in New Hampshire felsites and quartz-porphyries abound. They were regarded as eruptive by Hitchcock and by Hawes when they occur in dykes, although the latter regarded many of them, especially when interstratified, as sediments fused *in situ*."[2] This paper by Williams contains numerous references. A list of more recent articles on the subject is given by J. E. Pogue, Jr., in his "Geology and Structure of the Ancient Volcanic Rocks of Davidson County, North Carolina."[3]

[1] "Distribution of Ancient Volcanic Rocks along the Eastern Border of North America," *Jour. Geol.*, II (1894), 1–31.

[2] *Op. cit.*, p. 24.

[3] *Am. Jour. Sci.* (4), XXVIII (1909), 218–38.

NOTES ON THE DISINTEGRATION OF GRANITE IN EGYPT[1]

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INTRODUCTION

The disintegration of the granite in Egypt has been treated in a general way by Walther in his discussions of disintegration in desert regions. It has been commented on by Ball and others. The disintegration of the New York obelisk, composed of the Syene red granite, has been reported upon by Julien. The following notes were made by the writer in a recent trip to Egypt in which especial attention was paid to the disintegration manifested by the granite in the ancient quarries and ledges of the Aswan district and in the temples and monuments of Upper and Lower Egypt.

THREE PERIODS OF DISINTEGRATION IN THE ASWAN DISTRICT

The disintegration in the Aswan district seems to belong to two periods other than the present. The products of what seem to be the earliest period of disintegration are found at the contact of

[1] This paper is the result of work done as Sheldon Traveling Fellow, Harvard University.

coarse Syene red granite with the base of the overlying Nubian sandstone (Cretaceous) (Fig. 1). They form a zone of what Ball designates as "broken-down granite, a kaolinic mass with quartz grains." The zone is 1 to $1\frac{1}{2}$ m. in thickness, has a relatively sharp even contact with the overlying sandstone and conglomerate, but below grades through less and less disintegrated granite into comparatively unaltered rock. The upper part of the zone is composed of material that has suffered slight rearrangement, but the middle and lower portions consist of the untransported débris of disintegration. The feldspar of the upper portion is almost completely kaolinized. In the middle portion, the kaolinization

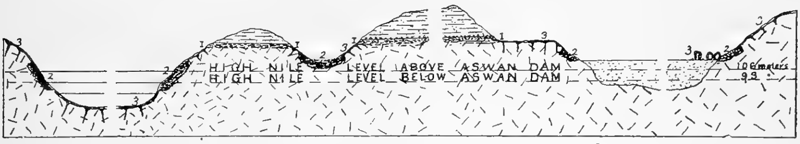

FIG. 1.—Diagrammatic section across the region of the Aswan Cataract. 1, Disintegrated and decomposed zone at the base of the Nubian Sandstone. 2, The massive granular disintegration. 3, Disintegration of the present.

is much less and in the lower portion it is not megascopically noticeable. Although the disintegration was seemingly not of the exfoliation type,[1] it nevertheless took place roughly parallel to the very level upper surface of the granite. The surface is so level as to suggest a peneplain surface. The disintegration would seem to have taken place contemporaneously with or immediately preceding the deposition of the Nubian sandstone, and the kaolinization may

[1] According to the present use of the term, it is possible to distinguish several types of disintegration. The term is applied in some cases to the breaking up of a rock-mass into blocks and in other cases to the breaking up of a rock-mass through the loss of cohesion between the constituent grains. The former process may be termed "block-disintegration" and the latter, "granular-disintegration." Allied to the block disintegration is what may be termed the "exfoliation" type of disintegration in which thin plates of rock rift off parallel to the surface of a ledge or block. The process seems to involve considerable loss of cohesion between the grains and readily goes over into granular disintegration. The term disintegration is also used in a loose sense to denote the chemical breaking up of the rock-mass. But as Merrill advises, it would seem better exclusively to use for that process the term "decomposition" and to reserve the term "disintegration" for the process of mechanical breaking up.

have taken place under the estuarine or marine conditions then prevailing or at some later time under the action of ground-water. The disintegration and decomposition penetrate cracks to the depths of 10 to 20 ft. and in one or two places may be seen to have taken place before the disintegration next to be mentioned.

The effects of the second period of disintegration are manifested in a tendency toward deep, granular disintegration massively affecting the coarse Syene red granite at a level which is approximately that of the Aswan Reservoir when full. This disintegration is best seen on the island of El Hesa, in some recently excavated graves at the site of the former village of Garba. The graves are cut back into hill slopes of various inclination and have a horizontal depth of about 3 meters on the average and a height of about $1\frac{1}{4}$ m. The roof at the back commonly has a thickness of 1 to 2 m. The greatest distance to which a grave was seen to extend horizontally backward from the surface of the hill slope was 4 m. The height of the grave was about $1\frac{1}{2}$ m. and the roof at the back was slightly over 2 m. in thickness. The graves are cut entirely in the disintegrated, or rather, partially disintegrated, granite and in no case were they seen to penetrate unaffected rock. The disintegration has therefore penetrated to a depth of at least 3 to 4 meters from the surface. The disintegration is of the granular type and, although affecting the rock uniformly, is not quite complete; blocks of the granite may be obtained which to the eye seem entirely sound but which crumble readily under the hammer. In the shallow sections that are afforded there is not any appreciable decrease of intensity of the disintegration with depth. The disintegration has been accompanied by slight but megascopically noticeable kaolinization and in its products resembles closely the partial granular disintegration which is found at a depth of about 4 m. in the Morvan and Plateau Central regions of Central France. This tendency toward massive granular disintegration is manifested also at several points along the old Nile Valley about 1 km. north-northeast of Shellal, at several points along the river trail from Shellal to the Aswan Dam, at several points immediately north of the village of Kuror along the river trail to Aswan, and about one-half mile northeast of Kuror in a small pass on the trail to Aswan. The disintegration in each of the cases is approximately at the elevation of that on El Hesa. It is a distinctly noticeable fact that in many of these cases, as for instance in the case of the grave on El Hesa cut 4 m. back into a northerly facing 40° slope lying at the foot of a cliff about 25 m. high, the disintegration has penetrated to a depth of at least 3 to 4 m. in spite of the fact that direct isolation is received only during the summer and then only at a low angle.

Disintegration taking place under the present conditions is abundantly shown by most of the exposed ledges and loose blocks of the region and is manifested in three ways: (1) Surfaces which have been exposed for a relatively short while show a slight roughening. Individual grains and fragments of feldspar and of quartz become loosened and are removed. (2) Surfaces which have been exposed for a longer time show in addition exfoliation of thin superficial layers commonly of about two-thirds of a centimeter in thickness. Cross-sections afforded by broken blocks show that megascopically noticeable incipient exfoliation has penetrated to a depth of 10 to 15 cm. from the surface. (3) Disintegration takes place also by the spalling and splitting of large blocks and fragments, but the amount of disintegration taking place in this manner in the Aswan region is not very great. Of these three methods of disintegration that by exfoliation is by far the more important. In the excavation for the dam and navigation canal, concentric disintegration and decomposition were found to have penetrated to a depth of several meters below the high Nile level and are probably to be considered as going on at the present.

The chief granite of the Aswan region is the famous Syene red granite, a coarse red porphyritic granite composed chiefly of large phenocrysts of orthoclase. Where the joints are comparatively far apart, its outcrops under the effect of the concentric exfoliation of the joint blocks resemble huge piles of bowlders. Where the jointing is more pronounced and the joint blocks of much smaller size, the concentric exfoliation is much less in evidence and the outcrops are composed of, and surrounded by, detrital masses of angular and subangular blocks and in appearance are very similar to the outcrop and surrounding detrital slopes of similar types of rocks in New England.

The fine-grained granite of the region, somewhat similar in composition to the coarse red granite, although with a lower content of colored silicates, is not so severely affected by the disintegration. Exfoliation takes place very slowly, and although the edges and corners of exposed blocks have in most cases been rounded, the general form of the blocks is angular. The outcrops in general aspect are not unlike these of the more jointed phases of the coarse red granite. The fine-grained granite is, however, itself much jointed. It was not seen massively disintegrated and small dikes cutting the massively disintegrated coarse granite showed merely slight exfoliation of the edges and corners of the joint blocks into which the dike is broken. Flaking and the loosening of single grains on exposed surfaces do not seem severely to affect the fine-grained granite.

THE RATE OF THE DISINTEGRATION OF THE GRANITE

The rate of disintegration of exposed surfaces of granite at Aswan is not as rapid as at first might seem. Many of the numerous hieroglyphic inscriptions of this region show noticeable disintegration and on this account relatively rapid rates of disintegration have been postulated. These inscriptions almost without exception are carved on bowlders of exfoliation, and in but few cases was there seemingly much effort on the part of the ancient Egyptians to remove more than the most readily detachable plates of exfoliation. The greater number of the inscriptions therefore were carved on surfaces that were already partially disintegrated. In the few cases in which the writer was able to satisfy himself that the inscriptions had been cut in surfaces dressed back into fresh rock, there was no disintegration noticeable and the inscriptions were entirely fresh and sharp. Such inscriptions can be seen on one of the two natural obelisks on the island of El Hesa. The inscriptions date from the reigns of Mentuhotep I, about 2100 B.C.; Thutmoses IV, 1420–1411 B.C.; Amenhotep III, 1411–1395 B.C.; and Psammeticus II, 588–583 B.C. The inscriptions show no noticeable disintegration, and tapping with the finger or hammer does not reveal the presence of incipient exfoliation or flaking. The exposure is southerly and therefore one that affords the maximum exposure to insolation. These rocks, as can be seen from Fig. 2, rise directly out of the Nile and there would seem to have been no chance of their having been buried and protected by accumulations of sand or débris. Other examples of inscriptions carved in fresh surfaces and not showing disintegration are those

Fig. 2.—The Island of Konosso. View taken looking north-northeast. The hieroglyphics mentioned are on the south face of the right hand of the two natural monoliths.

along the trail from Aswan to Shellal numbered by Weigall 323, 326, 334, 343, and 350 and dating from the eleventh, twelfth, and thirteenth dynasties; an obelisk and a statue lying unfinished in the ancient quarries and referred by Wiegall to the reign of Amenhotep III, 1411–1375 B.C., and numerous discarded quarry blocks in the ancient quarries and along the ancient quarry roads, dating probably from not later than the last century B.C. These blocks in many cases consist of a half, a quarter, or an eighth of a bowlder of exfoliation and in most cases it is readily possible to determine which were the originally fresh and which were the originally exfoliating surfaces. The surfaces which were originally fresh are still fresh and show merely an infinitesimally thin film of tarnish and alteration. Tapping revealed no incipient exfoliation. In microscopic thin sections taken at right angles to the surface of a block, the orthoclase is seen to be comparatively fresh; the oligoclase is much clouded by decomposition products, but the alteration is not sufficient to obscure the specific determination of the feldspar. The ferro-magnesian minerals show slight decomposition and in one of the sections there is considerable limonitic staining. The degree of decomposition is no greater than that which is very commonly observed in sections of granite and is no greater toward the surface than deeper in. There is no tendency, as far as could be seen, toward incipient rifting parallel to the surface. The sections were taken at right angles to surfaces which had a southerly exposure and which were therefore exposed to the maximum heating effects of the insolation.

Farther north in Egypt the rate of disintegration is more rapid. At Luxor, Thebes, Gizeh, and in the museum at Cairo, the granite (chiefly the coarse Syene granite) of statues, of obelisks, of portions of the temples, and of the facing of the pyramids, shows in the greater number of cases noticeable disintegration. That manifested by the statues is manifested chiefly as exfoliation of a thin film, 0.5–0.7 cm. in thickness, from the pedestal, feet, and lower portion of the legs. Above the knees, the original high polish is commonly still intact, and tapping does not reveal incipient exfoliation or flaking. Examples of this type of disintegration can be seen on many, but not all, of the statues of Rameses II in the Forecourt of the Temple of Luxor and by the statue of Rameses II at the north entrance, by the colossal statue of Rameses II at the entrance to the great Hypostyle Hall, Karnak (Fig. 3), and by the medium-sized statue in the temple of Ptah, and by about half the statues of the coarse red Syene granite and also those of dark medium-grained rock possibly diorite in the museum at Cairo. The statue in the Temple of Ptah is situated in a small dark sanctuary and is not directly exposed to insolation. The other statues at Luxor and Karnak are less well protected, but nevertheless are only very poorly exposed to the temperature changes consequent upon solar heating. In the Great Temple of Karnak, disintegration manifests itself as the spalling of the corners of the uprights; as the exfoliation to the depth of about 1 cm. of the walls in the Granite Sanctuary, erected in 313 B.C. by Phillip Arrhidaeus; and as spalling and exfoliation of the lower 6 to 8 ft. of the fluted columns in front of the Sanctuary, and also of the obelisk of Queen Hatshepsut, 1591–1447 B.C. The obelisk of Thotmes I, now lying in pieces on the ground, shows scattered, patchy flaking and under tapping much incipient exfoliation is revealed. At the Temple of

FIG. 3.—Statue of Rameses II. Entrance to the Great Hypostyle Hall, Karnak, showing in a characteristic manner the exfoliation of the pedestal, feet, and lower legs.

Medinet Habu, Thebes, disintegration is shown by the granite pillars of the doorway both on the sides which are exposed to the sun and on those which are not. In the Serapeum at Sakkara, on the other hand, the surfaces of the huge sarcophagi, which are hewn out of the coarse Syene red granite, still retain the high perfection of their original polish and show not the faintest trace of incipient disintegration or exfoliation. The sarcophagi, however, are in dry underground chambers whose temperature, according to Baedecker, remains very constantly at about 80° F.

At Gizeh, the granite blocks which formed a part of the facing of the second and third pyramids show for the most part on their exposed surfaces a very marked exfoliation to the depth of 0.5 to 0.8 cm. Minor exfoliation, in addition, is found along the joints between the blocks. Exposed surfaces not exfoliating commonly show marked granular flaking. The orientation of the surface, with north, east, south, or west exposure, does not seem appreciably to affect the intensity of the disintegration and exfoliation. Disintegration and exfoliation are shown also by the granite facing that extends for 30 ft. down the shaft on the north side of the second pyramid, by the granite pavement of the temple at the east base of the second pyramid, and by the granite blocks immediately to the north of the east entrance to the temple. A striking feature

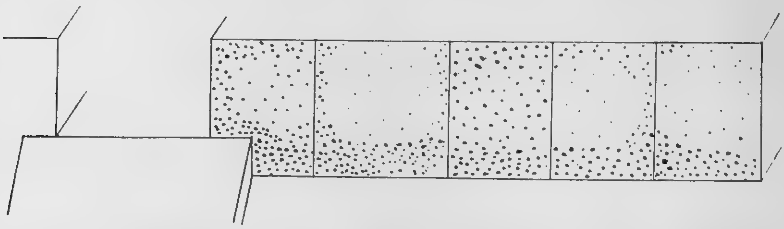

FIG. 4.—Diagrammatic sketch showing the greater degree of disintegration below the old soil line than above. East entrance to the temple of the second pyramid, Gizeh.

in this latter case, as can be seen from the accompanying sketch (Fig. 4), is that the disintegration is distinctly stronger below what seems to have been an old soil line than above it. A similar case was noted at one of the pyramids at Sakkara. The débris resulting from the disintegration and exfoliation in all these shows slight but megascopically noticeable decomposition. The degree of the alteration of the colored silicates is greater than that of the feldspars, and that of the plagioclase is greater than that of the orthoclase.

The pyramids of Gizeh date from the Fourth Dynasty, about 2850–2700 B.C., the statues of Rameses II at Karnak and Luxor date from the Nineteenth Dynasty, 1292–1225 B.C., and the Granite Sanctuary, Karnak, dates from the reign of Phillip Arrhidaeus, 318 B.C. The average rate of disintegration and exfoliation would therefore seem to be about 1 cm. to 0.5 cm. in five thousand years.

The maximum rate, shown by the Granite Sanctuary, would seem to be about 1 cm. in two thousand years, and the minimum rate would seem to be so low that the effects are not apparent in three thousand years. In addition to this variation in the rate of disintegration apparently corresponding to a variation in the conditions to which the granite is exposed, there is apparently also a variation depending upon the orientation of the disintegrating surface in reference to certain directions within the rock, possibly the rift and the grain, or possibly a faint schistosity which is almost universally present in the Syene granite.

THE CAUSES OF THE DISINTEGRATION

The conventional explanation of disintegration in a region of desert climate like that of Egypt is that the disintegration results from the racking to pieces of the rock through the contraction and expansion consequent in the high-temperature ranges. In the case of Egypt, there would, however, seem to be serious objections to this explanation, although some disintegration undoubtedly does take place in that manner. The first objection is that, although the temperature range is of the same magnitude at both Aswan and at the pyramids of Gizeh, the rate of exfoliation is very much less at the former place than at the latter, and furthermore, that, although the statues in the temples are exposed in many cases only to very low temperature ranges, the rate of exfoliation in many of these cases is of the same magnitude as that at the pyramids of Gizeh. The second objection is that the massive granular disintegration of the Aswan region penetrates to a greater depth than appreciable temperature changes can be expected to extend. The depth of the zone of warming at midday in desert regions is given by Walther as the result of many observations as only about 19 cm. The annual temperature variation is said by Sir William Thompson to be reduced at a depth of 8 m. (25 ft.) to one-twentieth of its superficial amount. The mean annual temperature range in Egypt is less than 20° C and, at the depths to which disintegration can be seen to have penetrated at Aswan, 3 to 4 meters, must be reduced to amounts which are essentially negligible, especially since the period of the range is so long. The mean monthly range is only 24° C. and at those depths must be even more seriously reduced in amount. The diurnal temperature range, furthermore, should be entirely absent at those depths, especially on slopes such as those in which many of the graves on El Hesa are cut, where direct insolation is received only during the summer and then at a low angle. Granite itself has a low coefficient of conductivity and that of dry granitic sand must be much lower; it would therefore not seem surprising that a blanket of several feet of disintegrated granite is found to be an effective insulating agent for the fresh rock beneath.

At Aswan and at the pyramids of Gizeh, the only factor by which the conditions of exposure of the exfoliating rock differ is in the humidity. At Aswan there is no rainfall, there is only a light dewfall at night, and the relative humidity at 8:00–9:00 A.M. varies from 28 to 58, average 39; while at the pyramids of Gizeh there are several light showers each year, there is a moderately heavy dewfall at night, and the relative humidity at 8:00–9:00 A.M. runs from 64 to 87, average 72.

In the case of the exfoliating statues, their sheltered positions in the temples and the connection between the exfoliation and the lower portions of the statues would seem to indicate that the cause of the exfoliation lay not so much in the temperature changes as in some factor connected with the ground, as for instance, in the ground-water or moisture, and it is to such a cause that the exfoliation is ascribed by G. Daressy of the Department of Antiquities, Egypt, who says: "Les granites exposés continuellment à l'eau ou au soleil se conservent bien, mais où ils se degradent, c'est lorsqu'ils ont été enfouis dans un sol humide. La formation de sels nitrate et autre fait alors decomposer le granite, sûrtout lorsque le terrain est alternatement sec et humide." The expansion consequent upon the kaolinization of the feldspar is emphasized by Merrill as the cause of the disintegration of the granite near Washington, D.C. Although kaolinization is megascopically very noticeable in these cases, it would scarcely seem to be of sufficient amount alone to account for the observed disintegration and exfoliation.

The massive granular disintegration of the Aswan region possibly also may be attributed directly or indirectly to the effect of moisture. The disintegration is found at and for some few meters below the level at which the Nile must have flowed when in the old Nile Valley between Aswan and Shellal. At that time the granite at the level of this disintegration must have been alternately above and below the ground-water level, as the Nile rose and fell, and must consequently have been alternately wet and dry. At the present level of the Nile, the granite was found in the excavations for the navigation canal and for the dam foundations to be almost completely disintegrated and decomposed to a depth of several meters below the level of the high Nile. Decomposition in this case has, however, rather predominated over simple disintegration.

These observations in the light which they throw on the cause of the disintegration of granite are in agreement with similar observations which the writer made in the Odenwald, in the Vosges Mountains, in the Norvan and Auvergne districts of France, and in the eastern United States. In the many places in which the disintegration has reached the depth of 20, 30, or even 40 ft., it seems impossible to believe that the temperature changes are of sufficient amount to be of any appreciable effect. Diurnal, weekly, and monthly temperature changes must be completely eliminated at those depths, and according to Sir William Thompson the annual temperature range is reduced at a depth of 25 ft. to one-twentieth of its superficial amount. The disintegration in these places is accompanied in many cases by very much more and in other cases by only slightly more decomposition than is the disintegration in Egypt.

A RECORDING MICROMETER FOR GEOMETRICAL ROCK ANALYSIS

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The quantitative estimation of minerals in rock sections is generally recommended as a valuable exercise, but in practice it is far too seldom performed. The reason is that the recognized methods of estimation are very tedious, while the results, when obtained, have not hitherto been put to any systematic use in the classification of rocks. The usual methods are of two kinds, viz., (1) separations, either gravitational or magnetic, the separated portions being weighed directly; and (2) geometrical methods, involving measurement either of areas or of diameters, and subsequent calculation of percentage volumes and percentage weights.

Of estimations of the latter class, the following variants are known to me:

1. The method of Delesse: The surface of the rock is polished and oiled, and the outlines of the grains are traced on transparent paper, the areas corresponding to different minerals being distinctively colored. The paper is then pasted upon tinfoil, and cut up along the boundaries of the grains. The fragments having been grouped according to color, the paper is removed and the tinfoil weighed. The weights so found are proportional to the areas traced upon the paper, hence also to the volumes occupied by the different kinds of grains, provided that the rock is uniform throughout. To get the proportions of the various minerals by weight, each volume must be multiplied by the specific gravity of the corresponding mineral.

2. The outlines of the grains may be traced upon squared paper, and the areas obtained by counting the number of squares occupied by each mineral, all broken squares being reckoned as half-squares.

3. Methods 1 and 2 can be applied to microscopic sections by the aid of a camera lucida attached to the microscope. An ordinary photographic camera can also be used, the outlines of the grains being sketched from the enlarged image on the focusing screen.

4. If a dark room is at hand, it is sometimes preferable to photograph a rock section instead of sketching it. The print can be examined either by weighing or by means of squared paper.

5. A squared ocular micrometer, by means of which the areas of the grains in a section can be measured directly under the microscope, was tried by Rosiwal. It was found to be less advantageous than the following method, viz.:

6. Rosiwal's linear traversing method:[1] If the work be executed with care and under all necessary precautions, this is the simplest and perhaps for that reason the most accurate of all geometrical methods of rock analysis. The measurement of areas is replaced by the measurement of diameters along a selected line or lines. Either a microscopic section or the smooth face of a hand-specimen of the rock may be employed, according to whether the rock is of fine or coarse grain. In the latter case, a graduated rule or tape is required; in the former, an ocular micrometer. Any kind of micrometer will do, but the estimation is facilitated by the use of certain special types, such as the "planimeter ocular" of Hirschwald.[2] Subject to certain conditions, the number representing the sum of the diameters of all grains of one kind is proportional to the volume of the mineral concerned.

So far as tediousness is concerned, all these methods are more or less on the same level; the measurements are very wearisome and take a long time to perform. Generally speaking, one would expect weighing to be a more exact process than the use of squared paper, but then the weighing must be preceded by sketching and cutting out, and appreciable errors may creep in during these manipulations; furthermore, one cannot be sure that the material weighed, be it tinfoil, cardboard, or paper, is everywhere of the same thickness. On the other hand, the counting of innumerable

[1] Rosiwal, "Über geometrische Gesteinsanalysen," *Verhandlungen der k.k. geolog. Reichsanstalt*, Wien (1898), No. 5.

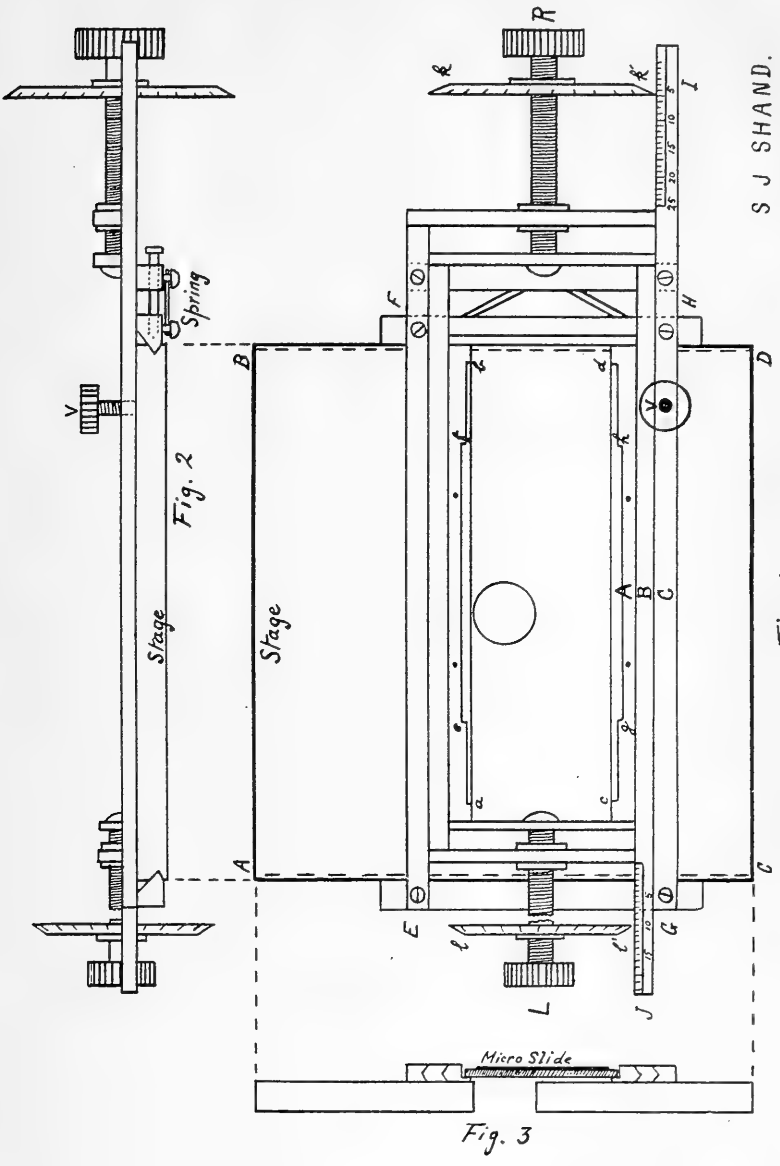
[2] J. Hirschwald, *Centralblatt für Min., Geol., Pal.* (1904), No. 20.

tiny squares is a most aggravating business, and the fewer the squares, the greater the probable error in the result. On the whole, the advantage seems to be with the Rosiwal method, as being both simpler and more direct than the others. The practical disadvantages of the method are two: First, the making of very many minute measurements by the aid of the scarcely visible scratches on the eyepiece micrometer puts a severe strain upon the eyesight, as well as upon the patience, of the observer. After an hour or two of such work I have sometimes been nearly blind. Secondly, the writing down and adding up of some hundreds or even thousands of measurements is itself a most tedious operation.

To obviate these serious disadvantages of the Rosiwal method, I have devised a stage micrometer which both makes the measurements and performs the addition of them; it consequently effects a great reduction in the time needed for the estimation, and incidentally reduces the strain on the eyes to a minimum. The first instrument was made from my drawings by Mr. T. A. Linton, at the South African College, Cape Town, and I have pleasure in expressing my appreciation of his excellent workmanship.

The design is very simple, and will easily be followed with the aid of the drawings (Figs. 1, 2, 3). The rock section, mounted as usual on a glass slide, fits into a rectangular brass sledge *A*, which is movable to right or left of the observer, within another sledge *B*, the movement being accomplished, and its amount recorded, by the micrometer screw *L*. Sledge *B* moves in the same manner and direction within sledge *C*, the movement being performed and recorded by the micrometer screw *R*. Sledge *C* has no transverse movement; it carries two runners on its under surface which travel in grooves on the sides of the rectangular stage of the microscope; the only movement of this sledge is to and from the observer and is effected simply by hand.

Suppose it is required to estimate the volume of augite in a dolerite. The section is put in place and adjusted till one edge of it appears against the point of intersection of the cross-wires in the eyepiece of the microscope. The readings of screws *R* and *L* are written down. Then screw *R* is turned continuously until a grain of augite is brought up to the cross (i.e., the point of inter-



FIGS. 1, 2, 3.—Working drawings of recording micrometer.

section of the cross-wires); screw L is now turned until the grain travels past and its other margin lies exactly beneath the cross; then screw R is turned till the next augite grain comes into position; then screw L till the grain has passed, and so on. When the traverse has been completed, which with a section of ordinary size may take from one to three minutes, the readings of the micrometer screws are again noted and written down below the former readings. It is obvious that the difference between the two readings of screw L gives the sum of the diameters of all the augite grains which were intersected during the traverse, while the difference for screw R gives the sum for all other minerals in the rock. Without stopping to make these subtractions, however, sledge C is pushed forward into a new position and a second traverse is made in the return direction; at its completion the micrometers are again read and the readings jotted down beneath the previous ones. Sledge C is again pushed forward, and another traverse made, and so on until the number of traverses is considered sufficient. One may now proceed to the subtraction of the successive readings, and the calculation of the percentage of augite, which is obviously

$$\frac{\text{sum of successive differences of } L}{\text{sum of successive differences of } L + \text{sum of successive differences of } R} \times 100.$$

The most expeditious manner of recording the readings is to write them down in parallel, vertical columns in the middle of the page; then, when all the measurements have been made, the differences of L are quickly filled in to the left and the differences of R to the right, as in Table I, on p. 399, which is part of an actual estimation.

It will be seen that by this method only two numbers have to be recorded for each traverse after the first, while by any other method some twenty or more may be necessary.

It may be advisable at this stage to recall the conditions which, as Rosiwal has pointed out, must be observed if the linear traversing method is to give reliable results.

1. The length measured must be at least one hundred times the average grain of the rock. (With the additional facility afforded by the recording micrometer, it would involve little extra labor

to increase this minimum to two hundred or even four hundred, and I strongly advocate the increase.)

2. Two measured lines should be at least the width of a grain apart.

3. When the constituents are fine-grained and uniformly distributed, measurement of a single section may be sufficient; if coarse-grained, several sections may be necessary in order to satisfy conditions 1 and 2.

TABLE I

Diff.	*L*	*R*	Diff.
	3.82	8.05	
6.43			16.60
	10.25	24.65	
9.18			13.40
	1.07	11.25	
5.86			17.45
	6.93	28.70	
6.93			16.25
	0.00	12.45	
7.62			15.23
	7.62	27.68	
36.02			78.93

$$\text{Percentage} = \frac{36.02}{36.02+78.93} \times 100 = 31.3$$

Total distance traversed, 57.5 mm.; time taken for measurements and calculation, 12 minutes.

4. In the case of a rock with parallel structure it is necessary, and in most cases it is desirable, to take measurements both along and across the section.

5. The most accurate method is to measure all the minerals present at the same time, rather than one at a time, although the latter is the quicker way. (This recommendation applies to the use of an ordinary micrometer; it is of course inapplicable to the recording micrometer.)

6. In the case of coarse-grained rocks it is often quickest to measure a polished face macroscopically, using sections only for minor or microscopic constituents.

Rosiwal's practice is to draw fine lines on the cover-glass with ink, and then measure along these lines. This is not necessary if the stage of the microscope happens to be ruled with cross-lines, as is often the case.

The method having been described, it remains to add some details about the construction of the instrument. In making the first model, we took the micrometer screws out of two small spherometers; these had just the right length (about $1\frac{1}{2}$ inches) and pitch

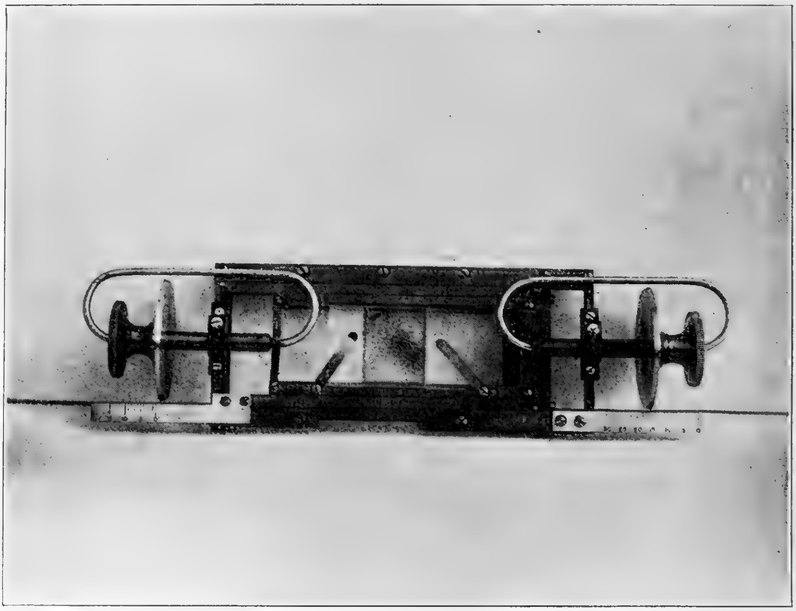


FIG. 4.—Photograph of original micrometer

(0.5 mm.) and were used almost without modification. The numbers on the graduated disk run in the correct direction for screw *L*, but must be reversed for screw *R*. These screws proved, on trial, to be unsatisfactory, having been taken from a cheap type of spherometer (the only kind obtainable in South Africa at the time), and better ones have since been substituted for them by Messrs. Swift & Son, London. It is of course essential that the screws shall be machine-cut with the highest degree of accuracy; that the axis shall be perfectly straight; and the graduated disks truly plane and set exactly at right angles to the axis. The precise pitch of the screw does not matter at all, but a pitch of about one-half to one millimeter is convenient. The scales which record the movement of the screws are of course graduated to correspond to the pitch, and the divisions on both scales are numbered from right to left.

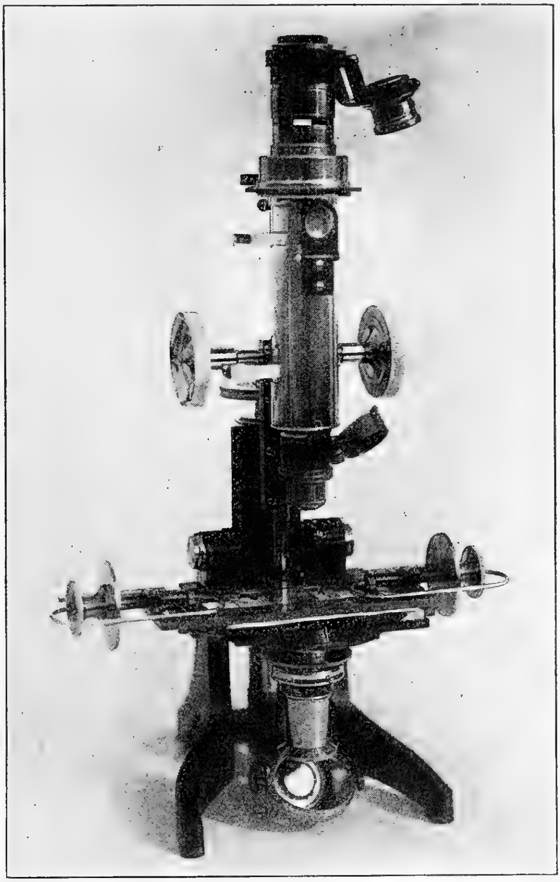


FIG. 5.—The micrometer in position on the stage of an "Allan Dick" petrological microscope (Messrs. Swift & Son, London).

The ends of the screws may be rigidly attached to the sledges *A* and *B*, but can be more simply secured by means of backlash springs. The innermost sledge *A* carries two slots, one of them (*abcd*) made to take the standard English size of slide (75×25 mm.), the other (*efgh*) to take German slides (48×28 mm.). Two small spring clips (not shown in the figure) serve to prevent any slight movement of the glass. In order to allow of measurements being made in two perpendicular directions across a rock section, four short pins are inserted in the sides of sledge *A*; these make it possible to fix a German-sized slide in cross position upon the micrometer, but the English slides are too long to permit this.

The attachment of the outermost sledge *C* to the stage of the microscope is effected by means of runners with beveled edges which fit into grooves in the sides of the stage. One runner is fixed directly to the under surface of the sledge, the other is attached by a simple wire spring to a fixed cross-bar on the under surface of the sledge. This simple arrangement could be replaced, if desired, by a mechanical movement; in any case it would be an advantage to have an additional screw (*V*, Figs. 1, 2) by means of which the instrument could be clamped to the stage in any desired position. My instrument was made to fit the stage of an "Allan Dick" microscope (Swift & Son), but it is obviously adaptable to any microscope with a rectangular stage. It could even be adapted to a circular stage by means of a rectangular plate clamped temporarily on top of the stage.

The instrument, as actually made for me, differs in some minor points from the drawings. For instance, the micrometer screws are not rigidly connected to the sledges *A* and *B*, as the drawing suggests, but are attached by simple backlash springs which can be seen in the photographs (Figs. 4, 5). The dimensions of the side- and end-pieces of the sledges were slightly increased for the sake of greater strength. The figures relating to these parts are as follows:

Length of sledge *A*, 85 mm.
Width of sledge *A* (including bevel), 37 mm.
Travel of sledge *A*, 16 mm. (this might be increased).
Length of sledge *B*, 108 mm. (this might be increased).
Width of sledge (including bevel), 45 mm.
Travel of sledge *B*, 35 mm.
Length of sledge *C*, 127 mm.
Width of sledge *C*, 54 mm. (might be reduced to 52).
Thickness of material throughout, 3.5 mm.

It would be well to allow a greater travel to sledge *A* by slightly increasing the length of sledge *B*—say to 112 mm.

A well-finished instrument of this kind could not be made for much less than £5, hence it is not likely to become part of every petrologist's equipment; but in view of the saving of time and eyesight which it effects the initial outlay is inconsiderable, and the gain to descriptive petrography, if it should succeed in popularizing the geometrical analysis of rocks, would be very great.

The instrument has been examined by Messrs. J. Swift & Son, London, who have all the information necessary for executing copies of it.

EXPRESSION OF THE "COLOR RATIO" OF A ROCK

It has always appeared to me to be a matter of great importance in rock descriptions to state the proportion of light to dark minerals accurately. The terms "leucocratic" and "melanocratic" have proved extremely useful in giving a rough indication of this proportion (which I am in the habit of calling the "color ratio" of the rock), but something more is urgently required. Of course the fundamental point of difference between the light and the dark minerals does not lie in their color, but in their specific gravity, to which, however, the color affords a convenient index, inasmuch as all minerals of gravity less than 2.8 are leucocratic (predominantly light-colored) and those of higher gravity are melanocratic (predominantly dark-colored). It is becoming more and more apparent that differences of specific gravity must be reckoned among the chief causes of magmatic differentiation, and for this reason, as well as for its purely descriptive value, the color ratio must receive quantitative recognition in the future.

With the micrometer described above, it is possible to measure the color ratio of a fine-grained rock with a high degree of accuracy in a period of ten to thirty minutes, according to circumstances. Having ascertained the ratio, the next question is how best to express it, and the way which does least violence to our accepted, illogical system of nomenclature is to resort to a system of prefixes.

The following ratio and the corresponding prefixes are simple and expressive:

Light minerals more than	97	per cent	l_{10} or L			
" " " "	90	"	l_9	or *l*		
" " " "	80	"	l_8			
" " " "	70	"	l_7	or l		
" " " "	60	"	l_6			
" " " "	50	"	l_5	or lm		
Dark " " "	50	"	m_5			
" " " "	60	"	m_6	or m		
" " " "	70	"	m_7			
" " " "	80	"	m_8	or *m*		
" " " "	90	"	m_9			
" " " "	97	"	m_{10} or M			

Examples: L=granite (alaskite); l_8=syenite; lm=dolerite; m=syenite (shonkinite); m_{10}=pyroxenite, etc.

Reviews

Origin of the Bighorn Dolomite of Wyoming. By Eliot Blackwelder. Bull. Geol. Soc. Am., XXIV, 607–24, plates 8, December 22, 1913.

The Bighorn dolomite is widely distributed in northwestern Wyoming. Its fossils, mostly corals and crinoid stems, are rare and seldom well preserved, but indicate an Ordovician age, possibly including Silurian also. Chemically the formation is a very pure, normal dolomite, with very little terrigenous matter. Its weathered surface is characteristically coarsely pitted and fretted, owing, not to intermingling of siliceous with calcareous matter, but to compact fine-grained dolomite structures imbedded in a matrix of more coarsely crystalline and porous dolomite. The ill-defined branching patterns due to differential weathering are probably of organic origin, more likely representing banks of calcareous algae than plantlike animals. The obliteration of original organic structures is assigned to the process of crystallization of the dolomite, probably taking place almost simultaneously with deposition on the sea floor. The deposits were doubtless made in an epicontinental sea less than 100–120 meters deep.

R. C. M.

On Oceanic Deep-Sea Deposits of Central Borneo. By G. A. F. Molengraaff. Koninklijke Akademie van Wetenschappen te Amsterdam, Proceedings of the meeting Saturday, June 26, 1909. Pp. 7, map 1.

The Danau formation, which outcrops over an area of approximately 40,000 sq. km. in central Borneo, consists of cherts and hornstones formed almost entirely from the tests of Radiolaria. The character of the formation is very constant throughout the area. It consists of two types: the one, a true Radiolite, is semitransparent, hard, and brittle, with a color varying from milk-white to red or green, and is composed almost exclusively of the closely packed tests of Radiolaria; the other is an argillaceous chert, always red in color. The latter contains fewer Radiolaria and is analogous to modern deep-sea red clay deposits. The former corresponds to Radiolarian ooze. This large area of deep-sea deposits clearly indicates a very deep submergence of this region, probably during the Jurassic period. The deposits probably occur in geosynclines developed at the edge of the permanent Australasian continental segment.

R. C. M.

Glaciology of the South Orkneys: Scottish National Antarctic Expedition. By J. H. HARVEY PIRIE. Trans. Roy. Soc. Edin., XLIX, Part IV, pp. 831–61. Figs. 14, pls. 11, including one map.

The South Orkneys have such a climate that the line of perpetual snow is practically at sea-level; the summer temperatures are rarely above freezing-point. The mean annual temperature is 22°.7 F. The mean temperatures of the warmest and coldest months are 31°.5 and 12°.0 F., respectively. Foehn winds having passed over the central highlands sometimes produce as high a temperature in midwinter as in summertime.

The islands are almost entirely snow-covered throughout the year. The resulting glaciers are characteristically antarctic in type. The surfaces are practically all covered with névé, there are no surface moraines, crevasses are rare except at escarpments, the whole mass of the glaciers shows stratification, and the glaciers terminate in sea-cliffs. The land-relief gives rise to various forms of glaciers:

I. Ice-sheets, including:
  a) Inland ice.
  b) Ice caps of the Norwegian type.
  c) Much of the Spitzbergen type of ice caps. These are ice sheets which conform to the topography, overlying both valley and hill.

II. Glaciers properly so called.
  a) Valley glaciers.
  b) Suspended cliff glaciers.

III. Piedmont glaciers.
  These cover the low slopes between the mountain sides and the seashore. They end in cliffs from 15 to 20 meters high; their surfaces are uniform and snow-covered, having a gentle slope from the sea to the hills behind. They are fed by local precipitation and are not dependent upon snow-field reserves; they show well-marked horizontal stratification.

IV. Glaciers of the coastal belt and shelf.
  a) Shelf-ice, such as the Great Ross Barrier.
  b) Ice-foot glaciers which lie in the zone between land and sea. They are composed of layers of névé ice formed in place chiefly of drift snow supplied by wind action.

The surface of the ice is undulatory, conforming to the surface of the underlying ground. In one place the slope is opposite to the movement of the ice. The glacier as a whole may be traveling uphill for several hundred feet, but the total rise of the upper surface is thought not to exceed 20 feet.

The glaciers are not notably advancing or retreating; in most places cliff terminations at the shoreline indicate advance, but occasional rounded "snout" endings bear witness to a slight retreat. The small number of ice falls from the cliffs also disproves any notable advance. In certain places the ice strata are slightly turned up at the glacier edges, but there is no sudden upturning at the end; this conforms to the other indications of but slight movement.

Englacial material is rare and consists chiefly of wind-dropped rock; sand, pebbles, and bowlders are uncommon. In one place the ice grains were seen to be drawn out and arranged in sweeping curved lines which follow the direction of glacial flow. The bounding crystal faces are usually not plane but curved.

From imperfect data collected on the speed of temperature waves through the ice, it appears that a wave of about 5° change in temperature penetrates 2 feet in about 2 days, and 4 feet in about 5 days.

The islands seem to be the serrated tops of a mountain range which has been deeply dissected by glaciers while the islands stood at a markedly higher elevation above the sea.

T. T. Q.

The Upper Devonian Delta of the Appalachian Geosyncline. By JOSEPH BARRELL. In three parts. Am. Jour. Sci. [4th Ser.], XXXVI (November, 1913), 429–72; XXXVII (January, 1914), 87–109; XXXVII (March, 1914), 225–53, Figs. 5.

The Upper Devonian Oneonta and Catskill formations, that consist of alternating red shales and gray sandstones, of the Appalachian geosyncline in southeastern New York and northeastern Pennyslvania are believed to be "subaerial delta deposits [of westward-flowing streams] in a dry but not arid climate; a climate probably equable in temperature but subject to seasonal rainfall." The Oneonta is 1,000 feet thick in the Catskill Mountains; the Catskill runs up into thousands of feet in thickness. The Portage and Chemung formations are the shallow-sea equivalents of the Oneonta and Catskill beds. The inland sea in which the former were deposited bordered the subaerial delta on the west and southwest. The included map "shows the shore line at the close of the

Devonian farther west than any previous map but the margin of the sediments farther east, except for the New Jersey strait of Schuchert which is here eliminated." The Upper Devonian sediments are believed to have extended northward beyond Lake Ontario and as far eastward as the margin of the present coastal plain; their removal over a great part of this area is referred to pre-Newark (Mid-Triassic), Jurassic, and post-Jurassic (Comanche and Cretaceous) erosion epochs. These Upper Devonian beds apparently formed a great piedmont plain that stretched westward from Appalachia; the Skunnemunk conglomerate (2,500 feet thick) is a remnant. This plain thickened from east to west and in so doing changed from coarse to fine sediments. The indications are that the drainage divide of Appalachia "was at least as far east as the present 100-fathom line southeast of Long Island and New Jersey."

V. O. T.

Geology and Ore Deposits of the Monarch and Tomichi Districts, Colorado. By R. D. CRAWFORD. Bull. Colo. Geol. Surv. No. 4, 1913. Pp. 317, pls. 15 (including 4 maps), figs. 15.

The Monarch district lies in the southwestern part of Chaffee County, Colorado, on the east slope of the Sawatch Range. The Tomichi district, which is in Gunnison County, is on the west slope of the range and joins the Monarch district on the west.

The sequence of formations is as follows: pre-Cambrian gneisses, schists, granites, pegmatite, and quartzite; the probably Upper Cambrian Sawatch quartzite (20± feet); the mid-Ordovician Tomichi limestone (400 feet); the Upper Devonian and early Mississippian Ouray limestone (600–800 feet); the Pennsylvania Garfield formation (2,800 feet); the Permo-Pennsylvanian (?) Kangaroo formation (about 3,000 feet); post-Carboniferous quartz monzonite, granular rocks, porphyries, flow, and volcanic breccia; Pleistocene and later glacial and fluvio-glacial deposits; recent deposits.

The Sawatch quartzite does not outcrop in the Monarch district. In the Tomichi district, the Garfield formation is only a few hundred feet thick, and the Kangaroo formation is wanting.

Unconformities exist between the following formations: the pre-Cambrian and Sawatch, the Sawatch and Tomichi, the Ouray and Garfield, the Garfield and Kangaroo, the Kangaroo and volcanic breccia, the Pleistocene and older deposits. Regarding the interval between the Tomichi and Ouray, the author notes that "although one or more stratigraphic breaks may be present, the beds show no angular unconformity." An unconformity is probable between the Devonian and Mississippian portions of the Ouray.

Pronounced folding and faulting occurred in post-Kangaroo (Permo-Pennsylvanian(?)) time.

The primary ore minerals of the Monarch and Tomichi districts are believed to be genetically related to the quartz monzonite intrusion.

The principal ores produced in the Monarch district are of lead, silver, gold, copper, and zinc. They occur as replacements in limestone and dolomite, filling of fault fissures in limestone and quartzite, fissure veins in igneous rocks, contact deposits, and as deposits in pegmatite, gneisss, and schist. Further development is encouraged.

The silver-lead ores now mined in the Tomichi district are chiefly sulphide ores. The iron ore bodies are of magnetite and limonite. The ores occur as replacements in limestone and dolomite, contact deposits, fissure veins, and as bog iron deposits. The future of the district lies in "the development of claims in groups."

Detailed descriptions of the mines of both districts are given.

V. O. T.

Reconnaissance of the Geology of the Rabbit Ears Region, Routt, Grand and Jackson Counties, Colorado. By F. F. Grout, P. G. Worcester, and Junius Henderson. Bull. Colo. Geol. Surv. No. 5, Part 1, 1913. Pp. 57, pl. 1.

The Rabbit Ears region includes about 212 square miles in Routt, Grand, and Jackson counties, Colorado, "along and near the west end of the Rabbit Ears Range."

The geological sequence is as follows: Archean gneisses, schists, and granites; Permian or possibly Triassic "Red Beds"; the Upper Jurassic or Lower Cretaceous Morrison formation; the Cretaceous Dakota(?), Benton, Niobrara, and Pierre formations; early Eocene coal-bearing beds; post-Eocene volcanic breccia, dikes, and sheets; Pleistocene and Recent deposits.

Unconformities occur between the Archean and the "Red Beds," the "Red Beds" and the Morrison, probably between the Morrison and the Dakota(?), the Pierre and the early Eocene coal-bearing beds, and the coal-bearing beds and later deposits.

Folding "began at or just after the close of Cretaceous time, probably continuing for some time into the Tertiary. . . . . " It is "probable that igneous activity began in late Cretaceous or very early Eocene time and continued till very recently, and that there were several quite distinct periods."

V. O. T.

Permian of "Permo-Carboniferous" of the Eastern Foothills of the Rocky Mountains in Colorado. By R. M. BUTTERS. Bull. Colo. Geol. Surv. No. 5, Part 2, pp. 65–101. Fig. 1.

This report is concerned with the determination of the age of the Lykins formation, which was assigned by Fenneman to the upper part of the "Red Beds" in the Front Range of eastern Colorado.

The Lykins formation, which varies considerably in thickness, consists of red shales and shaly sandstones, with a few sandy or shaly limestone beds. On the basis of the faunal evidence, the lower part of the Lykins is placed in the Pennsylvanian and an intermediate zone above is tentatively correlated with the Rico formation (Permian(?)) of the San Juan region. "This leaves 100–400 feet of shales to represent the Permian or the remainder of the Permian, the Triassic, and all the Jurassic up to the Morrison."

V. O. T.

The Geology of Central Ross-shire. By B. N. PEACH, L. W. HINXMAN, E. M. ANDERSON, J. HORNE, C. B. CRAMPTON, R. G. CARRUTHERS. Petrological Notes by J. S. FLETT. Memoirs of the Geological Survey of Scotland, No. 82, 1913. Pp. 114, pls. 8, figs. 10.

The western quarter of County Ross is cut off by the great Moine thrust line. The Strathconan fault is the dominant one in the area considered. It is of the type described as a "wrench fault." The direction of the fault line is a little east of north, and the lateral movement was to the northeast on the east side, and to the southwest on the western side. There are many Lewisian inliers thrust upon the younger Moine series.

The Lewisian gneiss is a basement complex of various rocks of different ages and includes altered sedimentary rocks that were denuded and affected by contact metamorphism before the deposition of the Moine sediments.

The Moine series comprises quartzose schists or quartz-biotite granulites and garnetiferous mica-schists or pilitic gneiss, representing respectively metamorphosed silicious and argillaceous sediments. Locally the base of the series is conglomeratic. They are divided into an upper and a lower silicious zone.

Torridonian strata occupy most of the unmoved area east of the fault line. The beds are chiefly coarse, chocolate and red arkoses and pebbly grits which carry occasional layers of shale and flagstone.

Unconformable upon the Torridon beds lie the Cambrian. The Cambrian is based with a gritty quartzite; the upper Fucoid limestones carry an Olenellus fauna.

An apparent metamorphic transition of Torridon into Moine schists is reported, but no suggestion is made as to the age of the Moine schists relative to the Cambrian and Torridonian.

The petrology of the district is marked by unusual lamprophyre dikes of minette and monchiquite relationships.

The last twenty pages are given to a discussion of Pleistocene glaciation and glacial deposits.

T. T. Q.

The Archean Geology of Rainy Lake Re-studied. By ANDREW C. LAWSON. Geol. Surv. Canada, Memoir No. 40, 1913. Pp. 115, pls. 9, map 1.

Field study confirms the author's earlier opinion (of 1887) that the Coutchiching sedimentary series is older than the Keewatin igneous rocks. He found that there were two widely separated periods of plutonic activity; to the earlier he proposes to confine the name Laurentian, and for the younger he introduces the term Algoman.

Lawson's classification of Archean formations from the top downward is as follows:

1. Eparchean interval—peneplanation.
2. Algoman. Vast batholiths of granite- and syenite-gneisses.
3. Seine series (Upper Huronian, Middle Huronian of some authors). Conglomerates, quartzites and slates.
4. Uplift, deformation and erosion, followed by depression.
5. Steep rock series (Lower Huronian). Sediments and volcanics. Several hundred feet of fossiliferous limestones.
6. Erosion which extensively exposed the granite batholiths.
7. Laurentian. Granites and granite-gneiss.
8. Keewatin. Chiefly volcanic rocks with intercalated sedimentary beds. Certain intrusive gabbros.
9. Coutchiching. Sedimentary strata. Mica schist and paragneiss.

Only two divisions of the Huronian are admitted, and the Animikie and Keweenawan are not grouped with the Archean but with the Paleozoics. However, these two divisions are associated under the higher name Algonkian. He also proposes the name Ontarian to cover the closely associated Keewatin and Coutchiching.

The major part of the report is given to a detailed discussion and description of the criteria whereby the Coutchiching is represented to be older than the Keewatin. The arguments presented are based upon structural relations, and actual contacts at which the Keewatin lies upon the Coutchiching.

The conglomerate which Lawson formerly thought part of the Coutchiching, and which others used to show that the Coutchiching is younger than the Keewatin, Lawson now distinguishes as part of another, very much younger, group, the Seine series. The stratigraphical position of this series is not clearly established, and therefore the upper part of his Archean classification is not much more than tentative.

T. T. Q.

The Pre-Cambrian Geology of Southeastern Ontario. By WILLET G. MILLER and CYRIL W. KNIGHT. Report of the Bureau of Mines, Vol. XXII, Part II, 1914. Pp. 151, illustrations 67, portraits 4, maps 13.

The chief results of the work were to show that: (1) the sedimentary rocks have a basement of Keewatin green schists and ellipsoidal lavas; (2) the Grenville series were deposited upon the Keewatin lavas, but no erosional interval has been proved; (3) granites of two ages have been recognized; the older one is gneissoid and intrudes the Keewatin and Grenville rocks, the younger granite intrudes all the local pre-Cambrian rocks; (4) most of the metamorphosed blue limestones are classed with the Grenville series, but the conglomerates and some other sediments are younger and differentiated as the Hastings series; (5) post-Hastings igneous rocks are gabbro, basalt, and tuffs, and the Algoman granite which is later than the gabbro group.

Because the great Grenville limestone series (94,000 feet thick—Adams) was pre-Laurentian, the authors think there is no special significance to be attached to the Laurentian as an epoch-marking time. They drop the terms Algonkian and Archean, and Proterozoic and Archeozoic. They do not reach definite conclusions about the correlation of the limestone conglomerate and other formations in the Madoc area.

As an appendix the authors present their correlation of the pre-Cambrian rocks of Ontario, western Quebec, and southeastern Ontario. They follow Lawson in calling the older granites Laurentian and the younger ones Algoman. They drop the name Huronian because they think confusion of application has ended its usefulness. They group the sedimentary rocks of the classic Huronian district at Bruce as "Animikean," and correlate with them the Cobalt and Whitewater series and the Ramsey Lake Conglomerate. All post-Algoman, pre-Keweenawan rocks are classed as Animikean. Pre-Algoman, post-Laurentian rocks are "Temiskamian." This name covers the Sudbury, Temiskaming, and Hastings series. For the group including the Keewatin and Grenville they propose the name "Loganian." They think it unnecessary to retain the name Coutchiching, nor do they consider that the position of those beds has been proved to be below the Keewatin.

Their classification is as follows:

Keweenawan. Upper copper-bearing rocks of Lake Superior. Igneous rocks are both massive and in flows. Sedimentary rocks are little altered in horizontal positions.

Unconformity.

Animikian. Upper Huronian, Cobalt series, etc. Quartzite, arkose, conglomerates in usually only gently folded positions.

Great unconformity.

Algoman. Lorrain, Moira, Killarney, Younger Laurentian granites. Generally massive, color pink.

Temiskamian. Lower Huronian, Sudbury series. Quartzites, arkose, conglomerate, Hastings limestone. Usually dips at high angles and is schistose.

Unconformity.

Laurentian. Granites and gneiss. Color typically gray.

Loganian. Grenville and Keewatin. Highly metamorphosed. Limestones, iron formations, and igneous flows.

T. T. Q.

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THE GEOLOGICAL SIGNIFICANCE AND GENETIC CLASSIFICATION OF ARKOSE DEPOSITS[1]

DONALD C. BARTON

Arkose has been held by different geologists to be significant respectively of several different types of conditions at the time of its formation. By Walther,[2] for instance, it is considered to be so distinctive of desert formations as to be, next to salt deposits, the the most important index of the desert origin of a formation. Mackie,[3] although not mentioning arkose by name, in his discussion of the significance of fresh feldspar in sediments seems to consider the rock especially characteristic of deposits that have formed under rigorous climatic conditions. Von Hauer[4] believes that arkose is especially characteristic of coal-bearing formations. Shaler[5] is of the opinion that it is formed when a granitic terrane, long under moist temperate climatic conditions, is exposed to more rigorous conditions or to marine or lacustrine transgression. Mansfield[6] believes, on the other hand, that the conditions for the formation

[1] Portion of a thesis accepted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at Harvard University.

[2] J. Walther, *Das Gesetz der Wüstenbildung*, 2d ed., p. 174.

[3] William Mackie, *Trans. Edin. Geol. Soc.*, VII (1898), No. LV.

[4] Franz von Hauer, *Die Geologie*, 1875.

[5] W. S. Shaler, *U.S.G.S. Monograph XXXIII*, 1899, pp. 50–55.

[6] G. R. Mansfield, *Bul. Mus. Comp. Zoöl. Harvard*, XLIX (1906), 293–94.

of arkose are intermediate between these extremes, and that a moderately cool and arid climate such as would prevail at moderately high altitudes in the lee of high mountain ranges or in continental interiors would more probably be suitable. The present paper is an attempt to delimit the significance of arkose.

The fundamental conditions essential for the formation of arkose[1] are: (*a*) a granitic terrane, (*b*) conditions favorable to the disintegration of the granite or gneiss with but slight accompanying decomposition, and (*c*) conditions favorable to the erosion and deposition of the débris of disintegration with merely slight loss of the feldspar. In the investigation of the regions which today can supply débris of disintegration for the formation of arkose (Figs. 1 and 2), it was found that disintegration is much more widespread than is perhaps usually realized, and that it takes place in marked amounts under practically all the conditions under which a granitic terrane is exposed (see Table I, a list of the occurrences of disintegration which have been observed by the writer, or which he has been able to find described in the literature, together with a tabular view of the conditions under which the disintegration is taking place). The investigation of the conditions under which the disintegrated material could be eroded and deposited as arkose seems to show that in some cases the conditions favorable to the disintegration are likewise favorable to contemporaneous erosion and deposition of the disintegrated material as arkose, as, for instance, in desert regions, and that in other cases erosion can take place only after some change of conditions, as, for example, a change from the conditions of a moist temperate climate to those of a semi-arid climate. In yet other cases, erosion may take place contemporaneously with disintegration but be followed by decom-

[1] Arkose by original definition and according to most general usage is a rock formed of the relatively undecomposed débris of granite or of rods of granitic mineralogical composition. It may be thought, however, that the original definition should be extended to cover feldspathic clastics derived from the disintegration of syenites, diorites, gabbros. Feldspathic clastics of this type, however, should be rare, since there are practically no purely syenitic, dioritic, or gabbroic terranes, and since the plagioclase feldspar of the diorites and gabbros is more or less readily decomposed. No specimen of this type of feldspathic clastic has been seen by the writer, and only one or two reputed occurrences are reported in the literature.

E

Loca	…nter Temperature			Rainfall			Remarks
				Yearly	Monthly		
	x.	Min.	Mean		Summer	Winter	
S.E. Ireland ..	...	....	....	50 in.	4 in.	5 in.	
Dartmoor, Engl	...	38 F. (Mean min. Jan.)	43 F.	60 to 80 in.	4 in.	5 in.	Medium-grained granite
Forez, France. Plateau Central	...	7 F.	36 F.	32 in.	4 in.	3 in.	Coarse porphyritic granite; fine-grained granite not affected
Morvan, Franc	ut the same as above			....	....	....	Coarse and porphyritic granites; fine-grained granite not affected
Hohkönigsburg, Alsace	...	....	34 F.	70 in.	....	....	Coarse, porphyritic granite
Heidelberg Shee	..	....	34 F.	60 in.	....	....	Coarse, porphyritic granite
Adlersberg, Thü	..	2 F.	32 F.	....	....	....	Medium-grained granite
Grimsel Pass, A	..	....	....	....	....	....	Medium-grained gneissic granite
Mer-de-Glace, A	..	....	....	....	....	....	Medium-grained gneissic granite
Aswan, Egypt.	.	45 F.	62 F.	0	0	0	Coarse, porphyritic, biotite granite
Pyramids of Giz	.	39 F.	55 F.	1.5 in.	0	0.3 in.	Coarse, porphyritic, biotite granite
Sinai..........	..	....	....	Less than 10 in.	....	....	
Bushmanland, S	. m- h 1)	....	....	Less than 10 in.			
Himalayas....	..	....	....	....	....	....	
Ceylon........	..	....	80 F.	Over 50 in.	¼ in June–July ¼ in Oct.–Nov.		
Lung-wang-shan	..	....	10 F.	30 in.	....	....	
Around Inland S	..	....	32 F.	85 in.	7 in.	9 in.	
Mt. Chocorua, I	..	....	....	....	....	....	Medium-grained pyroxene granite
Jackson, N.H. .	..	....	....	....	....	....	Medium-grained, with a slight amount of biotite
Rockport, Mass	.	−13 F. (For Boston)	65 F.	45 in.	3 to 4 in.	3 to 4 in.	Medium- to coarse-grained granite; hornblende granite
Sykesville, Md.	..	....	....	....	....	....	Fine-grained biotite granite
Washington, D.	.	−15 F.	34 F.	41 in.	3 to 4 in.	3 in.	Moderately fine mica granite
Richmond, Va.	..	....	....	....	....	....	Medium-grained mica granite
Georgia.......	. t-)	−8 F.	44 F.	49 in.	3 to 4 in.	5 in.	Fine- to medium-grained, porphyritic mica granite
Iron Mt., Mo. .	.	45 F.	74 F.	40 in.	4 in	2 to 2.5 in.	
Mt. Stuart, Was	..	....	....	....	....	....	Medium-grained granodiorite
Wasatch, Utah	..	....	....	....	....	....	
Butte, Mont. .	.	−29 F.	24 F.	13 in.	1 in.	0.8 in.	Medium to coarse-grained mica, hornblende, quartz monzonite
Pike's Peak, Col	..	....	6 F.	30 in.	1.5 to 4 in.	1.2 to 2 in.	Coarse to coarse and porphyritic granite
Globe District, A	.	22 F.	50 F.	17 in.	4 in.	....	
California: Si Sierra Madre	..	....	....	Very light	....	....	Granodiorite
Lower California	..	....	....	Very light	....	....	Granodiorite
Valparaiso, Chil	..	....	62 F.	29 in., ⅔ in June and July			Fe-bearing minerals decomposed
Sao Francisco, B	..	....	82 F.	12 in.	0 in.	1 to 2 in.	

Fig. 1.—Distribution of the occurrences of marked granular disintegration as reported in the literature or observed by the writer.

TABLE I

Tabular View of the Occurrences of Disintegration and of the Conditions under Which the Disintegration Is Taking Place

Locality	Lat.	Long.	Topography	Elevation	Situation of Disintegration	Depth to Which Disintegration Extends	Depth to Which Decomposition Extends	Amount of Decomposition Shown by Disintegrated Rock	Vegetative Covering	Summer Temperature			Winter Temperature			Rainfall			Remarks
										Max.	Min.	Mean	Max.	Min.	Mean	Yearly	Monthly: Summer	Monthly: Winter	
S.E. Ireland	53 N.	7 W.	Mature to old	Under 2,000 ft.	....	....	....	....	Grass and brush	......	......	57 F.	......	......	......	50 in.	4 in.	5 in.	
Dartmoor, England	51 N.	4 W.	Old	1,500 ft.	General	6 to 15 ft.	3 to 8 ft. Locally some hundreds of feet	Considerable	Heather and moss	68 F. (Mean max. July)	......	60 F.	......	38 F. (Mean min. Jan.)	43 F.	60 to 80 in.	4 in.	5 in.	Medium-grained granite
Forez, France; Plateau Central, France	45 N.; 46 N.	4 E.; 3 E.	Old	1,500 ft.	General	10 to 30 ft.	1 to 4 ft.	Noticeable though not very advanced	Grass and woods	95 F. (Mean extremes)	......	64 F.	......	7 F.	36 F.	32 in.	4 in.	3 in.	Coarse porphyritic granite; fine-grained granite not affected
Morvan, France	47 N.	4 E.	Old	1,500 ft.	General	5 to 25 ft.	1 to 4 ft.	Noticeable though not very advanced	Grass and woods	About the same			About the same as above			......	......	......	Coarse and porphyritic granites; fine-grained granite not affected
Hohkönigsburg, Vosges Mts., Alsace	48 N.	7 E.	Mature	1,500 ft.	General	8 to 20 ft. plus	1 to 4 ft.	Noticeable though not very advanced	Forest	......	......	64 F.	......	......	34 F.	70 in.	......	......	Coarse, porphyritic granite
Heidelberg Sheet	49 N.	9 E.	Mature	800 ft.	General	5 to 10 ft.	1 ft.	Noticeable though not very advanced	Forest	......	......	64 F.	......	......	34 F.	60 in.	......	......	Coarse, porphyritic granite
Adlersberg, Thüringerwald	51 N.	11 E.	Late maturity	2,000 ft.	....	5 to 8 ft.	1 to 2 ft.	Noticeable though not very advanced	Forest	......	......	......	......	2 F.	32 F.	......	......	......	Medium-grained granite
Grimsel Pass, Alps	47 N.	8 E.	Young, glaciated mountains	6,500 ft.	Only valley seen	Superficial	....	Very slight	Light or none	(Rigi-Kulm)		39 F.	......	......	......	......	......	......	Medium-grained gneissic granite
Mer-de-Glace, Alps	46 N.	7 E.	Surface of alpine glacier	5,500 ft.	Surface	Superficial	....	Very slight	None	......	......	......	......	......	......	......	......	......	Medium-grained gneissic granite
Aswan, Egypt	24 N.	32 E.	Shallow young valley	400 ft.	General	Superficial, locally 10 ft.	None	For the most part very slight	None	112 F. (Mean extremes)	72 F.	93 F.	90 F.	45 F.	62 F.	.0	0	0	Coarse, porphyritic, biotite granite
Pyramids of Gizeh, Egypt	30 N.	31 E.	Pyramids on a plateau	Less than 400 ft.	Surface of the pyramids	2/3 cm.	....	Very slight	None	104 F.	64 F.	82 F.	75 F.	39 F.	55 F.	1.5 in.	0	0.3 in.	Coarse, porphyritic, biotite granite
Sinai	30 N.	34 E.	Rugged	....	Valley sides	Partly superficial	....	Very slight	None	......	......	......	......	......	......	Less than 10 in	......	......	
Bushmanland, S. Africa	30 S.	20 E.	....	....	....	Superficial	....	Very slight	None or very light	......	......	51 F. (Coldest month)	82 F. (Warmest month mean)	......	......	Less than 10 in			
Himalayas	34 N.	76 E.	Young, mountainous	Above 14,000 ft.	Exposed surfaces	Superficial	....	Very slight	None	......	......	......	......	......	......	......	......	......	
Ceylon	8 N.	80 E.	Mountainous	....	General	Few feet	Slight	....	Forest	......	......	82 F.	......	......	80 F.	Over 50 in.	¼ in June–July; ¼ in Oct.–Nov.		
Lung-wang-shan, China	41 N.	124 E.	Mountainous	....	Rolling valley in mountains	"Tiefgreifend"	Slight	....	None	......	......	75 F.	......	......	10 F.	30 in.	......	......	
Around Inland Sea, Japan	38 N.	138 E.	High coast hills	....	General	....	Slight	Very slight	Light forest	......	......	75 F.	......	......	32 F.	85 in.	7 in.	9 in	
Mt. Chocorua, N.H.	44 N.	71 W.	Mature, mountainous	3,500 ft.	Summit and flanks of mountain	Mostly superficial	....	Very slight	Mostly none; some forest	......	......	......	......	......	......	......	......	......	Medium-grained pyroxene granite
Jackson, N.H.	44 N.	71 W.	Mature, mountainous	700 ft.	Valley	5 ft. plus	Slight	Noticeable though slight	Forest and grass	......	......	......	......	......	......	......	......	......	Medium-grained, with a slight amount of biotite
Rockport, Mass.	43 N.	71 W.	Glaciated peneplain	100 ft.	Chiefly shown in glacial boulders	Superficial	....	Noticeable though slight	Lichens	100 F. (For Boston)	45 F.	65 F.	70 F.	−13 F. (For Boston)	65 F.	45 in.	3 to 4 in.	3 to 4 in.	Medium- to coarse-grained granite; hornblende granite
Sykesville, Md.	39 N.	77 W.	Old	400 ft.	Surface generally	30 ft. plus and minus	15 ft.	....	Grass and forest	See Washington			......	......	......	......	......	......	Fine-grained biotite granite
Washington, D.C.	39 N.	77 W.	Old	50 ft.	Surface generally	20 to 80 ft.	Considerable	Considerable; at surface complete	Grass and forest	104 F.	36 F.	75 F.	78 F.	−15 F.	34 F.	41 in.	3 to 4 in.	3 in.	Moderately fine mica granite
Richmond, Va.	37 N.	77 W.	Old	50 ft.	Surface generally	10 ft. plus	5 ft. plus	Considerable; at surface complete	Grass and forest	See Washington			......	......	......	......	......	......	Medium-grained mica granite
Georgia	34 N.	84 W.	Old	1,200 ft.	Surface generally	Incipient decay to 350 ft. (around Atlanta)	95 ft.	Considerable; at surface complete	Grass and forest	100 F.	55 F.	75 F.	73 F. (For Atlanta)	−8 F.	41 F.	49 in.	3 to 4 in.	5 in.	Fine- to medium-grained, porphyritic mica granite
Iron Mt., Mo.	37 N.	91 W.	Old	1,200 ft.	Surface generally	20–80 ft.	20 to 80 ft.	Considerable; at surface complete	....	105 F.	45 F.	75 F.	76 F.	45 F.	74 F.	40 in.	4 in	2 to 2.5 in.	
Mt. Stuart, Wash.	47 N.	121 W.	Ruggedly mountainous	9,470 ft.	Summit and exposed portions of flanks	Superficial	....	Slight	Light	......	......	......	......	......	......	......	......	......	Medium-grained granodiorite
Wasatch, Utah	40 N.	111 W.	Ruggedly mountainous	6,000 ft.	Oldest moraine at base of range	20 ft.	Slight	Slight	Light	94 F.	33 F.	60 F.	......	......	......	......	......	......	
Butte, Mont.	46 N.	112 W.	Rugged maturity	6,000 ft.	General	20 ft. plus and minus	Slight	Slight	Light	94 F.	33 F.	60 F.	58 F.	−29 F.	24 F.	13 in.	1 in.	0.8 in.	Medium to coarse-grained mica, hornblende, quartz monzonite
Pike's Peak, Colo.	39 N.	105 W.	Monadnock and peneplain	9,000 ft. 14,000 ft.	Summit and plateau	30 ft. in places; superficial in others	Slight	Slight	Light	......	......	37 F.	......	......	6 F.	30 in.	1.5 to 4 in.	1.2 to 2 in.	Coarse to coarse and porphyritic granite
Globe District, Arizona	34 N.	111 W.	Rugged maturity	6,000 ft.	....	Superficial	Slight	Slight	Grass and woods and light	117 F.	64 F.	90 F.	80 F.	22 F.	50 F.	17 in.	4 in.	......	
California: Sierra Nevada, Sierra Madre	34 N.	119 W.	Ruggedly mountainous	Above 6,000 ft.	Higher slopes	....	Slight	Slight	Light	......	......	......	......	......	......	Very light	......	......	Granodiorite
Lower California	29 N. 31 N.	115 W.	Mountainous	....	....	....	Slight	Slight	Light	......	......	......	......	......	......	Very light	......	......	Granodiorite
Valparaiso, Chile	33 S.	72 W.	Rugged	Less than 1,000 ft.	On ridge	....	....	Slight	Light	80 F. (Mean extremes)	44 F.	52 F.	......	......	62 F.	29 in., ¾ in June and July			Fe-bearing minerals decomposed
Sao Francisco, Brazil	9 S.	40 W.	....	....	....	100 ft. to 300 ft. 60 ft. average	....	Noticeable; at surface complete	....	88 F.	72 F.	76 F.	......	......	82 F.	12 in.	0 in.	1 to 2 in.	

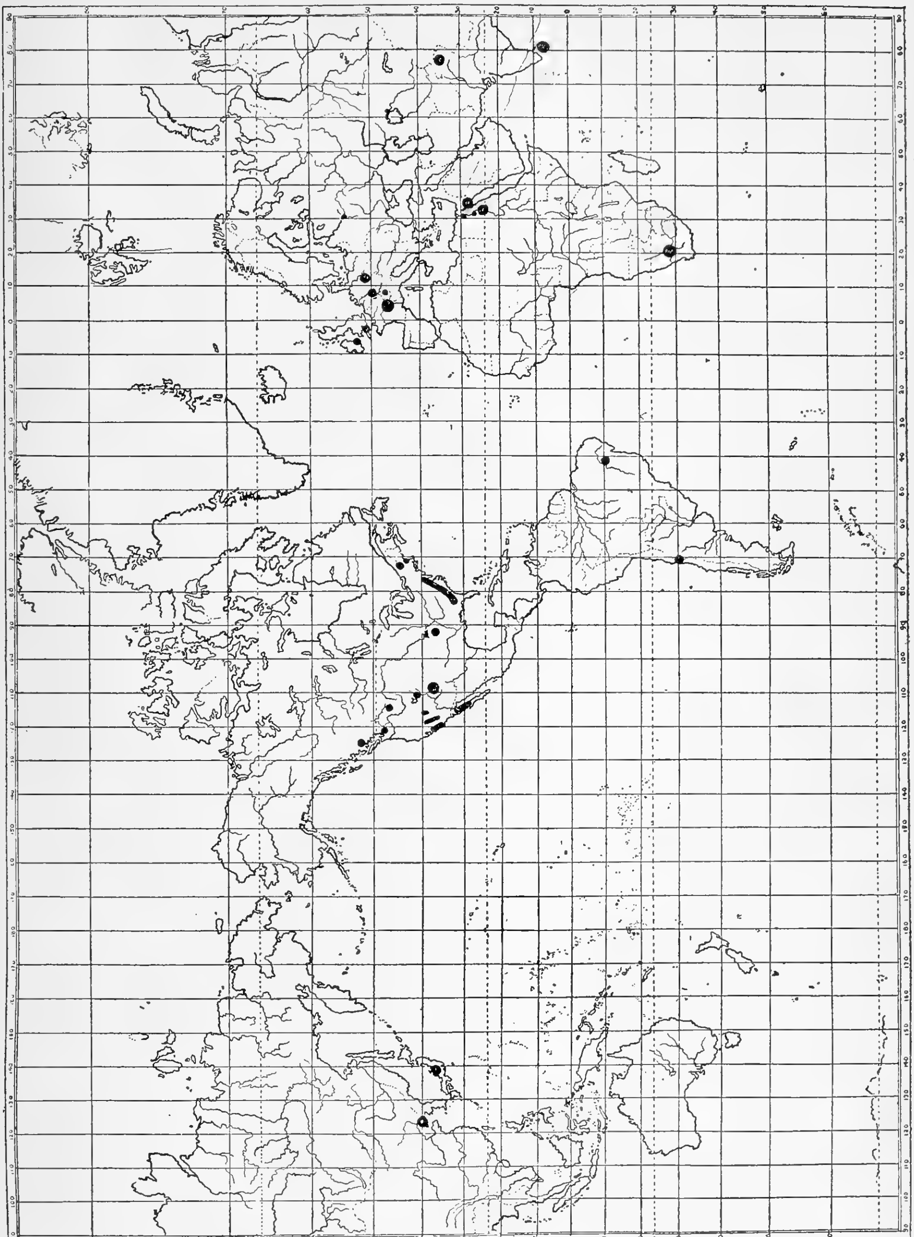

FIG. 1.—Distribution of the occurrences of marked granular disintegration as reported in the literature or observed by the writer.

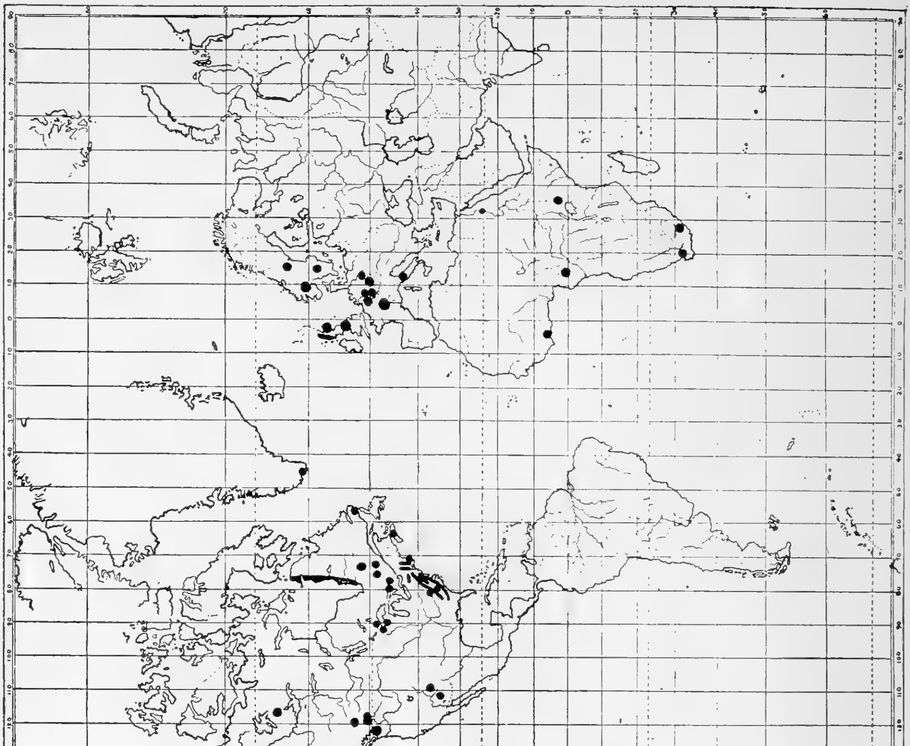

FIG. 2.—Occurrence of arkose deposits as reported in the literature or observed by the writer.

position of the feldspar, with the consequent loss of the material as a possible source of arkose. It was therefore found impossible to limit the significance of arkose to significance of any one or two special sets of conditions. The arkose deposits forming under the different conditions should expectedly be of certain characteristic types, which as a matter of fact agree with the types of arkose deposits as they are found (see Table II). The genetic classification of arkose deposits which appears in the following pages is therefore intended to embrace these various types of arkose deposits.

GENETIC CLASSIFICATION OF ARKOSE DEPOSITS

Arkose deposits may be divided broadly into two classes: (*a*) those formed directly through the effects of rigorous climatic conditions; and (*b*) those formed, at least indirectly, through the effects of moist and more temperate climatic conditions. The latter conditions allow much decomposition, which, however, commonly takes place at a slower rate than the disintegration. The arkose formed directly or indirectly under these conditions therefore has feldspars showing considerable decomposition, has in many cases a matrix of argillaceous material derived from the more easily decomposed grains of feldspar and other silicates, and is associated with beds of argillaceous material derived from the totally decomposed portions of the rock. The former conditions are unfavorable to decomposition, and the arkose deposits forming under them have comparatively unaltered feldspars, have little or no argillaceous matrix, and are not associated to any great extent with argillaceous beds. The distinction, however, is not absolute. At Aswan, Egypt, in a region in which no rain is recorded over a period of many years, the disintegrated granite in some places shows marked decomposition, and the feldspar of modern arkose deposits in the beds of the wet-weather streams of the region is deeply decomposed. In regions of moist, temperate climate it is not uncommon, on the other hand, to find below the zone of complete disintegration a zone of rock which to the eye seems fresh but which crumbles readily under blows from the hammer, and from this rock, within a region of moist, temperate climate, it would be possible for arkose with relatively fresh feldspar to form.

TABLE II

TABULAR VIEW OF THE OCCURENCE, CHARACTER, AND ASSOCIATIONS OF THE ARKOSE DEPOSITS KNOWN TO THE WRITER THROUGH THE LITERATURE OR THROUGH PERSONAL OBSERVATION

Formation and Region	Section	Character of Arkose	Remarks
	NORTH AMERICA		
	PRE-CAMBRIAN		
Hudson Bay (east coast)	Red sandstone and argillite and greywacke 600 ft. Arkose and greywacke 1,000 ft. Arkose	More or less rounded grains and pebbles of quartz and feldspar	Arkose, coarse at base, grading upward
Quebec: Nottaway River, St. Michel, Ranges III, X, XI	With dolomite, quartzite, conglomerate, and greywacke	More or less angular grains of orthoclase quartz and plagioclase	
Copper Cliff arkose, Sudbury, Ont.	Quartzite Greywacke Arkose	Felsitic-looking, interlocking grains, quartz and feldspars	Greywacke well stratified Arkose with little or no stratification
Loraine arkose, Cobalt, Ont.	900 ft. {Quartzite, Arkose} Granite		Transition both into quartzite and into the granite
Temiscaming arkose, Nipissing District, Ont.	Arkose Granite	Quartzose and sericitic	Arkose grades into the granite
French River Quad., Ont.	With greywacke, quartzite, dolomite, agglomerate	In heavy bands	Possibly not arkose but tuff
Arkose, quartz slate, Penokee District, Lake Superior	Quartzite Arkose	Quartz, feldspars, mica and fine matrix	Arkose one phase of the quartz slate
Oak Portage	Arkose Sagana granite	Angular quartz and decayed feldspar in fine matrix	
Amnicon Formation, St. Louis River, Wis.	730 ft. {Red shale, grits, sandstone and conglomerate, and arkose}	Grains angular, poorly assorted	Three out of forty-five beds are arkose. Mud-cracks, raindrop prints, cross-bedding

Orienta sandstone, Wisconsin	1,500 ft.	White and red sandstone, brownstone, white and pink sandstone	Quartzose argillaceous	Mud-cracks, raindrop prints, cross-bedding
	1,800 ft.	Brown, red, and white sandstone, grading into arkose		
Belt Formation, Albert Canyon, B.C.		Limestone and argillite Quartzite Arkose Granite	Metamorphosed	Arkose is really a subordinate basal phase of the quartzite
Hotauto conglomerate, Shinumo Quad., Colo.		Limestone		Unsorted
	0.6 ft.	Arkose conglomerate and arkose argillite		
		Quartz diorite		
		CAMBRIAN		
Eastern United States:		The base of Cambrian arkosic Georgia to Vermont		
Snowbird Formation, North Carolina	300–2,500 ft.	Conglomerate with arkosic matrix	Moderately rounded quartz and feldspars in a fine-grained quartz-sericite matrix	The arkose is the basal of the quartzite
	900–1,500 ft.	Slate, greywacke, and feldspathic sandstone and limestone		
	350–5,000 ft.	Quartzite with arkose and conglomerate		
		Granite and gneiss		
Hardistonville quartzite, New Jersey		Limestone Quartzite and arkose Granite and limestone	Moderately rounded quartz and feldspar in fine matrix	Arkose a phase of the quartzite
Vermont Formation, Massachusetts and Vermont		Limestone Quartzite Arkose conglomerate Granite and gneiss	Metamorphic	
Labrador: Straits of Belle Isle		Limestone		
	231 ft.	Red and gray sandstone and arkose Arkosic conglomerate		

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	CAMBRIAN—*Continued*		
Reagan Sandstone, Oklahoma	370 ft. {Grit, sand with green sand, and clay 30 ft. Arkose and quartzite Granite and porphyry	Arkose, coarse	
Bolsa Quartzite, Bisbee, Ariz.	Quartzite with arkosic matrix and phases Granite and gneiss		
	SILURIAN		
Littleton, N.H.	150–500 ft. Dev. argillite 200–300 ft. Arkose 200 ft. {Limestone and slate Limestone} 2–80 ft. Arkose and quartzite Granite-gneiss	Basal arkose, granitic in appearance, feldspars and quartz in fine matrix Upper arkose finer, more uniform, becomes quartzitic at top	Basal arkose grades into the granite Faint stratification
	DEVONIAN		
Igaliko sandstone, Greenland	Sandstone 30–40 ft. Reddish and greenish arkose Granite	Granitic in appearance	The arkose is a basal phase of the sandstone
	CARBONIFEROUS		
Narraganset Basin	> 100 ft. Sandstone and shale, arkose and coal and conglomerate < 100 ft. Red shale < 100 ft. Arkose Granite	Basal arkose, sometimes granitic, more often quartzose Fine matrix—coarse Upper arkose fine-grained quartzose with fine matrix, both gray in color	Locally arkose grades into granite—massive or much cross-bedded—interbedded with the red shale, which has raindrop prints and sun-baked surfaces

Rockwell Formation, Meadow Branch Mts., W.Va.	540 ft.	Arkose, sandstone, and shale with thin coal beds	Coarse, gray	Arkose basal phase of the Carboniferous
Myers Shale, Meadow Branch Mts., W.Va.	60 ft.	Red shale Arkose	Coarse, gritty, reddish-gray	Arkose cross-bedded
Horton Series, Nova Scotia		Arkose Granite and sediments	Medium and fine-grained, granitic in appearance, micaceous gray	Arkose with red shale intercalations carrying plant-fossils
		PERMIAN		
Cutler Formation, Colo.	1,500 ft. (total) 215 ft. (arkose)	Reddish Sandstones Arkose, grits, conglomerates, shale, and limestone	Quartzose and reddish	Part of the "Red Beds." Cross-bedding common
Fountain Formation, Colo.	500–1,500 ft.	Rough arkose grading into conglomerate, shale, and sandstone—all red	Coarse, rough, reddish	Part of the "Red Beds." Cross-bedding common
		TRIASSIC		
Sugar Loaf Arkose, Connecticut River, Mass. and Conn.		Sandstone Shale Arkosic sandstones and conglomerate with shale—base arkose Granite and gneiss	All rocks reddish Arkose varies from arkose conglomerate to granitic arkose and to arkosic grits Matrix of argillaceous material	All beds but shale much cross-bedded. Shale with mud-cracks, raindrop prints, reptile tracks, etc.
Stockton Arkose, N.Y., N.J., Md.	1,800–3,600 ft. 2,300–3,100 ft.	Argillite Reddish and yellowish to gray sandstone with some red shale and arkose and conglomerate at the base	Same as Sugarloaf arkose	Same as Sugarloaf arkose Arkose in thick beds or lenses

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	TRIASSIC—*Continued*		
Tackahoe Group, Richmond Coal Basin, Va.	500 ft. Coarse sandstone (often feldspathic)	Granitic in appearance	Arkose occurs not only at base but in beds at nearly all horizons. Cross-bedding common
	2,000 ft. Black shale with gray sandstone	Angular grains quartz and feldspars in fine-grained matrix	
	500 ft. {Coal, black shales, feldpathic sandstones	Upper arkose reddish	
	0–300 ft. Sandstones, shale		
	Arkose	Main arkose gray	
	Granite		
	JURASSIC		
Skwenta Series, Alaska	Tuffs, slates, and arkose	Fine-grained, dark-green, massive	
Terra-cotta Series, Alaska	Impure limestones, slates, and diorite-arkose		
Naknek Series, Alaska	Arkose and conglomerate	Coarse to fine, hard and massive, in thick beds	Marine fossils in the arkose
	COMANCHEAN		
Patuxent Formation, Atlantic Coastal Plain	350 ft. Sand, arkose, and clay; granite	Decomposed	Fossil plants present
	CRETACEOUS		
Tordrillo Series, Alaska	Black and carbonaceous shales with limestone, sandstone, and arkose		Plant remains in the arkose and in the shales
Holiknuk Series, Alaska	Alternating sandstone and limestone, shale and arkose	Shale and arkose carbonaceous locally	Plant remains and ripple-marks in the shale and the arkose
Oklune Series, Orca Series, Alaska	Very similar to the preceding		

Paysaten arkose, Mt. Hozomeen, B.C.	3,000 ft. Gray to black argillite 7,100 ft. Gray to green feldspathic sandstone with black argillite lenses 1,400 ft. Coarse conglomerate 300 ft. Argillite 3,500 ft. Green feldspathic sandstone 200 ft. Coarse conglomerate 1,500 ft. Gray to green feldspathic sandstone 100 ft. Conglomerate 1,100 ft. Feldspathic sandstone 600 ft. Red argillite and sandstone 10,000 ft. Massive arkose Volcanic agglomerate Granodiorite	Light-gray, medium-grained, granitic in appearance; angular grains of feldspars and quartz with no matrix; feldspar fresher than in most arkose	Arkose shows little variation in character and little stratification. Plant fossils at two horizons
EOCENE AND OLIGOCENE			
Kettle River Formation, Phoenix, B.C.	Conglomerate, coarse and fine sandstone, carbonaceous shales, and arkose	Quartzose	
Swank Formation, Yakima Valley, Washington	3,500–5,000 ft. Arkose, carbonaceous shales, sandstone with arkose or conglomerate at the base		
Puget Formation, Puget Sound, Washington	5,500 ft. Sandstone and arkose with shale and coal beds	Arkose variable in different layers—some granitic in appearance, some grading into sandstone, bluish-gray in color	All the beds carbonaceous Formation is thinly bedded and with much cross-bedding
Kenai Formation, Alaska	Sandstone, shale, and conglomerate, with coal seams Arkose Quartz diorite	Arkose in part granitic in appearance	

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	EOCENE AND OLIGOCENE—*Continued*		
Controller Bay region	2,500 ft. Shale and sandstone with coal, arkose, and conglomerate		The different rocks are in monotonous repetition
	EUROPE		
	PRE-CAMBRIAN		
Torridonian sandstone, Scotland	3,000–4,000 ft. Red and gray sandstone and flags, dark shales 5,000–8,000 ft. Red arkose with rare red shales 500 ft. Red sandstone and mudstone with dark shale breccia at base 7,200 ft. In Skye, gray, and buff arkose Lewisian gneiss	Upper arkose (Applecross) granitic in appearance, composed of moderately rounded to well-rounded grains of fairly fresh feldspar and quartz with no matrix	Arkose massively bedded and almost always cross-bedded Dreikantes and raindrop prints occasionally present The arkose is very uniform throughout
Sparagmite, Norway	>5,000 ft. Red arkose and sandstone with breccia, quartzite, and conglomerate	Subangular to moderately well-rounded grains of fresh feldspar and quartz	Similar to Torredonian arkose
Jotnian, Angermanland	White or yellow quartzite with brown shale and with conglomerate Arkose Granite		
	CAMBRIAN		
Scandinavia	Sandstone grading into arkose at base Arckaean crystallines		

		DEVONIAN		
Gedinnian Formation, Ardennes and Eifel districts	10–300 ft.	Shales and sandstones Arkose and sandstone, thin conglomerate	Sericite meta-arkose Quartz grains partially rounded	Bedding even Arkose in beds 3–5 ft. thick. Associated beds with marine fossils
Old Red sandstone, Great Britain			Some granitic in appearance, some conglomeratic Color, pink to red Feldspar fresh	Several phases of the Lower Old Red Sandstone would seem to be arkose
		CARBONIFEROUS		
Berghaupten, Baden	300 ft.	Interbedded arkose, coal, shale, and conglomerate Granite and gneiss	Arkose granitic in appearance, often coarse, sometimes fine, massive, carbonaceous	Coarse cross-bedding common Carbonized plant remains in arkose
Baden-Baden, Baden		Small basin much similar to the preceding		
Hinterohlsbach Basin				
Openau, Baden				
Hohengeroldseck, Baden	130 ft. 90 ft.	Arkose with coal and sandstone Brown micaceous sandstone Coarse arkose Gneiss		
Relsen Coal Basin		Red and white sandy clay Arkose Clay Sandstone Black argillite Arkose Argillite		
Braunau and Kalna Formations		Arkose, reddish sandstone and shale and marl		
Riesengebirge				
Kladrio-Rakonitzer Coal Basin		Base of coal measures sandy slate and arkose		

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	CARBONIFEROUS—*Continued*		
Laach, Vosges Mts.	210 ft. Grayish arkose with fine conglomerate 6 ft. Coarse conglomerate 18 ft. Small bed of coal Grayish arkose Gneiss	In part granitic in appearance; subangular grains quartz and much kaolinized feldspar in fine matrix	Carbonized plant remains in the arkose
Erlenbach and Weiler, Vosges Mts.	Arkose of similar character and relations		Thought to be a delta deposit
Lower Rotliegendes and Upper Carboniferous, Ottweiler, Rhine Province	Conglomerate and feldspathic sandstone Black shale and yellow, fine-grained sandstone Shale and sandstone with coarse conglomerate Gray sandstone and shale with a little coal Reddish arkose, shale, and feldspathic sandstone Gray shale Red sandstone and shale	Quartzose, grains subangular, matrix about 20 per cent	Stratification rough; beds roughly 3 ft. thick, cross-bedding common Very similar to arkose of Triassic of Massachusetts, New York, and New Jersey
Yorkshire Coal Field, England	In coal measures	Granitic in appearance; color bluish or grayish	Irregularly bedded; much cross-bedding
Flint Ruthin and Mold, England		Gray in color; granitic in appearance	
	ROTLIEGENDES		
Cuseler and Tholeyer Beds, Saar and Nahe District, Germany	Reddish feldspathic sandstone, arkose, shale, and conglomerate with rare gray shale and limestone	Quartzose; feldspar now decomposed	Roughly bedded; cross-bedding common

Tholeyer Beds, Mainz Basin, Germany		Red arkose with red shale, sandstone, mudstone, and marl	Quartzose; feldspar now completely decomposed	Arkose is in massive, even layers, with rare cross-bedding Lithologically very similar to arkose of the Triassic of Massachusetts, Connecticut, New York, and New Jersey
Heidelberg, Germany		Tuffs		
		Arkose and tuffs	Coarse and granitic in appearance	
		Granite		
Baden-Baden, Germany		Red sandstone, shale conglomerate with arkose		
		Black and variegated shale		
		Arkose and variegated shale		
		Granite		
Oppenau, Black Forest		Arkose with dark shales, sandstone, and conglomerate		
Lebach beds, Schramberg, Black Forest	100 ft.	Alternating gray arkose and shale		Plant impressions in the shale
Schöpfheim, Black Forest		Feldspathic sandstone with arkose and dolomite	Quartzose, red feldspar now completely kaolinized	Stratification rather even, massive. Facetted pebbles possibly present
		Reddish shales, mudstones		
		Conglomerate, arkose, and sandstone		
Trienbach beds, Vosges Mts.	90 ft.	Purple shale with arkose intercalations	In part very granitic in appearance	Plant fossils present
	60 ft.	Gray arkose with shale		
	60 ft.	Arkose with conglomerate granite, schist, or Erlenbach beds		
Kohlbachel beds, Vosges Mts.	540–600 ft.	Reddish arkose, shales, conglomerate, and breccia	Quartzose	The arkose is only a local phase of the sandstone

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	ROTLIEGENDES—*Continued*		
Thuringia Forest	Conglomerate, shale, sandstone, arkose, and breccia Granite	Coarse, gray, with fine matrix	The arkose is a basal phase, but is not derived from the underlying granite
	TRIASSIC		
Morvan district, France	Limestone and gypsum 30 ft. Arkose and marl 90 ft. Arkose with clayey intercalations Granite	Quartzose and heavily silicified, constituent grains showing much rounding; fine-grained silicified matrix	Lower arkose in massive, even beds at the base, with thin shale beds toward the top with reptile tracks
Rémilly, near Dijon Aubenais, Ardecke Chessy, near Lyons	Somewhat similar arkose, possibly the equivalent of the preceding arkose		
Rhaetic beds Bunt Keuper beds Franconia	600 ft. Sandstone, grading into arkose in the Palatinate at Parkstein and vicinity 150 ft. Red argillite 60 ft. Sandstone, locally feldspathic Dolomitic arkose, limestone, reddish clay, and marl Sandstone, clay, marl, and arkose	Mostly very quartzose with or without much matrix	The deposits, especially of the arkose, are supposed by Thürach to be shore deposits
	TERTIARY ARKOSE		
Stampian Beds Sannoisian beds Limagne, France	Marls and limestone Arkoses, sandstones and marls, grits (Sandy clays, limestone and basal arkose in southern part of the basin only) Granite	Coarse to fine, in part very granitic in appearance, usually with more or less argillaceous matrix	Arkose is in more or less massive beds; rarely there is some cross-bedding

Basin of Lembron Basin of Forez France	Arkose deposits similar to the preceding and probably equivalent to them		
ASIA			
Yang-Tzi Province	Tillite (Cambrian) 150 ft. { Coarse sandstone and conglomerate Arkose and conglomerate } Granite		
Wu-t'ai System	Pelites Psammites Arkose T'ai-shan gneiss	Much metamorphosed	
Alwar Formation, India	Quartzite with basal arkose		
Araveli Group, India	Gneiss, schist, and quartzite		The gneiss is believed by Oldham possibly to represent arkose
Bawar Formation, India	Limestone and carbonaceous shales Quartzite and arkose Granite	In parts granitic and very similar in appearance to the underlying granite	
Eocene beds, Upper Indus	Heterogeneous sandstones and conglomerates, possibly with some arkose		
AFRICA			
Congo Series, Matjé's River, Cape Colony		Coarse, granitic in appearance, matrix of quartz and sericite	
Congo Series, French Hock, Cape Colony	Limestone Arkose and feldspathic grits Conglomerate Granite	Granitic in appearance	Locally the arkose grades into the granite

TABLE II—*Continued*

Formation and Region	Section	Character of Arkose	Remarks
	AFRICA—*Continued*		
Nieuwerust Series, Cape Colony	Dark shale and sandstone Arkosic conglomerate with shale and sandstone Gneiss		
Black Reef Series, Cape Colony	Quartzite and slate Arkose and conglomerate Granite		
Gold Coast	Arkose with clayey and pebbly beds	Reddish grit with angular grains	
Carboniferous and Devonian, French Congo	Arkose, whitish sandstone and dolomitic layers Greenish and reddish shales and calcareous sandstones Arkose Crystalline schists		
Lake Rudolf, British East Africa	Grauwacke and arkose Crystalline schists	Reddish, quarfzose with fine matrix	
Nubian sandstone	Argillaceous sandstone and conglomerate Arkose Granite	Very granitic in appearance	Faint stratification possibly present in upper part of the arkose; the arkose grades into the granite
	AUSTRALIA AND SOUTH AMERICA		
No account of arkose either in Australia or in South America has come to the notice of the writer			

A. ARKOSE DEPOSITS FORMED ENTIRELY UNDER RIGOROUS CLIMATIC CONDITIONS

Feldspar showing merely slight decomposition.[1] Argillaceous material absent or present in minor amounts.[2]

1. *Deposits formed in desert regions.*—The deposits are massive, homogeneous, and in some cases of very large size. In desert regions, the disintegration takes place chiefly on outcrops directly exposed and not protected, as in moist temperate regions, by a mantle of vegetation. The débris of disintegration is easily eroded and the processes of erosion and disintegration and deposition of the eroded, disintegrated material as arkose can therefore take place contemporaneously, and can continue as long as the desert conditions persist and as long as the granitic terrane remains unburied. The size of an arkose deposit formed under such conditions will therefore depend chiefly on the size of the terrane of disintegration, the size of the basin of deposition, and the length of time the desert conditions prevail. The constancy of the conditions during the period of formation should be marked by a massiveness and homogeneity of the deposits.

a) Terrestrial: In deserts, wind action prevails the greater part of the time, but rare storms do occur and in the short space of their existence do an immense amount of work. Deposits of arkose formed in desert regions therefore are likely to be in part of eolian and in part of aqueous origin. The arkose shows in part the eolian characteristics of well-rounded sand grains, faceted pebbles, local lag-gravels, dune stratification, etc., and in part the ordinary characteristics of water action. In deposits of arkose forming in arid mountain regions, the greater part of the transportation of the disintegrated material may be by water action, during the rare cloudbursts, and by the streaming of the débris down the hill slopes under gravity. The constituent grains in this case are subangular, and quartz and feldspar grains should be present in about the same proportions as in the original granite or gneiss, since the amount of

[1] At the time of formation of the arkose. Subsequent exposure may produce complete decomposition.

[2] The possibility of the presence of exotic material brought in by a river whose headwaters lie in a temperate or tropical region should not be forgotten.

transportation undergone should not be sufficient to cause marked comminution and loss of the feldspar. The deposits as a whole should be rather massive, but with cut-and-fill stratification rather common, and with considerable intercalation of coarse block débris toward the sides of the valleys.

An example of this type of deposit is found in the Applecross group of the Torridonian sandstone, a pre-Cambrian formation extensively developed in the Northwest Highlands of Scotland. The ideal section of the Torridonian sandstone is given by the Geological Survey[1] as shown in Table III. The Applecross group

TABLE III

Groups	Thickness	Composition	Chief Occurrence
3. Aultbea....	3,000–4,000 ft.	Sandstone, flags, dark and black shales, and calcareous bands passing down into chocolate and red sandstones, and gray micaceous flags with parting of gray and green shale	Loch Ewe and Loch Broom
2. Applecross..	5,000–8,000 ft.	Chocolate and red arkose with pebbles of quartzite, quartz-schist (felsite, jasper, etc.), and occasional red and chocolate shales	Cape Wrath to Skye
2. Diabaig....	500 ft. in Gairloch; 7,000 ft. in Skye	At top, fine red sandstone with red mudstone and gray shale; at base, coarse breccia of Lewisian gneiss. In Skye, gray and buff arkose in great thickness	Assynt to Skye

is a formation composed of massive arkose of very uniform character (Fig. 3), marked off by thin intercalations of fine quartzitic and shaly sandstone into persistent layers of rather uniform thickness—in each case three, six, or ten feet or so. Although extremely massive in texture, the arkose shows most irregular stratification and almost invariably is strongly cross-bedded. Walther reports cross-bedding indicative of dune formation, and faceted pebbles. The lithologic character of the arkose may be seen from the accompanying photomicrograph. In the finer-grained phases, quartz composes a slightly greater proportion of the whole than in this medium-grained phase (quartz about 60 per cent and feldspar 40 per cent), and the grains

[1] B. N. Peach, J. Horne, and others, "The Geologic Structure of the Northwest Highlands of Scotland," *Mem. Geol. Surv. Great Britain*, 1907.

show a slightly greater degree of rounding. It is notable that the predominant feldspar of the arkose, microcline, does not occur in the underlying terrane. Where the arkose rests directly on the mountainous topography of the underlying terrane, the arkose basally becomes a coarse breccia. One of the most striking features of this formation, with the exception of this basal portion, is its uniformity throughout its great thickness.

To this type of arkose deposit should be referred the following:

The Torridonian Arkose, pre-Cambrian of Scotland.

Arkose of the Sparagmite formation, pre-Cambrian of Scandinavia

Lower Old Red Sandstone, Scotland (in part)

Paysaten Arkose, Cretaceous, British Columbia–Washington

FIG. 3.—Photomicrograph of Terridonian arkose, Applecross, Scotland, showing the lack of matrix in a desert arkose. The rounding of the grains is rather obscured by secondary growth of the grains. Magnification, 15 diameters.

b) Marine: If marine conditions prevail adjacent to a granitic terrane in a desert region, marine arkose may form, having in part the characteristics of an eolian arkose. Some of the constituent grains in this case should show the rounded outlines of eolian sand grains. The deposits as a whole, however, should show the structure and stratification of marine sediments. To this type of deposit should be referred the arkose that is now forming along the east shore of the Gulf of California.

2. *High-altitude deposits.*—Local deposits, of small size and extent. The conditions of high altitude, according to Oldham and others, are peculiarly favorable to disintegration. Erosion of the disintegrated material takes place rapidly, with rapid deposition of it in many cases as arkose in local catchment basins of the intra-mountain valleys. As such a region is subject to general

degradation in the course of time, the deposits must be temporary in character, and usually of recent geologic age. They may be wholly or in part lacustrine, fluviatile, alluvial (cone or fan), landslide, or fluvioglacial. The stratification should be rather irregular, and the constituent grains should be angular to subangular.

To this type of deposit should be referred possibly some of the deposits of the Upper Indus Valley, although from the descriptions of the deposits it is not quite clear whether they are really arkosic or not.

Fig. 4.—Photomicrograph of Pondville (Mass.) arkose, an arkose formed under moist temperate conditions, showing the quartz and feldspar grains in a fine-grained matrix of quartz and argillaceous material. Magnification, 15 diameters.

3. *Deposits of cold (high-latitude, subglacial) climate.*—In the high latitudes, the effects of disintegration are not pronounced, or at least they are, not noted in the literature. "Disintegration" is reported many times, but in most cases it is clearly block disintegration that is meant, and in no case has the writer been able to make it out clearly to be granular disintegration. That the effects of the latter are not noticeable may be due in large part to the relatively recent glacial erosion of the products of the preglacial disintegration, or, in regions of considerable relief, it may be due in part to excessive block disintegration and erosion. As the temperature range is often great, and the lower part includes the critical point of freezing, and as, furthermore, hydration can take place at the surface during the summer and, in regions not too far north, at all times below the level of freezing, there would seem to be no theoretical reason why granular disintegration should not take place. Granitic and gneissic blocks exposed on the surface of glaciers in many cases show noticeable disintegration, although

the amount that takes place in this manner is slight. If disintegration takes place, the conditions would seem favorable to the erosion of the disintegrated material and its deposition in arkose deposits of small or moderate size, probably in association with glacial or fluvioglacial beds. To this type of deposit may possibly be referred some of the pre-Cambrian arkose of Canada.

B. DEPOSITS FORMED DIRECTLY OR INDIRECTLY THROUGH THE EFFECTS OF MOIST AND USUALLY TEMPERATURE CONDITIONS

Deposits of small or moderate size; the arkose commonly with a matrix of fine-grained argillaceous material and usually associated with argillaceous beds; feldspars commonly showing a moderate amount of decomposition (Fig. 4).

In the present regions of moist temperate climate, especially where the topography is in a mature or old-age stage of development, there is almost universally present a very considerable accumulation of disintegrated material which is available as a source of material for the formation of arkose. The following section, from the vicinity of Autun, France, in its essential features is characteristic of such regions as the granite terranes of Morvan, the Plateau Central, and Forez, France; the Vosges Mountains, the Odenwald, and the Thüringerwald, Germany; Dartmoor, England; the Piedmont belt and the Pike's Peak region, United States.

1 ft.........Mantle of vegetation; surface soil and subsoil of gritty brown clay with quartz and feldspar grains
6 ft.........Granitic sand and gravel, stained with limonite; feldspar showing considerable decomposition toward the surface, the amount decreasing with depth
$2+n$ ft........Granite more or less fresh on superficial examination, but crumbling under light blows of the hammer; depth difficult to estimate; fresh granite

The relative and absolute proportions of these zones vary greatly. The maximum depth to which disintegration was observed by the writer to have extended was 40 feet, at Royat (Puy-de-Dôme), France, and at Hohkönigsburg, Vosges Mountains. On Dartmoor and in the Piedmont belt decomposition is more in evidence than in France and, in the Piedmont belt especially, the zone of soil and subsoil is much larger in proportion to the zone of disintegrated material. The rate of disintegration under the conditions of a moist temperate climate seems to be rather slow—in New England there has been since the Glacial Period disintegration sufficient barely to efface the glacial striae and polish on granitic and gneissic ledges—and the very considerable amounts of disintegrated material generally found in those regions are the result of slow accumulation under the protection of the mantle of vegetation. General erosion of this disintegrated material and its subsequent deposition as arkose can take place only when the mantle of vegetation is critically weakened or destroyed. When this has once happened and the mantle of disintegrated material has been swept away, a long time must elapse before considerable amounts of the disintegrated material can again accumulate. The arkose deposits formed from the accumulated débris of disintegration in a moist temperate climate will therefore be of small or moderate size. As the mantle of soil and completely decomposed rock is eroded at the same time as the mantle of disintegrated material, the arkose is commonly associated with mudstones and shales, and, as the disintegration is accompanied by considerable decomposition, the arkose itself is likely to contain much argillaceous material and to have feldspars showing noticeable decomposition. Since stream transportation of débris results in the rather rapid elimination of the feldspars, the arkose is likely to grade into quartzite.

The causes which might critically weaken or overcome the mantle of vegetation and result in the erosion of the accumulated products of disintegration are: introduction of arid or semi-arid conditions, introduction of subglacial or glacial conditions, a marked increase of rainfall, a marine transgression, deforestation by forest fire, and marked upwarping. A marked change of climatic conditions toward aridity in a region previously of moist temperate climate would necessarily result in a marked diminution of the vegetation and in the exposure of the underlying disintegrated material to erosion during the occasional storms. Glacial conditions might result either in the erosion of the disintegrated material by the ice itself or in the exposure of the disintegrated material to erosion through the destruction of the vegetation of the temperate conditions without the introduction of an arctic flora sufficiently luxuriant to form anew the protective mantle of vegetation. A marked increase of the rainfall, it was suggested by Shaler, might be such that the streams would be competent to waste generally the land surface. A marine transgression would necessarily result in the working over of the materials of the regolith, irrespective of the luxuriance of the mantle of vegetation, and might easily result in the deposition of arkose. Forest fires are not uncommonly due to lightning and often are effective agents of deforestation. It would seem possible that a period of heavy rains following a severe forest fire might result in the general erosion of the mantle of disintegration. Upwarping of considerable amount would result in an increase of the stream gradients, in an increase or decrease of the rainfall, and in the lowering of the mean temperature. The total effect might possibly be conditions favorable to the general erosion of the mantle of disintegration. A very special cause is to be found in volcanic activity of the explosive type, which not uncommonly results in deforestation and desolation in limited local area. Of this type of deposit, in which the arkose should be associated with tuffs, there is at least one example, the Rotliegendes arkose north of Heidelberg, Germany.

In regions of youthful topography and considerable relief in a moist temperate climate, there would seem to be no reason why disintegration should not take place. That it is not seriously in evidence is probably due to the fact that it is masked by block disintegration and by rapid erosion. If it does take place, the débris that can be eroded at one time is of small amount and is lost through decomposition of the feldspars or through intermixture with the heterogeneous stream-borne sediment.

In tropical regions, decomposition commonly prevails over disintegration, but in two localities disintegration is reported as occurring with but slight accompanying decomposition. The débris in these cases, if eroded under normal conditions, would probably be lost through decomposition, but if eroded under the conditions of a marine transgression, or under the conditions of aridity, there would seem to be a strong possibility that a deposit of arkose might be formed. Except by means of a contained fauna or flora, such deposits would probably be indistinguishable from the corresponding types of deposits of the temperate zone. No deposits have been recognized to be of this type.

1. *Terrestrial.*—(*a*) Deposits laid down under semi-arid conditions: Arkose reddish, composed of subangular iron-stained grains of quartz and partially decomposed feldspar deeply in an iron-stained matrix of fine-grained quartz and of argillaceous material.

When the moist temperate conditions give way to those of aridity, the mantle of vegetation, weakened by the change, is no longer able to protect the accumulated products of decomposition and disintegration, and during the occasional violent storms they are quickly eroded, to be deposited with rapidity usually in the near-by valleys and catchment basins. Owing to deposition from torrential streams, the materials of the mantle of disintegrated material are laid down in coarsely stratified banks and lenses of arkose, showing much foreset and cut-and-fill cross-bedding. The soil and mantle of completely decomposed rock are deposited, partially sorted, as cross-bedded, argillaceous sandstones and as more finely and evenly stratified gritty mudstones. As the temporary lakes dry up, these mud beds become sun-baked and glazed and cracked and may receive raindrop prints. Under the conditions of alternate wetness and dryness, there should be almost complete decomposition of organic matter and oxidation of the iron.

Deposits of this type are not rare, and a good example may be found in the Sugarloaf arkose of the Connecticut River Triassic. The formation occurs in what was possibly a Triassic basin, and consists essentially of an unordered alternation and repetition of gritty, argillaceous sandstones, conglomerates, arkose, and sandy and calcareous mudstones. There is a coarse, general stratification whose dip initially was apparently low. In the beds of mudstone, even, fine stratification is the rule, but cut-and-fill bedding is found in a few places. The coarser strata are strongly cross-bedded, mostly with the foreset type of bedding. Cut-and-fill bedding, however, is common. The mudstones show mud-cracks, raindrop prints, glazed surfaces, and reptile footprints. The arkose is found in banks and lenses, chiefly at or near the base, but also at numerous higher horizons. It is composed of subangular grains of quartz and subangular grains and pebbles of feldspar in a fine-grained matrix of argillaceous material. The color of the whole formation is deep red, due to a heavy stain of ferric iron. Fossils are rare in the formation.

The following deposits are apparently of this type:

Arkose of the Amnicon formation, pre-Cambrian, Wisconsin

Sugarloaf arkose (Triassic), Connecticut River area, Massachusetts and Connecticut

Stockton arkose (Triassic), New York, New Jersey, Pennsylvania

Arkose of the Upper Carboniferous, Ottweiler, Rhine Province, Germany

Arkose of the Lower Rotliegendes, Rhine Province, Germany

Arkose of the Rotliegendes, Mainz Basin, Vosges Mountains and Black Forest, Germany

Arkose of the Old Red Sandstone, England

Arkose of the Cutler formation, Permian, Colorado(?)[1]

Arkose of the Fountain and Lower Wyoming formations (Permian), Colorado(?)[1]

(*b*) Deposits laid down under moist, chiefly temperate, conditions of climate: Arkose grayish, composed of subangular grains of quartz and of considerably decomposed feldspar in a matrix of fine-grained quartz and argillaceous material, in most cases carbonaceous, and in some cases carrying plant fossils; the arkose commonly associated with coal deposits.

The causes of a general erosion of the regolith in a region of moist temperate climate are not completely evident. The suggestion of the introduction of subglacial conditions as a possible cause seems not well founded, since the several glacial epochs of the Pleistocene do not seem to have caused a general erosion of the regolith of the Piedmont belt to the south of the glaciated area. It would seem reasonable to expect, furthermore, that the effect of the change on the mantle of vegetation would be a replacement of the temperate by arctic flora. The suggestion that a marked increase in the amount of the rainfall might be a sufficient cause would likewise seem not well founded, as an increase in the rainfall characteristically results in more luxuriant vegetation, with a consequent increase in the protective power of the mantle of vegetation.

[1] Commonly considered marine, but apparently very like the Newark beds of the Connecticut River and the New York-New Jersey Triassi areas.

Forest fires are another possible cause. They are very commonly due to natural causes and often are effective agents of deforestation. It would seem possible that a period of heavy rains following a severe forest fire might easily result in the general erosion of the regolith. Upwarping of considerable amount, with the consequent increase of stream gradients and lowering of the mean temperature, if associated with decrease in the amount of the rainfall, might possibly result in the general erosion of the regolith.

While these causes are thus in doubt, the fact of the formation of deposits under these general conditions seems to be indubitable. There is a characteristic type of arkose deposit which is usually associated with carboniferous beds or coal, which is itself carbonaceous or may even carry carbonized plant remains, and which therefore must have formed under moist climatic conditions. As the feldspar shows much decomposition, as there is an argillaceous matrix, and as the quartz and feldspar grains are distinctly angular to subangular, the constituent materials of the arkose would seem to have been derived from the débris of disintegration under moist temperate conditions. The arkose, commonly in part, is coarse and granitic in appearance and seems not to have been transported far from the point of origin of its constituent material, and in part usually is finer and less feldspathic, and seems to have been transported for a greater distance. Besides being associated with coal beds, the arkose is associated with conglomerates, impure sandstones, and silty mudstones. Cross-bedding is common, and many of the beds seem to be the result of rather rapid deposition. The color of this type of arkose is gray.

As an example of this type of deposit, there may be taken the arkose of the Richmond (Triassic) Coal Basin in Virginia. The lower portion of the section in the basin is as follows:[1]

Productive Coal Measures	500 ft.	Interstratified beds of bituminous coal, black shale, feldspathic and micaceous sandstones
Lower Barren Beds	0–300 ft.	Sandstones and shales under the coal beds, often with arkose
Boscabel Bowlder Beds	0–50 ft.	Local deposits of bowlders of gneiss and granite

[1] N. S. Shaler and J. B. Woodworth, *U.S.G.S. Nineteenth Ann. Rept.*, Part II (1897–98), pp. 423–26.

The arkosic beds are best developed about the granitic masses of the eastern margin, but reappear from horizon to horizon with increasing marks of waterwear. The arkose of the basal horizons is granitic in appearance, and by the inexpert eye might not be distinguished from the granite. The arkose is gray in color and is composed of subangular grains of quartz and much decomposed feldspar in an argillaceous matrix of small amount. The arkose of the higher horizons is not so granitic in appearance, there is a somewhat lower content of feldspar, and the quartz and feldspar grains are slightly more rounded. Some of the associated shale beds are carbonaceous, and locally there are small intercalations in the arkose of carbonaceous silty material.

To this type of deposit there should probably be referred:

The Carboniferous arkose of the Narragansett Basin, Rhode Island and Massachusetts

The arkose of the Rockwell formation (Mississippian), Meadow Branch Mountains, West Virginia

The arkose of the Vosges Mountains, the Black Forest, and adjacent parts of Bavaria

The arkose of the Coal Measures of the Yorkshire Coal Field, England

The arkose of the Coal Measures of the Flint, Rhutin, and Mold districts, England

The arkose of the Richmond (Triassic) Coal Basin, Virginia

The arkose of the Corwin formation (Jurassic), Alaska

Comanchean arkose at the base of the Coastal Plain series, Maryland, Virginia, North Carolina

The arkose of the Swauk formation (Tertiary), Washington

The arkose of the Puget formation (Tertiary), Washington.

The arkose (Early Tertiary) of the Matanuska and Controller Bay regions, Alaska

c) Deposits formed under glacial conditions: If an ice sheet advances over a granitic terrane in which there is a mantle of disintegration, it would seem possible for small amounts of this débris locally to be preserved as arkose among the various glacial deposits. In New England, there is in several localities deep preglacial disintegration, showing that the mantle of disintegration of the Piedmont district probably extended in former times northward over this area. Arkose is apparently lacking however, in the New England glacial deposits. No example of this type of deposit is known to the writer.

2. *Marine and lacustrine.*—(*a*) The basal member of a new, transgressive marine series is commonly composed of the materials of the former regolith. If the shore forces are not too violent in their working over of the débris, the basal deposit in regions of granitic rocks may be arkosic. The constituent grains show more or less rounding. There may be present a small amount of argillaceous matrix. Through the elimination of the feldspar the arkose may grade into quartzite. Arkose deposits of this type may grade into deposits of the type discussed in (*b*).

To this type of deposit (*a*) there should be apparently referred:

Arkose of the Hotauto formation (pre-Cambrian), Shinumo Quad., Arizona.
The Cambrian arkose of Eastern United States (in large part)
The arkose (Silurian) of Littleton, New Hampshire (in part)
The arkose of the Igaliko formation (Devonian), Greenland
The arkose (Triassic) of the Morvan (in part), France
The arkose (Tertiary) of the Limagne (in part), France

(*b*) When erosion of the mantle of disintegration in a granitic terrane adjacent to the sea or to a lake occurs, deposition of the disintegrated material is likely to take place in the sea or lake with, as a consequence, the formation of arkose. Near the shore the arkose is in banks and lenses and is interstratified with beds composed of the material from the soil and zone of decomposition and of argillaceous material eliminated from the débris of disintegration. The constituent grains of the arkose are subangular to poorly rounded, the degree of rounding being greater in the more quartzose beds. There may in some cases be a slight amount of argillaceous matrix. Unless the feldspar is itself reddish, the arkose is grayish in color. Although not necessarily basal, the arkose is more likely to be near the base of the formation than not, since the change of conditions which causes the erosion of the mantle of disintegration is likely to mark the inauguration of a new period of sedimentation. The arkose formed far from shore is less granitic in appearance than that formed immediately at the shore, there is considerable rounding and sizing of the constituent grains, and there is elimination of much feldspar and argillaceous material. The arkose in many cases grades into quartzite.

An example of this type of deposit is the Tertiary arkose of the Limagne, France. During the Oligocene times the Limagne was first a brackish-water basin some thirty km. in width and later a fresh-water lake lying then as now in the granite plateau of the Plateau Central. The arkose is found chiefly near the base and is found in banks alternating with greenish marl and in some cases extending out a considerable distance from the edge of the basin. Some of the arkose, especially that at Royat, is massive, coarse, composed largely of good sized fragments of the coarse phenocrysts of the underlying granite, and is extremely granitic in appearance. The greater part of the arkose, however, is much finer, is more quartzose, is composed of more-rounded grains, and grades into quartzite. There is in some cases an argillaceous matrix, in some cases a sericitic matrix, and, in some of the more quartzose phases, there is very little matrix. There is a general even horizontal stratification. Where cross-bedding is present in individual strata it is usually of the simple foreset type.

To this type of deposit are probably to be referred:

Much of the pre-Cambrian arkose of Ontario
Arkose of the Congo Series, French Hoeck, Cape Colony
The Cambrian arkose, North Carolina–Tennessee
Fitch Hill arkose, Silurian, Littleton, New Hampshire
Haybes arkose and Weismes arkose (Devonian) Ardennes–Eifel District
Arkose of the Grés bigarrés and Grés vosgien (Triassic) of the Morvan region, France
Dolomitic arkose (Keuper), Franconia and Thuringia
Arkose of the Blasensandstein and Coburgerbausandstein (Keuper), eastern Palatinate
Lower Stampian–Sannoisian arkose (Oligocene), Limagne, Forez, and Roannais basins, France
Much of the Jura–Cretaceous arkose of southwestern Alaska
Arkose of the Cutler formation (Permian), Colorado(?)
Arkose of the Fountain and Lower Wyoming formations (Permian), Colorado(?)

C. UNTRANSPORTED OR SEDENTARY ARKOSE

Basal, unstratified deposits grading into the underlying granite. When deposition begins in a district, the original regolith locally may be buried before it has been eroded to any considerable extent. It is thus possible for arkose to be formed without the usual intermediate steps of erosion, transportation and deposition of the disintegrated material. The arkose is composed of the constituent minerals of the granite or gneiss in essentially their original proportions. Some of the silicates, especially the biotite, hornblende, and plagioclase, are in many cases highly decomposed. The constituent grains are angular. The upper part of the arkose may show a rude stratification and may grade upward into a well-stratified deposit. The lower portion is massive and grades downward into the granite, and may show the unaltered cores of bowlders of exfoliation.

A good example of this type of arkose is to be found in the lower arkose in the Silurian at Littleton, New Hampshire. Between the Niagaran Limestone and the granite there is from two to eighty feet of arkose which is coarse and granitic in appearance. The quartz and feldspar are the same as those of the underlying granite and are present in practically their original proportions. There is a slight amount of a fine-grained dark matrix. In its upper portion, the formation shows faint traces of stratification and in its lower portion it grades into the underlying granite-gneiss. Locally the original spheroidal weathering and the unaltered cores and shells of concentric weathering are distinguishable.

To this type of deposit are to be referred:

The arkose (in part) of the Vermont formation (Cambrian), Massachusetts and Vermont
The basal arkose (Silurian) at Littleton, New Hampshire
Pre-Cambrian arkose (in part) of the Cobalt District, Ontario
Basal arkose, Narragansett Basin, Massachusetts and Rhode Island
Nubian arkose, Aswan, Egypt

D. SUMMARY

The geological significance of arkose in brief, then, varies from case to case and cannot be limited in the general statement to significance of a special set of conditions. Each deposit is significant of some special set of conditions and these in many cases can be determined from the individual deposit or its associations. In the preceding discussions an attempt has been made to show a grouping of these in conformity with a genetic classification of arkose, each type of which is significant of some special type of conditions. But even if the premises of this classification should be seriously disputed, it still remains a fact that most formations lying unconformably on a former granitic terrane have arkose at or near the base, and there seems to be a more or less general rule that, whenever a period of deposition is inaugurated over a granitic terrane, arkose is the first or one of the first deposits to be laid down, whatever the prevailing conditions. This basal arkose commonly shows but slight effects of wear and is apparently near the point of origin of its constituent material. At higher horizons, there often is yet other arkose, in most cases showing more signs of wear and apparently having been transported for a greater distance; and in still other cases, as has been noted, arkose composes the whole of a formation, thousands of feet in thickness. The deposits are of such differing types and have such different associations with coal measures, with mud-cracked red beds, with beds containing faceted pebbles, and with beds carrying marine fossils, that the old conception of the limited significance of arkose is manifestly incorrect, and arkose must be significant of several types of conditions.

AN UNUSUAL FORM OF VOLCANIC EJECTA[1]

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In the course of a study of the eruption of Taal Volcano, in southwestern Luzon, Philippine Islands, during the month of February, 1911, I noted the presence of small concretion-like bodies in the finest-grained portion of the blanket of fragmental ejecta which the eruption spread over the surrounding country. It will be recalled that the eruption in question was characterized, by the expulsion of great volumes of water-vapor, charged with ash or sand, together with a small proportion of coarser fragmental material. The eruption destroyed completely a dozen small villages, with attendant damage to crops and live stock, and killed 1,335 people. A thin layer of mud and dust was spread over an area of about 1,000 square kilometers, extending principally to the north and west of the crater. I commented upon the presence of the spherical bodies in the ash-fall at the time as follows:

> An interesting feature of the fall of the ejecta is the formation of drops or balls of mud. These were observed most abundantly on the island itself, but were seen at Talisay and Bañadero also. They range in size from large shot to hazelnuts, and when broken sometimes show concentric markings. Apparently they fell late during the activity, being found just below the surface of the deposit. These mud balls cannot be classed as lapilli in the strict sense of that term, since they are built up, probably through the condensation of steam into drops of water. The accompanying vertical section of the fall of mud or ash [text Fig. 2] was taken on the southwest slope of the volcano.[2]

Text Fig. 2, referred to in the quotation, is reproduced herewith as text Fig. 1.

Taal Volcano forms an island near the center of a lake from 15 to 20 kilometers in diameter. Thus the mud balls, which were found both on the slopes of the volcano and at the villages of Talisay

[1] Published by permission of the Director, Bureau of Science, Manila, Philippine Islands.

[2] Wallace E. Pratt, *Phil. Jour. Sci.*, Sec. A (1911), VI, 71.

and Bañadero on the margin of the lake, from 6 to 8 kilometers distant from the crater, must have been widely distributed; nevertheless, at the time I was inclined to attribute their formation to accidental, rather than to common, conditions of explosive volcanism. The literature accessible to me revealed little evidence that ejecta of this character had been observed generally, although the following description by Edward Otis Hovey of "drops of mud," which he encountered after the eruptions on Martinique in 1902, shows that similar phenomena have been noted:

> In addition to the showers of dry dust and ashes, there fell during the eruption an immense amount of liquid mud which had been formed within the eruption cloud through the condensation of its moisture. This mud formed a tenacious coating over everything with which it came in contact. That drops of mud, too, formed in the air and fell as a feature of the eruption is proved by the condition of the walls the of houses in Precheur, on which I found flattened spheroids of dried mud which could have formed only in the manner indicated. These flecks of mud were two, four, and even six inches across, where two or more had coalesced. They occurred mostly on the northern and eastern walls of the houses. The testimony of the people as to the occurrence of rain during the great eruption is conflicting, but the evidence of the coating and these drops of mud proves that much aerial condensation of steam accompanied these outbursts.[1]

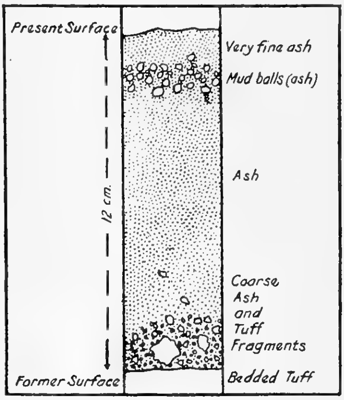

FIG. 1.—Section of ash which fell on the southwestern slope of Taal Volcano in January, 1911, showing balls of dried mud near top of layer.

More recently I have come upon evidence which leads me to the belief that the formation of mud balls has been rather characteristic of that type of volcanic activity which results in the explosive eruption of great clouds of dust-laden steam, at least where atmospheric conditions similar to those on the island of Luzon prevail. In the examination of samples of strata pierced in drilling for artesian water at the towns of Bauan and Taal, distant 25 and 15 kilometers, respectively, from the crater of Taal Volcano, abundant

[1] Edward Otis Hovey, *Am. Jour. Sci.*, XIV (1902), 343.

spheroidal and ellipsoidal inclusions were found which are indistinguishable from the mud balls of the last eruption of Taal. These ejecta may have come from Taal itself, or from some other of the numerous small craters which are known to have existed in southwestern Luzon formerly. The wells were drilled by the Bureau of Public Works with standard drilling rigs, and the samples

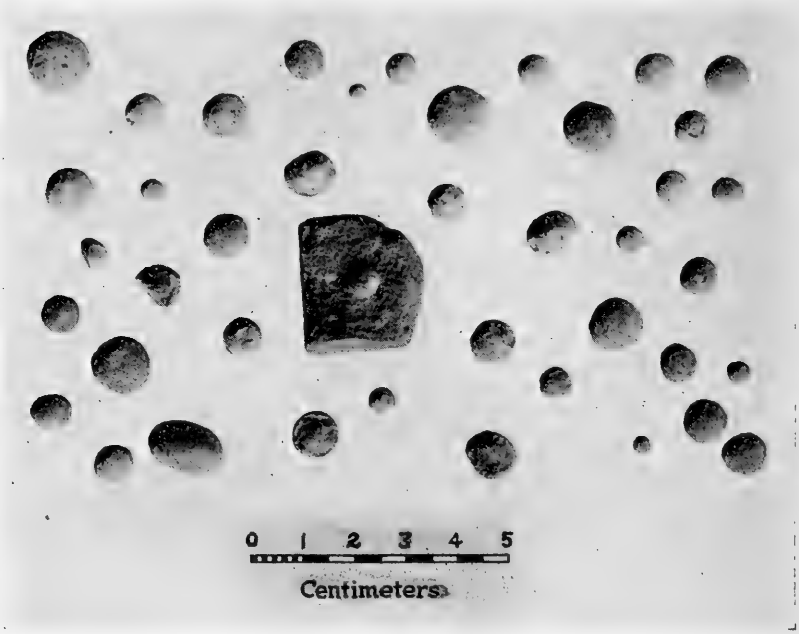

FIG. 2.—Photograph of balls of dried mud which fell with the fine tuff portion of the ejecta of Taal Volcano, in the eruption of 1911.

studied were submitted by the drillers. The balls of dried mud came from depths of from 100 to 150 meters in very loosely consolidated, silt-like volcanic tuff, fragments of which had evidently caved into the well and had been brought to the surface by the sand pump or bailer. Some of the balls were broken, but many were intact in spite of the disintegrating effect which the rushing action of the water into the bailer must have caused.

The size and appearance of the balls are well shown in the accompanying photograph (Fig. 2). One specimen still imbedded in the tuff appears near the center of the photograph. The broken surfaces display clearly the concentric structure which is characteristic of these bodies. The balls can be disintegrated between the fingers when wetted, and the individual particles prove to be like dust in size. That these aggregates have not resulted from solution processes nor from dynamism is evidenced by the facts that they do not contain calcium carbonate nor any other extraneous cementing agent, and that the beds in which they occur have certainly not experienced metamorphism. The theory which Dr. Hovey advanced to explain the presence of "drops of mud" in the ejecta from Mont Pelée accounts satisfactorily for the similar, although apparently smaller, balls of dried mud in the loose tuffs of southwestern Luzon.

W. H. Brown, botanist, Bureau of Science, has submitted to me several hundred balls of dried mud which he found included "in the upper part of a thick bed of volcanic tuff" on the slopes of Mount Maquiling, an extinct volcano about 20 kilometers northwest of Taal. He had been engaged in a study of the flora of Mount Maquiling and had encountered these balls in the course of a soil survey. They are precisely like those already described in shape and structure, but many of them are larger and they have a brownish-yellow color, whereas the Taal products are light gray in color. They consist of the same material as the inclosing bed—clayey, fine-grained tuff. The balls from Maquiling attain a diameter in rare specimens of as much as 4 centimeters, thus being comparable in size with the drops of mud observed by Dr. Hovey, and are so hard that they can be broken only with difficulty between the fingers. The appearance of a face in the tuff bed containing these balls is shown in Fig. 3. The concentric structure of the balls is again revealed in this photograph.

Recently, also, I have encountered well-preserved balls inclosed in clayey tuff on Bondoc Peninsula, Tayabas Province, and near the Santa Lutgarda iron mine at Angat, Bulacan Province, widely separated parts of Luzon. The tuff beds in these localities are of greater age than the recent tuffs in the Taal volcanic region, dating back, probably, to the late Miocene. The tuff is slightly indurated, but the balls have retained their form and display clearly the characteristics already recorded in describing the ejecta from Taal. I am confident that they originated in the same manner in each case.

The suggestion arises, in view of the foregoing observations, that the condensation of mud into drops or balls must be a rather common feature of volcanic eruptions which throw out great clouds of water-vapor and fine sand or dust. The product may be

FIG. 3.—Photograph showing close view of a face in a bed of clayey tuff containing "mud balls"; slopes of Mount Maquiling, southwestern Luzon. About one-third natural size.

described, perhaps, as a volcanic hailstone. Undoubtedly, the contour of such bodies is often destroyed by the impact of the fall to the ground surface. Probably only where the drops have had opportunity to dry out somewhat before reaching the earth and where they strike in soft, unconsolidated beds of recently fallen tuff, is their form preserved under subaerial conditions. It would appear to be equally remarkable that they should retain their form upon falling into water. Yet it is beyond question that the tuff series into which the wells at Bauan and Taal penetrated is in great part water-laid, and it is to be presumed that the mud balls encountered in the wells at these towns fell into the sea originally.

Unless conditions peculiar to the tropics, such as high temperature and, perhaps, excessive humidity, are essential factors in the phenomena which have been described, it would appear that mud balls should have been formed in the eruption cloud from Katmai Volcano in Alaska and in the recent eruptions of Mount Lassen in California. So far as I have observed, none of the published accounts of the eruptions of these volcanoes have mentioned ejecta of this character.

RIPPLE-MARKS IN OHIO LIMESTONES[1]

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INTRODUCTION

Dr. Edward M. Kindle, in a "Note on a Ripple-Marked Limestone" in the Devonian of northern Manitoba, published in 1912, stated that: "the occurrence of ripple-marks on sandstone is a common phenomenon to every geologist. . . . . The literature on ripple-marks relates almost entirely to these familiar sand or sandstone ripples. The occurrence of ripple-marks on limestone seems to be a phenomenon of such relative infrequency that it appears desirable to record an example which has come under the writer's notice."[2] In a later paper Dr. Kindle has described ripple-

[1] Published by permission of the State Geologist of Ohio.

[2] *Ottawa Naturalist*, XXVI (December, 1912), 1 (reprint).

marks in the Trenton limestone near Hull, Quebec,[1] and given a summary of previously described ripple-marks in American limestones.[2] At an earlier date Dr. August Foerste had noted the occurrence of wave-marks (ripple-marks) in the Ordovician and Silurian limestones at a number of localities in Kentucky, Ohio, and Indiana.[3] Recently Professor J. A. Udden has described ripple-marks in the Burlington limestone of Iowa and in limestones of Comanchean age in Texas.[4]

On account of the comparative infrequency of described observations of ripple-marks in limestone the writer has concluded to record the most conspicuous of those which he has seen while engaged in field work in Ohio. These will be grouped in the several geologic systems in which they were observed, arranged in ascending order.

ORDOVICIAN RIPPLE-MARKS

Elk Run.—The best ripple-marks seen in the Ordovician are in the upper part of the Richmond formation on Elk Run in the northwestern part of Adams County. This locality is on the Marion Dunlap farm, about 1¼ miles east of Winchester and 3 miles west of Seaman, where the ripple-marked layer of limestone forms the floor of the run for a considerable part of the distance between the Norfolk & Western Railway trestle and the highway bridge. An excellent view of these ripple-marks may be had from the Norfolk & Western passenger trains while crossing the trestle if one looks downstream to the north.

The first series of ripple-marks is on a layer forming the bed of the run a short distance below the trestle and continuing up a branch from the west for about two rods. The direction of the ripple-marks is about due north and south. The more gradual slope (stoss) is to the east, and the steeper (lee) to the west. The distance apart (amplitude) of the crests varies from 28 to 32 inches

[1] *Jour. Geol.*, XXII (1914), 707–9.

[2] *Ibid.*, pp. 709–11.

[3] *Jour. Geol.*, III (1895), 50–60 and 169–97; 1–40 (reprint); *Jour. Cincinnati Soc. Nat. Hist.*, XVIII (1896), 167; *Am. Geologist*, XXXI (1903), 333–61.

[4] *Jour. Geol.*, XXIV (March, 1916), 125, 126; illustrated by Fig. 3, p, 126, Fig. 4, p. 127, and Fig. 5, p. 128.

in the more normal ones, with, in some instances, shorter and more irregular ones between these crests. The depth of the troughs, from the crest to the bottom, varies from 2 to 3 inches. The crests undulate or curve slightly in crossing the surface of the limestone, and this undulation is conspicuous in the bed of Elk Run a little below the branch. Fig. 1 shows the ripple-marks in the

FIG. 1.—View of ripple-marks in bed of Elk Run, just below the Norfolk & Western Railway trestle, $1\frac{1}{4}$ miles east of Winchester, Ohio. Photograph by C. S. Prosser.

bed of Elk Run, just below the railway trestle, and also on the same layer of limestone in the bed of the small western branch.

There is a dip of at least 1° to the east as measured on the crests of the ripple-marks in the lower part of the branch, and farther up this stream it increases to 2°. The layer of limestone contains large numbers of shells which Dr. Foerste states are covered by sand.[1] It is rather difficult to make out the sand, although there is granular material to some extent. This horizon

[1] *Jour. Geol.*, III (1895), 59.

is given by Dr. Foerste as 60 feet below the top of the Richmond formation.[1]

The dip downstream carries this ripple-marked layer down Elk Run to where it covers the entire bed of the stream for some distance above the highway bridge. At this locality the bed of the stream which is covered by the ripple-marked layer is some 60 feet wide and extends 156 feet along the bed of the stream. This is a beautiful example on a large scale of a ripple-marked limestone. The trend of the crests of some of these ripple-marks is N. 3° W., and they undulate to a considerable extent in crossing the stream. The crests of the normal ripple-marks are from 27 to 32 inches apart. The crests of about three out of five are 29 inches apart, and the average over different parts of the surface of this layer is 29, 30, and 31 inches apart. The more gradual and longer slope (stoss) is to the east, the steeper and shorter slope to the west, and the ripple-marks are clearly asymmetrical. A view of the ripple-marked bed of Elk Run at this locality, looking downstream toward the highway bridge, is shown in Fig. 2. A view of the bed of Elk Run from the highway bridge looking upstream, with the railway trestle in the distance, is shown in Fig. 3.

The layers on the western side of Elk Run below the highway bridge are dipping from 3° to 4°.5 N. 10° E. The majority of readings on the different layers, however, gave 3° for the amount of dip. The barometer gave a dip of 5 feet to the east for the surface of the ripple-marked layer from the branch to the bed of Elk Run under the highway bridge, a horizontal distance of 500 feet.

Just below the highway bridge on the western bank is a ripple-marked layer, between 2 and 3 feet higher than the fine one in the bed of Elk Run which has just been described. The ripple-marks of this higher layer run N. 30° W., are not so conspicuous as in the lower layer, and do not show much difference in the slope of the two sides. On the western side of Elk Run, not far below the highway bridge, is the house of Mr. Charles L. Bailey, and near water-level above the house is a set that runs about northwest and southeast. The eastern slope of these ripple-marks is more gradual than the western slope. Just below the Bailey house a

[1] *Ibid.*, p. 58.

fall is formed by a ripple-marked layer in which the ripples run N. 3–5° W., and the steeper slope is to the west. The crests are from 27 to 28 inches apart, and the ripples are more irregular than those in the bed of Elk Run above the highway bridge. It is not certain that this is the same layer as the one above the highway bridge, and Mr. Bailey, who is interested in geology, states that

Fig. 2.—View of ripple-marked bed of Elk Run, looking downstream toward the highway bridge. Photograph by C. S. Prosser.

it is lower. Below the ripple-marked layer in the fall is another one with the ripples running N. 10° W., and the steeper slope to the east, with a more gradual one to the west.

Farther down Elk Run, shown for some rods in the bed of the stream and making a lower fall, is a conspicuous ripple-marked layer, which is 5+ feet below the one forming the Bailey fall. These ripple-marks run N. 10–16° W., the crests are undulating, the slopes steeper to the west than to the east, and the crests from 21, 26, to 27 inches apart. Farther down the run on the eastern side, opposite the E. E. Jamison house, where the pike comes down into the valley of the stream, is a ripple-marked layer. The ripple-marks are not so clearly defined as in the layers farther up the stream; but they apparently run about north and south. Loose blocks of limestone containing pebbles were noted at this locality; but the layer was not located in place. Probably this is the locality described by Dr. Foerste when he says, "Within half a

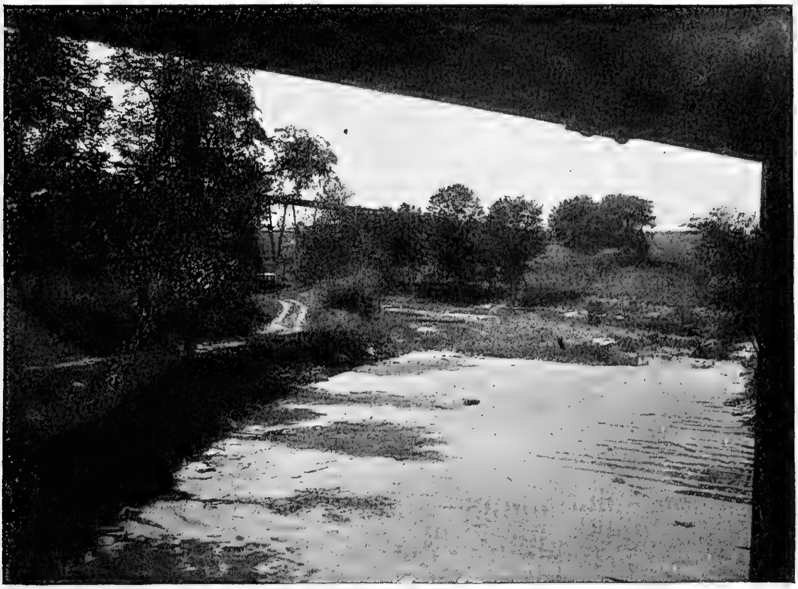

FIG. 3.—View of ripple-marked bed of Elk Run from the highway bridge looking upstream, with the railway trestle in the distance. Photograph by C. S. Prosser.

mile of the bridge, farther down, opposite a house on the east bank, plenty of pebbles occur in the rock."[1] Farther down the stream, below the next house on its western side and a ford, is a still lower layer, with not very clear ripple-marks.

As noted above, the ripple-marks in the limestones along this stream were first described by Dr. Foerste as wave-marks on Elk Horn Creek.[2]

Cherry Fork.—Ripple-marks in the Upper Richmond were also seen in the bed of Cherry Fork, below the highway bridge at

[1] *Op. cit.*, p. 59. [2] *Ibid.*, pp. 58–60.

Harshaville, 4 miles southeast of Seaman, Adams County. The ripple-marks in the highest limestone layer below the bridge run about N. 60° W. and have the more gradual slope to the east of south, and the more abrupt to the west of north. The crests vary from 20 to 28 inches apart. In another limestone layer about 6 inches lower than the first one the ripple-marks run north and south, with the steeper slope to the west and the more gradual one to the east. The crests are from 20 to 30 inches apart. Over part of the floor of the creek below the bridge is a less distinctly ripple-marked layer between the two which have just been described. These run almost directly northwest and southeast, the crests are from 22 to 28 inches apart and are rather flat, and the slope is about the same on each side, making them nearly symmetrical. The northeast slope on a few of them is a little steeper and these do not have such flat crests. Perhaps the tops of the crests of the others have been worn away, which gives them the present somewhat flattened form.

Trebers Run.—This stream is a western tributary of Lick Fork (called Lick Creek on the Highway Map of Adams County), about 5 miles northeast of West Union, 2½ miles below Young's Chapel, about a mile above Dunkinville, and 9 miles southwest of Peebles. On the southern bank of Trebers Run, about 150 yards above the covered bridge on the West Union and Jacksonville Pike, is a ripple-marked limestone layer exposed for 90 feet or more along the bank. This limestone layer is in the upper part of the Richmond formation. At the time this locality was visited the streams were high and the layer was partly covered by water, so that the conditions were not especially favorable for study. Three adjacent ripple-marks run as follows: N. 12° E., N. about 12° E., and the third one about N. and S. The distance between the crests varies from 2 feet 2 inches to 2 feet 7 inches, while the depths of the furrows (troughs) is from 2½ to 3 inches. The eastern slope of the ripple-marks is perhaps a little steeper; but there is comparatively little difference in the slope of the two sides. There is a heavy dip for this region downstream to the east, and certain layers on the northern bank some rods farther up the run dip from 4°.5 to 5° N. 100° E.

This stratum is known locally as the "washboard" layer, and it is apparently the one described by Dr. Locke in 1838. He stated that "the waved stratum at Treber's is exposed in the bed of the fork, about 400 feet in length, and 50 feet in width."[1] Mr. William Treber, now eighty-nine years old (July, 1915), who lives on the Treber farm just south of the run, remembers when Dr. Locke studied this locality, and his daughter, Lizzie Treber, stated that the layer described by Locke is believed to have been exposed in the field a few rods northeast of the lower part of Trebers Run, on the eastern side of the Pike. Lick Fork has shifted its bed somewhat to the east and the locality is now covered by soil. The strong easterly dip would probably carry the layer now exposed on Trebers Run down to the locality where it is stated that the ripple-marks described by Dr. Locke were exposed. The barometer gave a difference in altitude of 110 feet from Lick Fork at Trebers to the top of the Richmond formation on Lick Fork above Young's Chapel, 2½ miles above Trebers. Miss Treber also stated that formerly the ripple-marked layer was exposed in Lick Fork, about opposite their house, as well as above it; but the high water at the time this locality was studied prevented determining whether any of the layer is now shown when the water in the stream is at its normal height.

Review of previous work.—Ripple-marks in the Upper Richmond in Ohio, so far as known to the writer, were first described by Professor John Locke from outcrops on Lick Fork,[2] about 5 miles northeast of West Union, Adams County. Locke called it the "waved stratum" and located its horizon as 55 feet below the top of the blue limestone, No. V of his section, and he stated that near a house known as Trebers it was exposed "in the bed of the fork, about 400 feet in length, and 50 feet in width."[3] Professor Locke, however, stated that "these waves are not local, but may be traced in the same stratum over tracts of many miles. They have been called 'ripple marks'; but all geologists will agree that the blue limestone has been formed far below the reach of 'ripples.'"[4]

[1] *Second Ann. Rept. Geol. Survey Ohio*, 1838, p. 247 and bottom of Pl. 6, opposite p. 242.

[2] *Second Ann. Rept. Geol. Survey Ohio*, 1838, pp. 246, 247, and Pl. 6, opposite p. 242.

[3] *Ibid.*, p. 247. [4] *Ibid.*, p. 246.

Messrs. Joseph Moore and Allen D. Hole have described "ripple-marks in Hudson River limestone, in Wayne County, Indiana, 5 miles southwest of Richmond," which are illustrated by 3 plates.[1] These are probably in the Richmond formation and it is stated that "the mean distance from crest to crest is approximately uniform for the series, and the average for twenty such distances is found to be 2.63 feet. The average depth of lowest part of troughs below crests is $1\frac{1}{2}$ to $1\frac{6}{10}$ inches."[2] At an earlier date W. P. Shannon had described "wave-marks on Cincinnati limestone" in the bed of Salt Creek, 3 miles west of Oldenburg, in the southwestern part of Franklin County, Indiana.[3]

Dr. Orton called attention to the observations of Professor Locke and stated that "it is an even more striking characteristic of the rock in its lower beds [Cincinnati group], as shown in the river quarries of Cincinnati, or in the lowermost 100 feet that are there exposed. . . . The interval between the ridges varies, but in many instances it is about 4 feet. The greatest thickness of the ridge is 6 or 7 inches, while the stone is reduced to 1 or 2 inches at the bottom of the furrow, and sometimes it entirely disappears."[4] Dr. Foerste also noted wave-marks and ripple-marks in the "Lower Hudson, or Utica" opposite Cincinnati, at West Covington, Kentucky,[5] which in general "run slightly east of north."[6] Recently Dr. Kindle has reported Dr. Foerste as stating that "wave-marks (ripple-marks) occur in Ohio, Indiana, and Kentucky, in abundance in the Lower Eden, Upper Richmond, and Upper Brassfield limestones. They occur in great numbers, but not so abundant, also in the Middle Eden. In Kentucky they are common also locally in the Mount Hope bed, at the base of the Maysville. They occur often near the middle of the Arnheim and at various intervals in the Lower and Middle Richmond in the three states mentioned."[7]

[1] *Proc. Indiana Acad. Sci.*, 1901 (1902), pp. 216–20.

[2] *Ibid.*, p. 217.

[3] *Ibid.*, 1894 (1895), pp. 53, 54.

[4] *Rept. Geol. Survey Ohio*, I (1873), 377.

[5] *Jour. Geol.*, III (1895), 56–58.

[6] *Ibid.*, p. 58.

[7] *Ibid.*, XXII (1914), 709, 710.

SILURIAN RIPPLE-MARKS

Beasleys Fork.—Ripple-marks in the upper part of the Brassfield limestone (formerly called Clinton) were noted at several localities in Adams County. One of these localities is in the bed of the upper part of Beasleys Fork, some distance above the house of Walter D. Grooms, which is about $1\frac{1}{4}$ miles south of West Union on the Wrightsville Pike. This stream is crossed by three layers of limestone in which ripple-marks are conspicuously shown.

The lowest layer is a very crinoidal limestone, from 3 to 10 inches thick, which forms a small fall, and its top is about 8 feet 3 inches below the top of the Brassfield limestone. The ripple-marks run about east and west, with the more gradual slope to the north and the steeper toward the south. The top of the second or middle ripple-marked layer is 4 feet 11 inches below the top of the Brassfield formation, and the layer itself is 5± inches thick, but the ripple-marks are not so conspicuous as in the layer below and the one above. These ripple-marks run north and south with the steeper slope on the east side and the more gentle slope on the west. Finally, there is the third or highest ripple-marked layer, the top of which is 4 feet 5 inches below the top of the Brassfield, and opposite the small house on the bank of the creek on the Joe Morrison farm. The layer is a grayish, somewhat greenish-spotted, crystalline limestone, 8± inches thick. The ripple-marks run about north and south, with the steeper slope to the east and the more gradual to the west. These ripple-marks are heavy and the crests are 26, 31, 34, 35, and 38 inches apart. The distance from the bottom of the trough to the top of the ridge varies from 3 to 9 inches.

These ripple-marks were noted by Dr. Foerste in his description of the section "along the road to Beasley Fork." The following is that part of this section in which the ripple-marks occur, as described by Dr. Foerste:[1]

	Ft.	In.
Limestone, wave-marked		3
Clay		8
Limestone		3
Clay		3

[1] *Kentucky Geol. Survey, Bull. No.* 7, 1907, p. 42.

	Ft.	In.
Limestone, with large wave-marks		6
Limestone		6
Clay, with a little thin limestone	1	6
Limestone with large wave-marks and containing large crinoid beads		6

Lick Fork.—At least two ripple-marked layers in the upper part of the Brassfield limestone occur on Lick Fork (called Lick Creek on the Highway Map of Adams County) above and below the highway bridge on the West Union and Jacksonville Pike, about 2¼ miles northeast of West Union and about opposite the house of J. Frank Young. Stratigraphically, what is apparently the lowest ripple-marked layer outcrops a few rods above the bridge, where there is a strong dip downstream. The rock of this layer is a very crystalline and crinoidal limestone containing large cup corals and numerous fragments of other fossils in its upper surface. The ripple-marks are large and one of them runs N. 70° E., although some of them run perhaps more nearly east and west. The crests of two of them are 30 inches apart, and of another set 31 inches apart. The trough is 3½ inches deep and the slope much steeper on the southern than on the northern side. A few rods below the bridge is a layer with ripple-marks which run N. 20° W. and S. 20° E. The crests of these ripple-marks are about 31 inches apart and the western slope is steeper than the eastern one. This ripple-marked layer is about 19⅔ feet higher than the base of the Brassfield limestone. Not far above the highway bridge are ripple-marks running N. 18° W. and S. 18° E., which apparently occur in the same layer as those below the bridge, which have just been described. Farther upstream the direction of the ripple-marks, apparently on this same layer, has changed to N. 74° W. Not much farther upstream than the ripple-marked layer first described one is shown in the bed of the stream, which may be higher than the others; but its stratigraphic position was not certainly determined. The ripple-marks of this layer run north and south, the crests are 30–35 inches apart, and there does not appear to be a marked difference in the angles of the slopes.

This is probably the locality where Professor John Locke noted two waved layers in the Flinty limestone (Brassfield), No. III of his section, on Lick Fork.[1] He gave the top of the upper one (No. 13) as 4 feet 9½ inches below the top of a flinty layer (No. 1) (apparently one of the layers of the Dayton limestone), which he seemed to consider the top of the flinty limestone.[2] This upper "waved stratum" is given as 3 inches thick, with 20 inches mostly of marl between it and the lower "waved layer" (No. 17) which is reported as 7 inches thick.

Sproull Glen.—This glen is on the R. C. Sproull farm, now owned by Mrs. Jennie Black and Dr. O. T. Sproull, not far from Sproull Bridge over Ohio Brush Creek, 6 miles southwest of Peebles. The heavy rains of July, 1915, had deepened and cleared out the bed of this stream to such an extent that three layers of ripple-marked limestone were exposed which on a visit to the same glen in September, 1914, were not seen.

The lowest ripple-marked layer was shown on the northern side of the stream with ripple-marks running N. 10° W. to N. 30° W. One foot 5 inches higher is another limestone layer 7 inches thick with ripple-marks imperfectly shown on its upper surface. Also 3 feet higher ripple-marks occur on thin layered limestones; but the last two layers were so poorly shown that not many data could be obtained concerning the ripple-marks. The top of the third or highest ripple-marked layer is 9 feet 9 inches below the base of the 10-inch zone of *Whitfieldella quadrangularis* Foerste[3] in the Brassfield limestone, and 9 feet 3 inches below the top of this formation as exposed in the third fall, or 13 feet 6 inches below the top of the very hard Dayton limestone as exposed in the stream above this fall.

Lawshe quarry.—This old quarry is located on the Vincent Robbins farm, north of Lawshe, Adams County, on the Cincinnati Division of the Norfolk & Western Railway. Ripple-marks were noted near the western end of the quarry, which are not well exposed but run N. 16° E. The ripple-marked layer occurs from 1 foot 4 inches to 2 feet below the base of a rather conspicuous 2 foot 2 inch

[1] *Second Ann. Rept. Geol. Survey Ohio*, 1838, pp. 244, 246, and Pl. 6, opposite p. 242, on which only one waved layer is indicated in the flinty limestone.

[2] *Ibid.*, p. 244, where he states that "the upper layer of the flinty stratum is peculiarly marked. It is about one foot thick, and contains so much silex that it has the sharp conchoidal or flinty fracture, and gives fire with steel."

[3] *Kentucky Geol. Survey, Bull. No. 7*, 1906, p. 41.

layer, which is 12 feet 10 inches above the top of the "chert zone" in the basal part of the Brassfield limestone and 16 feet 10 inches higher than the lowest outcrop in this quarry. The 2 foot 2 inch layer is variously colored crystalline limestone, which on the weathered faces is apparently cross-bedded and contains a good many pebbles, more or less flat, and some of them of considerable size. The top of the massive layer just described is about 22 feet below the top of the Brassfield limestone and nearly $24\frac{1}{2}$ feet below the top of the hard Dayton limestone.

Elk Run.—On Elk Run (called Elm Run on the Highway Map of Highland County), $2\frac{1}{4}$ miles northeast of Belfast, Highland County, are ripple-marked layers in the Brassfield limestone, which are well shown in the stream a few rods below the iron highway bridge on the upper road from Belfast to Elmville. This layer is a crystalline limestone, from $\frac{1}{2}$ to 3 inches thick, which contains fossils and some pebbles. The ripple-marks run N. 80° E., the steeper slope is to the north and the more gradual one to the south. The crests range from 26 to 36 inches apart, 32 inches being the most frequent distance. The deepest trough noted is about $2\frac{1}{2}$ inches lower than the crest. A ferruginous limestone 1 foot 4 inches thick occurs just above the crystalline, ripple-marked layer, and another 4-inch ferruginous limestone layer just above this, the upper surface of which is apparently ripple-marked. Below the ripple-marked, crystalline limestone is a layer 1 foot thick containing fossils and numerous pebbles of Brassfield limestone. The majority of the pebbles are rather flat and fairly well rounded on the margins. The size of some of the larger pebbles is indicated by the following figures: one $8\frac{1}{2}$ inches long, and three rectangular ones respectively 9×6, 9×8, and $9\times8\frac{1}{2}$ inches. The pebbles as a rule lie flat (horizontal) or at least nearly so in the rock; but there are some that are imbedded at more or less of an angle.

Attention was first called to this locality by Dr. Foerste, who has written as follows concerning it:

> By far the most interesting feature of the locality, however, was the presence of great wave-marks, wonderfully distinct and well exposed for a distance of a hundred feet down the creek. The line of strike of these wave-marks was magnetically about north 65° east. The crests of the wave-marks

were about two inches above their greatest depressions, and the distance from one crest to the next was on the average about 28 inches. They sloped northwards a little more steeply than southwards. This wave-marked layer is only from one to two inches in thickness, and immediately overlies a great mass of pebbles, imbedded in the Clinton just beneath. These pebbles sometimes project strongly into the sandy layer above, which shows the wave-marks. The pebbles are on the average larger than at any place where pebbles have so far been seen in the Clinton. Plenty of them are 12 inches in

FIG. 4.—View of ripple-marks as formerly shown in the old Schoepfle quarry, Sandusky, looking southeast. Photograph by C. W. Platt.

diameter, and many of them range between four and eight inches. As usual, the pebbles are only an inch to an inch and a half in thickness. Lithologically they are similar to the sandy stratified layers of the Clinton limestone, found characteristically in the lower half of the Clinton in this part of the state, and occurring also at higher levels. If there had been any doubt hitherto about the Clinton age of these pebbles, it was dispelled by the fossils found in some of the pebbles at this locality.[1]

Sharpsville.—On Turtle Creek, above Sharpsville, in the western part of Highland County, ripple-marks were noted in the Brassfield limestone; but there was not an opportunity to measure

[1] *Jour. Geol.* III (1895), 184.

them. Opposite Sharpsville and farther down Turtle Creek than the place above mentioned Dr. Foerste reported "a thin, sandy layer, very undulated, like ripple-marks where waves have crossed from various directions. Their importance was not appreciated, when observed, and their direction was not carefully noted. Judging from the memory alone the larger ripples had a general northeast course and indicated currents transverse to this direction."[1]

Near Peebles.—In the Peebles Stone Company quarry, on the northern side of the Norfolk & Western Railway, one-half mile west of Peebles, is a layer 7 feet 10 inches above the base of the West Union limestone, the surface of which is conspicuously ripple-marked. The rock is bluish gray in color, massive, contains Brachiopods, and the upper surface is very crinoidal. On the crests of the ripple-marks are furrows which are apparently trails. The majority of the ripple-marks run in a regular direction, which is N. 6° W.; but an occasional one runs in an irregular direction. The distance between two parallel crests is 27 inches and the trough is $1\frac{1}{2}$ inches deep. The distance between two other conspicuous crests is 3 feet 10 inches, with a much smaller ripple-mark about half-way between them. In general the eastern slopes appear to be the steeper, although part of them do not show any particular difference, and one is apparently steeper on the western side.

About one-fourth mile west of Peebles in the bank of a small stream on the northern side of the Norfolk & Western Railway ripple-marks occur in Niagaran limestone. Ripple-marks are clearly shown in two layers of crinoidal limestone at this locality. In the lower layer one of the ripple-marks runs N. 6° W., and another one, N. 2° W. The crests are 22–23 inches apart and one trough is 4 inches deep. In general the more gradual slope is to the east and the steeper to the west, although in one of them the eastern slope appeared to be the steeper. In the upper layer the ripple-marks run N. 5° E., the crests are 44–45 inches apart, a trough is $4\frac{1}{2}$ inches deep, and the steeper slope is to the east.

This locality was described as follows by Dr. Foerste:

Along the railroad about a quarter of a mile west of Peebles, where the railroad crosses a creek, there are very good wave-marks in the rock on the

[1] *Jour. Geol.*, III (1895), 178.

north side of the railroad, in a sort of quarry. The rock is of a bluish tint, and is some distance above the Niagara shales. It is presumably of the Springfield horizon. The crests of the waves run here north 3° east; they are about 3½ inches above the troughs of the waves, and are about 42 inches apart, showing therefore approximately the same characteristics as the waves of Clinton age in Elk Run. They descend more rapidly eastward than westward. The wave-marks are seen at several levels through a thickness of 2½ feet

FIG. 5.—Nearer view of part of layer shown in Fig. 4. Photograph by C. W. Platt.

of rock. . . . . Where the railroad crosses the creek, 50 feet towards the southeast, the wave-marks are shown over a larger area. The crests here run north 5° west.[1]

Dr. Kindle has also made reference to this locality.[2]

Another locality of Niagaran ripple-marks is southwest of Peebles on the dirt road for Lawshe, about one-fourth mile west of the West Union and Locust Grove Pike. The ripple-marks are shown in the highway to the west of a run, and the first house to the west is that on the farm of James Graham. The ripple-marks run north and south, the crests are 20, 21, and three of them 24 inches apart. The more gentle slope appears to be to the west

[1] *Jour. Geol.*, III (1895), 190. [2] *Ibid.*, XXII (1914), 711.

and the steeper to the east. These ripple-marks occur in somewhat thin-bedded dolomites, like those to the west of Peebles, called Springfield by Dr. Foerste, and apparently are in the southern continuation of those beds.

Near Locust Grove.—On the western side of Locust Grove branch of Crooked Creek, 1 mile west of Locust Grove and nearly opposite the house of James Ogden, in the West Union limestone are ripple-marks running N. 12° W. and S. 12° E. Some rods farther down-stream and 30 feet higher on the bank in the West Union limestone are rather large ripple-marks running N. 10° W. and S. 10° E.

Leesburg.—Ripple-marks occur in Lee's Creek in the gorge below the Davis Mill and north of Leesburg in the northern part of Highland County. The ripple-marks occur in the Blue Cliff dolomite, which Dr. Orton correlated with the Springfield dolomite, and just below a massive layer 7½ feet thick, which is well shown on the eastern side of the creek where the rock has been quarried to a small extent. The ripple-marks are rather irregular; but one runs N. 30° E. and they appear to be steeper on the western slope than the eastern.

Monroe formation.—Ripple-marks were noted at three horizons in the Monroe formation, 2½ miles east of Peebles; but the area exposed in each case was too small and the ripple-marks too imperfect to make any definite measurements. The lowest layer is exposed in the bed of Morrison Run some distance below the spring and house of John K. Morrison, on the road to Bacon Flat schoolhouse, and it is about 15 feet higher than the base of the formation. The highest one is shown in the highway leading up the hill to the west of the John K. Morrison house, and is stratigraphically some 86 feet higher than the base of the Monroe. The direction of these ripple-marks is somewhat irregular; but they run about east and west. The third and intermediate horizon is on a layer in the Virginia Product quarry, just south of the Norfolk & Western Railway, about 2½ miles east of Peebles, and it is more than 25 feet above the base of the Monroe dolomite.

DEVONIAN RIPPLE-MARKS

Sandusky.—The best example of ripple-marks in the Devonian limestone that the writer has seen is in Plant No. 2 of the Wagner

Stone Company (formerly known as the Schoepfle quarry), on Hancock Street in the southern part of Sandusky. Formerly there was a considerable area of the floor of this quarry on which ripple-marks were beautifully shown, the three views of which reproduced in this article were furnished by Mr. DeLos C. Ransom, of

FIG. 6.—View of ripple-marks as formerly shown in the old Schoepfle quarry, Sandusky, looking northeast and at right angles to Fig. 4. Photograph by C. W. Platt.

Sandusky, Ohio, who first called the writer's attention to them in January, 1902. Most of this area, however, has been destroyed by the work of the Wagner Stone Company, and when studied on September 19, 1914, only a small portion of it remained, which was located about east of the crusher and on both the east and west sides of the quarry track running from the crusher around to the new part of the quarry to the northwest. This ripple-marked layer is in the upper part of the Columbus limestone, the western continuation of the Onondaga limestone of New York.

In general, the crests of the ripple-marks which remained in September, 1914, run N. about 20° W., but those farthest to the west run N. about 25° W. Occasionally two will run together and, in one case at least, then diverge again. The crests of those studied vary from 22, 24, 25 to 26 inches apart, the greater number of them being about 2 feet apart. Mr. Ransom reported those shown in the half-tones as "being 3 to 4 feet from crest to crest."[1] In the somewhat worn surface of the layer it is difficult to distinguish any particular difference in the angle of slope of the two sides; although, perhaps, some of the ripple-marks west of the quarry track are a little steeper on the southwest side, with a little longer slope on the northeast side. The troughs of these ripple-marks are rather shallow, although the exact depth was not determined. Figs. 4, 5, and 6 are from photographs, furnished by Mr. DeLos C. Ransom, of the floor of the old (Schoepfle) quarry, showing the ripple-marks as they formerly appeared before this layer was mostly destroyed by the extensive work of the Wagner Stone Company. Mr. Ransom has stated that in Figs. 4 and 5 the camera was pointed toward the southeast and parallel to the direction of the ripple-marks. In Fig. 6 the direction across the ripple-marks is toward the northeast, at right angles to Fig. 4, and the crests are three or four feet apart.[2] Mr. Ransom has written several times concerning these ripple-marks, and the following quotation is from one of his letters:

> Now such ripple-marks 3 or 4 feet wide as are in limestone must have been constructed in water 50 to 100 feet deep and waves of immense size in the ancient comparatively shallow and wide sea when our limestones were laid down. "Ripple-marks" hardly expresses or describes these large parallel stone *waves*. They are perpendicular to the direction of the wind, hence aeons ago winds were as now largely S.W. and N.E. and hence the poles of the earth have not changed since.[3]

[1] Letters of January 25, 1902, and October 28, 1903.

[2] Letter of September 25, 1915.

[3] Letter of October 28, 1903.

On September 19, 1914, a considerable area in the new (northwest) part of the quarry had been stripped of soil and this upper surface of the limestone was beautifully glaciated. It was all worn smooth and marked with striae of various degrees of strength; but part of them are rather strong. The direction of the striae was determined at different places on this surface and in all cases they ran N. 100° W. (W. 10° S.) and N. 80° E. (E. 10° N.).

THE RELATIONSHIPS OF THE OLENTANGY SHALE AND ASSOCIATED DEVONIAN DEPOSITS OF NORTHERN OHIO[1]

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In the flat glaciated region to the south and east of Sandusky there are few outcrops of the older rocks. The drainage is mostly by small, weak streams which have not yet had time to erode extensive valleys, and railroads have not been compelled to cut deeply in order to establish their grades. About seven miles south of Sandusky, however, where the land is a little higher than in the city and the mantle rock is exceedingly thin, some of the creeks have exposed small sections of bedrock which are somewhat exaggerated by a considerable local dip. Two of the more important of these are to be found along Plum and Pipe creeks. These sections have been discussed elsewhere,[2] but a recent study of the region has added some valuable facts to those formerly given and has made it possible to correlate this Ohio Hamilton with the Devonian deposits of the same age to the north of Lake Erie.

Plum Creek heads about nine miles southeast of Sandusky and flows, in a general northerly direction, to the lake. At a point about two miles east-northeast of Prout station, on the Baltimore & Ohio Railroad, it cuts into Huron shale, and a little farther north into the Hamilton beds, exposing the following section:

SECTION OF THE HAMILTON ROCKS AND HURON SHALE ALONG PLUM CREEK

	Thickness Ft.	In.
Huron Shale		
12. Shale, bituminous, black	4	0
Widder Beds		
11. Prout or Encrinal limestone. A very hard siliceous blue limestone containing a little chert and much pyrite. Silicified corals and crinoid stems are abundant, the latter especially in the middle layers	8	10

[1] Published with the permission of the Deputy Minister of Mines, Ottawa, Canada.

[2] *Geological Survey of Ohio, Bulletin No. 10*, 4th Series, 1909, pp. 119–22, Pls. VIII and IX.

FAUNA

Favosites billingsi, Zaphrentis prolifica, Fenestella sp., *Atrypa reticularis, Spirifer* sp., *Stropheodonta perplana*

Olentangy Shale

10.	Covered interval	6	0
9.	Limestone, soft, blue, very fossiliferous	0	6

FAUNA

Autodetus lindstroemi, Spirorbis angulatus, Streblotrypa hamiltonensis, Fistulipora corrugatus ?, *Hederella canadensis, Trematospira* sp., *Chonetes deflectus, Crania hamiltonensis, Leiorhynchus kelloggi, Leiorhynchus laura, Rhipidomella cyclas, Sprifer mucronatus, Stropheodonta demissa, Stropheodonta concava, Actinopteria boydi, Aviculopecten fasciculatus, Glosseletina triquetra, Leiopteri rafinesquii, Microdon bellistriatus, Modiomorpha subalata, Mytalarca oviforme, Pterinea flabellum, Pterinopecten vertumnus, Schizodus appressus, Tellinopsis subemarginata, Bembexia sulcomarginata, Cyrtonella mitella, Pleurotomaria capillaria, Orthoceras* sp., *Bairdia devonica, Bollia* sp., *Bythocypris indianensis, Primitiopsis punctulifera, Phacops rana*, Fish plates

8.	Shale, argillaceous, soft, blue	3	6

FAUNA

Chonetes deflectus, Chonetes setigerus, Crania crenistriata, Leiorhynchus kelloggi, Spirifer mucronatus, Styliolina fissurella, Bythocypris indianensis

7.	Limestone, quite hard, blue	0	6

FAUNA

Cystodictya hamiltonensis, Trematopora sp., *Chonetes deflectus, Leiorhynchus kelloggi, Leiorhynchus laura, Spirifer mucronatus, Actinopteria boydi, Platyceras erectum, Phacops rana*

6.	Shale, soft, blue	5	0

FAUNA

Chonetes deflectus, Bythocypris indianensis

5.	Limestone, blue, lower part shale, very fossiliferous	0	6

FAUNA

Ambocoelia umbonata, Chonetes deflectus, Leiorhynchus kelloggi, Stropheodonta demissa, Cypricardinia indenta, Glyptocardia speciosa, Grammysia arcuata, Grammysia bellatula, Grammysia bisulcata, Grammysia constricta, Modiomorphia subalata, Nucula corbuliformis, Nuculites oblongatus, Nuculites triqueter, Nyassa recta, Pholadella radiata, Schizodus appressus, Bellerophon lyra, *Pleurotomaria planodorsalis, Pleurotomaria rotalia, Orthoceras* sp., *Bairdia devonica, Barchilina* sp., *Bollia* sp., *Primitiopsis punctulifera, Bythocypris punctatus, Phacops rana,* Fish plate

4. Shale, argillaceous, soft, blue. This shale contains numerous small pyrite concretions, some of which are beautifully twinned crystals. The fossils are probably rare in most of it and appear to be in streaks or layers. Mostly covered	10±	0

FAUNA

Orbignyella monticula, Leiorhynchus laura, Spirifer mucronatus, Athyris spiriferoides

3. Shale, blue, with pyritized fossils	0	6±

FAUNA (PYRITIZED)

Leiorhynchus sp., *Leda rostellata, Nuculites triqueter, Bactrites arkonense, Tornoceras uniangulare*

2. Shale, blue. Fossils rather abundant	3±	0

FAUNA

Alveolites monroei, Aulopora cornuta, Aulopora serpens, Ceratopora rugosa, Zaphrentis prolifica, Spirorbis omphalodes, Acanthoclema hamiltonense, Ascodictyon stellatum, Batostomella obliqua, Fistulipora involvens, Fistulipora spinulifera, Hederella canadensis, Hederella filiformis, Heteronema monroei, Orbignyella monticula, Orbignyella tenera, Athyris spiriferoides, Chonetes coronatus, Chonetes deflectus, Crania hamiltoniae, Cryptonella planirostra, Cyrtina hamiltonensis, Leiorhynchus kelloggi, Philidostrophia iowaensis, Spirifer mucronatus, Stropheodonta demissa Tropidoleptus carinatus, Styliolina fissurella, Bairdia devonica, Primitiopsis punctulifera

1. Shale, soft blue, with some flat calcareous concretions. Fossils rare	5±	0

The other important Ohio outcrop is along the south branch of Pipe Creek, one-fourth mile east of Bloomville and about three miles west of the one just given on Plum Creek. At that point the Prout limestone has been quarried to a limited extent, and is therefore well exposed, although the beds of shale below are pretty well sodded over.

SECTION OF THE HAMILTON BEDS ALONG SOUTH BRANCH OF PIPE CREEK

Widder Beds	Thickness Ft.	In.
4. Prout or Encrinal limestone. An impure blue limestone some layers of which are very crinoidal and the upper one containing rather numerous corals	9	0

FAUNA

Baryphyllum verneuilanum, Cladopora canadensis, Cladapora roemeri, Cystiphyllum vesiculosum, Favosites alpenaensis, Favosites billingsi, Favosites placenta, Favosites radiciformis, Favosites turbinatus, Heliophyllum halli, Syringopora intermedia, Zaphrentis prolifica, Polypora; sp., *Atrypa reticularis, Athyris vittata, Chonetes mucronatus, Chonetes scitulus, Rhipidomella vanuxemi, Schizophoria striatula, Spirifer audaculus macronotus, Spirifer mucronatus, Stropheodonta demissa, Platyceras erectum, Phacops rana*

Olentangy Shale

3. Shale, blue, alternating with blue argillaceous limestone; very poorly exposed but weathered blocks of the limestone lie on the steep bank and numerous fossils have weathered out of the softer layers	15±	0

FAUNA

Ceratopora rugosa, Zaphrentis prolifica, Spirorbis, angulatus, Spirorbis omphalodes, Acanthoclema hamiltonensis, Batostomella obliqua, Botryllopora socialis, Cystodictya hamiltonesnsis, Fistulipora spinulifera, Hederella filiformis, Orbignyella monticula, Polypora sp., *Ambocoelia umbonata, Atrypa reticularis, Chonetes deflectus, Chonetes scitulus, Crania hamiltonensis, Cryptonella planirostra, Leiorhynchus laura, Rhipodomella cyclas, Schizophoria striatula, Spirifer mucronatus, Stropheodonta demissa,* Fish plate

2. Shale, marly, blue, badly weathered and soil-covered	10±	0
1. Shale, blue, with disk-like blue limestone concretions	5±	0

The lower part of the shales in these sections is apparently not very fossiliferous. The same is usually true of the Lower Hamilton of Ontario and in many places of the similar deposits in New York. This is probably even more characteristic of the Olentangy shale in central Ohio. However, at Delaware, Winchell's type section of the Olentangy, a few poorly preserved fossils[1] were found which, although only given generic identification, are believed to be identical with others found in the shales of the Sandusky region. It was at Delaware also that the crinoid bed was found in the Olentangy shale—a lens corresponding in every way with the thin lenses of crinoidal limestone common in the lower shales of

[1] *Geological Survey of Ohio, Bulletin No. 10,* 4th series, 1909, p. 89.

the Hamilton beds exposed along Aux Sable River in Ontario. The general make-up, appearance, and physical properties of the shale below the Prout limetsone and the Olentangy shale are the same (Figs. 1, 2, and 3). Moreover, the Delaware limestone, which underlies this deposit at Delaware and at Sandusky, carries the

FIG. 1.—A weathered bank of fossiliferous Olentangy shale showing one of the common calcareous layers in this shale along Plum Creek, near Prout station.

FIG. 2.—A bank of Olentangy shale along the Olentangy River at Delaware, Ohio. The limestone disks in this bank contain an occasional fragmentary fossil. The lens of crinoidal limestone was found at this locality. This is Winchell's type locality for the Olentangy shale and shows its marked contrast to the Ohio or even to the blue bands occurring in the middle portion of the latter.

same fauna at both places and extends northward into Ontario. Whitfield found the lower part of the Delaware to be the western extension of the Marcellus shale, to which he considered it to be in part equivalent.[1] Wherever the Delaware limestone becomes

[1] R. P. Whitfield, *Proceedings of the American Association for the Advancement of Science*, XXVIII (1879), 298.

especially shaly, as is often the case, the fauna tends to revert to that of the more typical Marcellus, so that these forms are not limited to the basal portion. But the occurrence in it of certain fossil forms more characteristic of the true Hamilton beds of New York than of the Marcellus of that region has led to the use of Marcellus-Hamilton or Lower Hamilton for the Delaware. In this use of the Hamilton, it is the older and broader sense of that term, rather than the restricted present usage, that was intended. It would more properly be called the lower Erian. The Olentangy

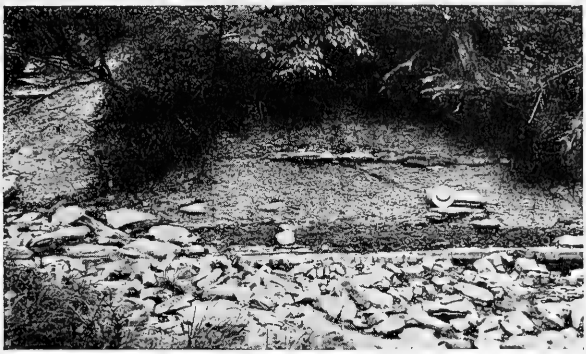

FIG. 3.—A bank of Olentangy shale downstream a short distance from the one illustrated in Fig. 2.

shale is overlaid by the Ohio shale in the central part of the state and by the Huron or lower Ohio shale at Sandusky. The stratigraphic position of the blue shale in question, therefore, suggests the same correlation that has been made on the meager fauna and the lithological similarity. When it is recalled that the regions in question lie within the same Devonian basin and that the deposits are a continuation of the same general line of Devonian outcrops, traceable by well-records in the covered interval between, this relationship seems worthy of consideration.

The relation of the Sandusky deposit to the Hamilton beds of Ontario is much more easily determined. In a memoir on the Devonian of southwestern Ontario, which was recently published by the Geological Survey of Canada, the correlation of the shale below the Prout limestone with the Olentangy has been adopted, and the

Hamilton beds have been divided, in descending order, into the Ipperwash limestone, the Petrola shale, the Widder beds, and the Olentangy shale. In the sections at Arkona, Lambton County, the two lower stages are well exposed. At no place in the province is the bottom of the Olentangy shale exposed, although well-records indicate that it rests directly upon the Delaware limestone. This latter formation is well shown in the excellent outcrops at St. Mary's and at several places in the vicinity of Brussels and Goderich. In the following section of the Hamilton beds in Rock Glen at Arkona, only the fauna of the Encrinal limestone and of the beds below are given, since the subsequent comparison is made with those portions of the section only.[1]

SECTION OF THE HAMILTON ROCKS AT ARKONA, ONTARIO

Widder Beds	Thickness Ft.	In.
11. Soil and drift	15	0
10. Limestone, argillaceous, massive, blue, partly cystalline, alternating with thin layers of shale. These beds form the falls at the old mill	10	8
9. Shale, soft, blue, with calcareous nodules or concretions	8	4
8. Limestone, argillaceous, blue	1	6
7. Shale, usually soft, blue, but some layers harder and more massive	17	5
6. Shale and shaly blue limestone	7	0
5. Coral zone. A decomposed blue or gray shale, often an impure shaly limestone, filled with corals	3	6
4. Encrinal limestone. A hard, pyritiferous, bluish-gray limestone which is full of crinoid segments, coral fragments, and other fossils. It includes some brownish shale near the base	2	4

FAUNA

Aulopora serpens, Ceratopora dichotoma, Cladopora canadensis, Cladopora roemeri, Craspedophyllum archiaci, Cystiphyllum vesiculosum, Favosites alpenaensis, Favosites placentus, Favosites turbinatus, Heliophyllum halli, Syringopora intermedia, Syringopora nobilis, Trachypora elegantula, Zaphrentis prolifica, Dolatocrinus liratus, Hederella filiformis, Streblotrypa hamiltonensis, Taeniopora exigua, Ambocoelia umbonata, Atrypa reticularis, Athyris vittata, Chonetes coronatus, Chonetes lepidus, Delthyris

[1] The fauna of the other beds may be found listed in the *Geological Survey of Canada Memoir* (No. 34, p. 164), on the Devonian of southwestern Ontario.

sculptilis, Leiorhynchus laura, Pholidops hamiltoniae, Pholidostrophia iowaensis, Productella productoides, Rhipidomella penelope, Rhipidomella vanuxemi, Schuchertella perversus, Spirifer divaricatus, Spirifer mucronatus, Stropheodonta concava, Stropheodonta demissa, Stropheodonta perplana, Pterinea flabellum, Platyceras erectum, Tentaculites bellulus, Phacops rana

Olentangy Shale

3. Shale, soft, gritless, blue, containing few fossils except in certain streaks or layers.. 19 0

FAUNA

Microcyclas discus, Arthracantha punctobranchiata, Chonetes lepidus, Pholidostrophia iowaensis, Platyceras erectum

2. Shale, soft, gritless, blue, with a few thin lenses of very fossiliferous crinoidal limestone. These beds include a thin zone in which the fossils are small and always pyritized............. 6 0

FAUNA (PYRITIZED)

Leda rostellata, Nucula lirata, Nuculites triqueter, Paracyclas lirata, Bactrites arkonensis, Tornoceras uniangulare

FAUNA (NON-PYRITIZED)

Arthracantha punctobranchiata, Gennaeocrinus arkonensis Palaeaster eucharis, Chonetes deflectus, Chonetes lepidus, Chonetes scitulus, Cyrtina hamiltonensis, Parazyga hirsuta, Productella spinulicosta, Schuchertella perversus, Spirifer mucronatus, Actinopteria boydi, Glypodesma erectum, Bellerophon triliratus, Platyceras erectum, Platyceras rarispinosum, Platyceras subspinosum, Pleurotomaria delicatula, Styliolina fissurella, Tentaculites attenuatus, Tentaculites bellulus, Primitiopsis punctulifera, Phacops rana

1. Covered interval to the level of the Ausable River.......... 10 0

The most important point of similarity between the Ohio and Ontario sections is to be found in the fauna of the thin layer about 25 feet below the base of the Prout limestone, and at a similar distance below the Encrinal limestone of Ontario. In both cases the fossils are pyritized and of small size. Although the fauna of this layer is somewhat more limited in Ohio, the four species that have been found in it are identical with those of the similarly located layer of the Arkona section. At no other horizon has this fauna been found in Ohio, and three of the species have not been found outside of it in Ontario, and even the fourth but sparingly. It seems certain, therefore, that this is the same horizon in both cases. From the prominence of *Bactrites arkonensis* in this layer at Arkona and Sandusky, it may be termed the Bactrites horizon.

The question next arises as to the relationship of the beds above the Bactrites horizon. In the Sandusky region the fossils of this portion of the formation seem to be more abundant in certain streaks or beds. To a limited extent the same is true of the shales below the Encrinal limestone in Ontario, but there the great body

FIG. 4.—The Prout or Encrinal limestone overlain by the Huron shale at Slate Cut along the Lake Shore and Michigan Southern Railway three miles east of Sandusky, Ohio.

of the deposit between the Bactrites layer and the Encrinal limestone is very sparingly fossiliferous. The Encrinal limestone may be described as several layers of a hard, pyritiferous, bluish-gray limestone which is often full of crinoid fragments—a description which fits equally well the Prout limestone (Fig. 4) in the sections here under consideration and especially the middle layers at Bloomingville. Along Eighteen Mile Creek, New York, one of the important fossils of the Encrinal limestone is *Delthyris sculptilis*. Grabau says: "This species is entirely restricted in this region to the Encrinal limestone, and may be regarded as the typical fossil of the fauna."[1] This is also the case in Ontario and probably led Shimer and Grabau to correlate the limestone in Ontario with

[1] *Bulletin of the Buffalo Society of Natural Science*, Vol. VI (1898), 32.

the similar one in western New York,[1] although many other forms are also common to the Encrinal limestone of the two regions.

The fossils in the beds immediately below the Prout limestone are more abundant than in the shale just below the Encrinal limestone of Ontario. In this respect the northern Ohio deposit shows more decided relationship to the western New York section. In fact, the upper part of it includes a portion of the fauna of the "Demissa bed," although it lacks *Spirifer granulosus* and some of the other prominent forms. However, this suggested relationship with the New York section is not fully substantiated.

In addition to the marked lithological similarity and stratigraphic relation of the Prout and Encrinal limestones, over 75 per cent of the fauna of the Prout limestone also appears in the Encrinal limestone of Ontario, and the upper layers contain many of the corals of the coral zone at Arkona, Ontario. It seems reasonably certain, therefore, that the Prout limestone is the Ohio representative of the Encrinal limestone to the north and perhaps to the east as well.

At Kettle Point, Ontario, the Devonian black shale rests upon a limestone of the Hamilton which lies about 150 feet above the Encrinal limestone, and well-records[2] show that this is the usual succession of beds in Lambton County, Ontario. In Middlesex and Kent counties, which lie to the south of Lambton, this limestone is sometimes present, but at other places is wanting,[3] as might be the case where erosion has taken place prior to the deposition of the black shale. The Huron, or basal portion of the Ohio, lies directly upon the Prout limestone at Sandusky. It therefore either represents the upper Hamilton shale and limestone of Ontario, or these deposits are wanting in northern Ohio and the Huron shale rests unconformably on the Encrinal limestone. On the basis of the fossils and the occurrence of spheroidal concretions in both deposits, Kindle has correlated the black shale at Kettle Point, Ontario, with the Huron shale of northern Ohio.[4] If this correlation

[1] *Bulletin of the Geological Society of America*, Vol. XIII (1902), 164, 166.

[2] H. P. H. Brumell, *Geological Survey of Canada, Ann. Rept.*, V, Part Q (1892), 61–70.

[3] *Ibid.*, pp. 52, 73, 74.

[4] *Geological Survey of Canada, Summary Report for 1912* (1914), pp. 287, 288.

is correct, as seems probable, the Huron shale does not represent the Upper Hamilton, but rests unconformably on the Prout or Encrinal limestone.

Mr. Allen R. Stuckey, who has drilled numerous wells in Crawford and adjoining counties, reports that at Bucyrus the drift ranges from 55 to 80 feet in thickness. Under this is 35 to 200 feet of black shale, which is usually succeeded below by about 10 feet of gray shale, so tough and sticky that it is difficult to drill. This gray shale immediately overlies the limestone, but in a few wells it has been found to be absent where the black shale rests

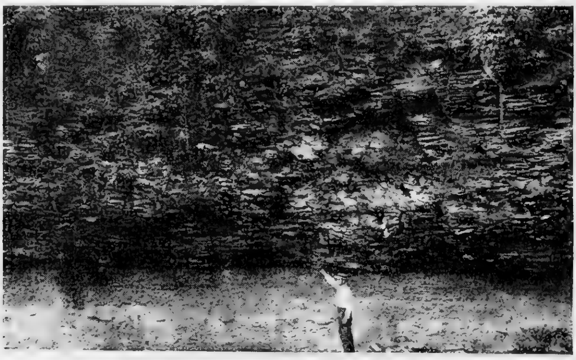

FIG. 5.—The Olentangy-Ohio shale contact at "Dripping Rock," near Liberty Church, Delaware County, Ohio. Here again there is an undulating contact.

directly upon the limestone. In the eastern part of this county, 30 feet of the gray shale is found at many places. It is evident, therefore, that in Crawford County the Olentangy shale is even more variable in thickness than it is in central Ohio and that the Prout limestone of the Sandusky region has disappeared. At "Dripping Rock" (Fig. 5), in Delaware County, where the Prout limestone is wanting and the Olentangy shale is only about 31 feet in thickness, the contact between it and the overlying Ohio shale is most marked and slightly undulating. The contact is equally marked at High Banks, near the Franklin-Delaware county line, and again in the town of Delaware (Fig. 6). At this latter place the basal Ohio shale is somewhat arenaceous. Near the Ohio River, at Kinkead Springs, Pike County, the Ohio extends down to the Silurian limestone and is firmly welded to it.

Southward from Kettle Point, Ontario, therefore, the Huron or lower portion of the Ohio shale rests on older and older beds to which its relationship must be that of unconformity (disconformity). This relation is not strikingly perceptible at any one place, but in southern Ohio the time interval between the Silurian and Devonian strata, which are in contact, is enormous. When it is recalled that the first effect of running water on a newly uplifted land surface is to roughen it, and that continued erosion tends to produce planeness, it is clear that, where little or no folding or tilting of the stratified rocks has taken place, slight (apparent) unconformities are likely to

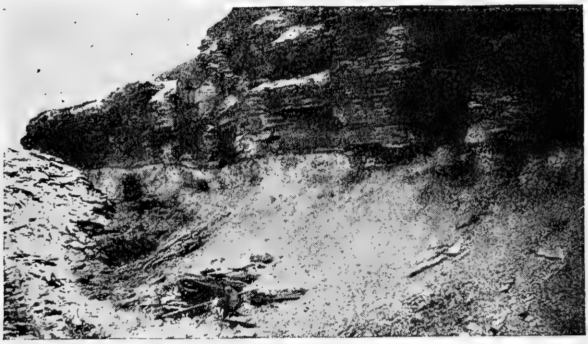

FIG. 6.—The sharp and slightly undulating contact between the Ohio and the Olentangy shales in the clay pit at Delaware, Ohio.

represent great intervals of time, while conspicuous ones may stand for shorter intervals. Or, in other words, the greater the time interval which is represented by an erosional unconformity (disconformity) in undisturbed strata, the more evasive it is likely to be. This is probably one of the chief reasons for the marked differences in the interpretation of sections where such gaps in sedimentation occur. With the Hamilton beds at Sandusky and in central Ohio resting on the Delaware limestone (Lower Erian) and overlaid unconformably by the Ohio shale in both places, the advisability of calling the soft marly beds to the south of Sandusky, Olentangy shale seems to be justified, even though the faunal evidence may not be as conclusive as could be desired.

EVOLUTION OF THE BASAL PLATES IN MONOCYCLIC CRINOIDEA CAMERATA. I

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PART III

PART I

INTRODUCTION

Most students of fossil crinoids have been interested in the morphological results of evolution rather than in the morphological processes of evolution and their results, and the description of extinct, fossil crinoids as well as of most living ones has been in general a tabulation of those results. In many cases the tabulation is incomplete, not only because of the rarity and incompleteness of the specimens described, their poor preservation and sometimes poorer preparation, but also because the obscure morphological processes which have given rise to their characteristics are either overlooked or misinterpreted. The greatest difficulty in establishing a natural classification lies in the fact that processes giving rise to morphological characteristics must be known before a correct interpretation and classification can be made. From necessity paleontologists are familiar with the obscurity of processes. The ontogeny of the fossil crinoid is only partially revealed, and that mostly in the phylogenetic succession, for the delicately constructed embryos are ill-adapted for preservation, and comparatively few immature individuals have been preserved. The complete embryonic and larval development of modern crinoids is known only in one highly specialized genus, *Antedon;* the larval stages, however, are partially known in four other genera, *Promacocrinus*, *Thaumatocrinus*, *Comactinia*, and *Hathrometra.*

Various phases of the evolutional changes in the basal plates of crinoids have been considered by both paleontologists and zoölogists. The relation of these plates to the column, their modification by the anal plate, and their characteristic decrease in number and size with the passage of geologic time attracted attention long before the importance of tegminal structure was realized,[1] and some interesting though unsuccessful attempts have been made to use basals as a foundation for classification.[2] Such artificial classifications have been swept away, but the fact remains that the changes of each plate and system of plates, as they have passed through the varying stages of evolution, must have classificatory value. When, where, and from what the monocyclic Crinoidea originated are questions of great importance, yet not of special import for the subject as herein discussed. The fact that monocyclic crinoids have existed, that their basal plates exhibit a series of remarkable changes, and that certain features in their phylogeny throw much light upon the character of the changes and their succession, is sufficient for present purposes. The process by which these changes came about is the problem to be considered here.

In this paper no attempt at reclassification will be made, but the changes exhibited by the basal plates will be reviewed, the nature of these changes studied, and suggestions arising from these studies will be applied to certain theories of descent that have arisen from similar studies made by others.

ACKNOWLEDGMENTS

The writer desires to express his sincere appreciation to Professor Stuart Weller, of the University of Chicago; Mr. Frank Springer, Mr. Austin Hobart Clark, Dr. E. O. Ulrich, and Dr. R. S. Bassler, of the United States National Museum; and to Professor R. A. Budington, Dr. Charles G. Rogers, and Dr. Maynard M. Metcalf, of Oberlin College, for the material assistance given by them in the use of specimens and literature, and for a broad view of the

[1] Ref. 38. (The reference figure is the number assigned to the work cited in the Bibliography.)

[2] Ref. 2; ref. 22.

processes operative in the growth and modification of many groups of invertebrates.

To Professor Weller, Mr. Springer, and Mr. Clark the writer is especially indebted for their many kindnesses, their helpful advice, and the privilege of freely studying their collections of fossil and recent crinoids.

REVIEW OF WACHSMUTH AND SPRINGER'S THEORY OF BASAL PLATE EVOLUTION

While various phases of basal plate evolution have been touched upon by numerous writers, the discussion by Wachsmuth and Springer[1] is the only one in which a general treatment of the subject has been undertaken, and, in order that the reader may have their theory clearly in mind before going farther, it will be quoted in substance.

The base of a monocyclic crinoid is composed of a single cycle of plates, termed the basal plates, lying at the proximal end of the cup, between the stem and the first plates of the radial series. This plate cycle was primarily composed of five separate plates, but, by anchylosis or the union of two or more members, they were reduced from five plates to four, three, two, or one. The first monocyclic crinoids had five basals.

Before the close of the Lower Silurian (Ordovician) there appeared two monocyclic genera with four basals, both having a special anal plate interposed between the radial. The quadripartite base reached its culmination in the Upper Silurian (Silurian), and disappeared before the close of the Devonian. The earliest genera with a tripartite base occur in the Upper Silurian; some of them have an anal plate, and others not. When that plate is represented, the basals are of equal size; when absent, two of the basals are equal, and the third about half smaller. The two forms continue to exist side by side to the end of the St. Louis group of the Carboniferous (Mississippian) when both became extinct. The bipartite base is restricted to the Carboniferous (Mississippian and Pennsylvanian). It occurs from the Kinderhook group up to the Coal Measures, but is found only among genera with a large[2] anal plate.

[1] Ref. 39, pp. 52–68.

[2] The exact meaning of the statement that the bipartite base is found only among genera with a large anal plate is doubtful, as *Pterotocrinus*, a genus with a hexagonal bipartite base, usually has, in proportion to the size of its basals and radials, the

It is evident from these observations that the number of basals was gradually reduced in Paleozoic times, and that in the Camerata the anal plate was introduced after the quadripartite base had made its appearance. It will now be shown that this diminution of number was the result of fusion of two or more of the five original plates, and that by the introduction of the anal plate the base underwent further modifications. The manner in which the modifications in the number of basals were effected may be best understood by reference to the diagrams on Table A. [This table is photographically reproduced as Fig. 1 of this article.]

Looking at these diagrams, the transmutation in the Camerata from five basals to a less number is readily understood among genera in which the anal plate is wanting. When the base is quadripartite, it is invariably the two anterior plates of the elementary five which are consolidated (2). In the tripartite base there is a fusion of the posterior with the left postero-lateral basal, and another between the right posterior and the adjoining antero-lateral plate (3). The figure shows that a bisection of the two larger plates will reproduce the original five pieces, interradially disposed.

The case is not so simple in genera with an anal plate, where the form of the basal disk is changed from pentagonal to hexagonal (4), as a bisection of

smallest anal plate now known among Camerata in which the anal plate is in apposition with the base. See Pl. III, No. 11, and Ref. 39, Pl. 79, Figs. 2–9.

When preparing figures for this paper from specimens in Mr. Springer's collection, with his permission, I overlooked the fact that the dorsal cup of this species had never been described or figured. As to this, Mr. Springer has furnished me the following note:

"When proposing the species *Pterotocrinus coronarius* (*Geology of Kentucky*, III, 470, Pl. I, Figs 1*a*, *b*) Lyon described and figured only the tegmen with the ponderous wing plates, as did Wachsmuth and Springer after him (*N.H. Crin. Cam.*, p. 795). While this work was in press I discovered in the Museum of Comparative Zoölogy at Harvard a lead cast of what was apparently the same specimen, with the dorsal cup attached, which fact I mentioned in a footnote on the page cited. When I acquired in 1903 the collection of the late Col. Sidney S. Lyon, I found associated with the tegmen constituting the published type the dorsal cup reproduced in the cast; the two parts were separated, but I have again united them. It is probable that they belong to the same specimen, and the fact that they pertain to the same species is proved beyond question by another specimen from the same locality having the same dorsal cup with one of the wing plates attached. The species is remarkable, not only for its extraordinary wing plates, but also for the construction of the dorsal cup, in which the basal plates are very small and flat, while the radials are of enormous size, larger than all the other plates of the cup combined; this being the reverse of the structures in *Pt. capitalis* and all other known species of the genus. It occurs in the Birdsville formation of the Kaskaskia group, in Crittenden County, Kentucky, where it is extremely rare; and also in the Renault formation in Monroe County, Illinois, from which region a fragmentary specimen was described by Hall (*Geol. Iowa*, II, 689, Pl. XXV, Fig. 7) under the name *Dichocrinus protuberans*."

the larger plates would produce six plates instead of five. This difficulty, however, is overcome if we consider that the introduction of the anal plate into the ring of radials necessitated corresponding modifications among the basals, as otherwise these plates would lose their interradial position. It

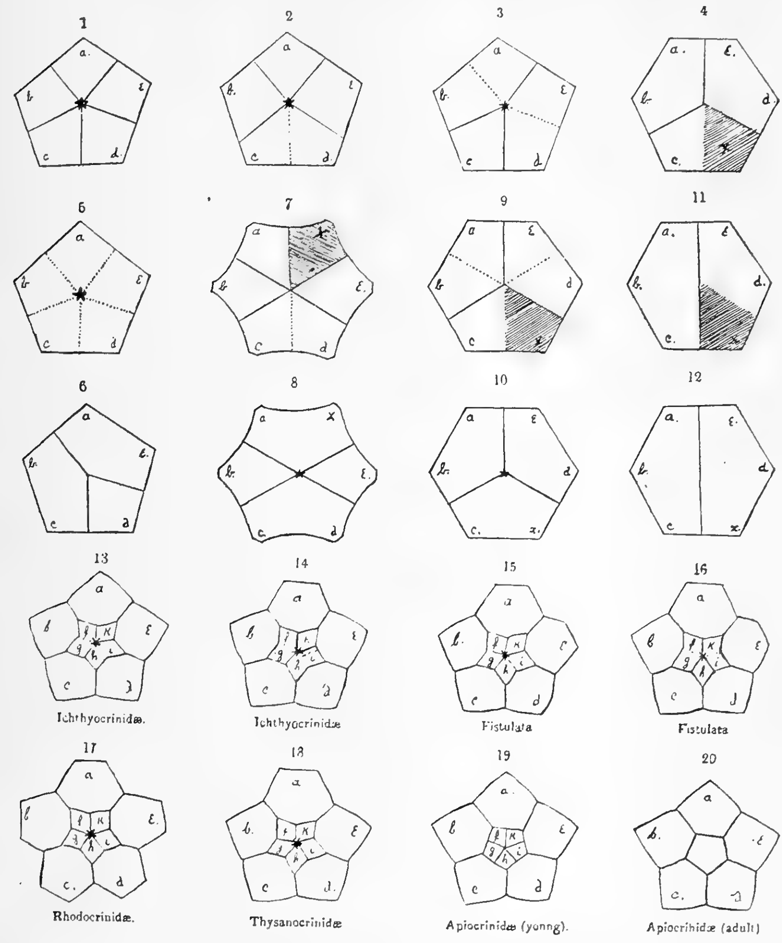


FIG. 1.—Diagrams illustrating the evolution of the basals and infrabasals: all figures represent the anal side at the top; *a*=posterior basal; *b* and *e*=postero-lateral basals; *c* and *d*=anterior basals; *f*, *g*, *h*, *i*, *k*=infrabasals.

required either the introduction of a basi-anal plate, or an increase in the size of the original pieces. That the latter occurred among the Camerata is clearly shown by the diagrams, and the evidence leaves no doubt at what part of the base the extra width was inserted.

Taking first the quadripartite base, and comparing 2 of the diagrams with 8—one pentangular, the other hexangular—we find that in the latter the posterior basal has doubled in size (7), without materially changing the orientation of the plates, or disturbing their general arrangement. . . . .

In the tripartite base the change was accomplished in a different way. There *x* is added to plate *c* (9 and 10), and plates *ab* and *ed* have coalesced, and hold relatively the same position as in 3.

The bipartite base is probably derived from the tripartite (4), which preceded it in time, and *x*, which in the latter constituted a part of *c*, is united with *de*, and *ab* with *c* (11 and 12).

Now taking up 7 and eliminating *x*, so that the side of plate *a* rests against the plate *e*, we obtain 2, and by a similar procedure we are enabled to transform 9 into 3. The hexagonal base is thus restored to its primitive pentagonal form without disturbing the orientation of any plate, compound or simple.

This theory was thought by Wachsmuth and Springer to have been confirmed by an abnormal example of *Teleiocrinus umbrosus* n which the anal plate was wanting.

Teleiocrinus umbrosus has normally three equal basals, but in this specimen the basal plate to the left of the anterior ray is reduced to one-half its normal size, leaving the basal disk exactly like that of forms which are normally without the anal plate.

It is very remarkable that while in all crinoids with an unequally tripartite, monocyclic base, the smaller plate is located to the *left* of the anterior radial, this plate in the base of the blastoids lies invariably to the *right* (6).

In the discussion of the changes from the pentagonal, five-basal form to the hexagonal, four-basal form, it is stated that the enlargement of the posterior basal took place upon the right side of that plate, but no evidence is submitted for this statement. Why could not the enlargement have taken place as well upon the left side, or by symmetrical development upon both sides of the posterior basal? The statement that "the evidence leaves no doubt at what part of the base the extra width was inserted" is not sufficient, and it in itself creates a doubt. Again we are told that "the introduction of the anal into the ring of radials necessitated corresponding modifications among the basals, as otherwise these plates would lose their inter-radial position."[1] However, in the discussion of the basals in dicyclic crinoids the statement is made that "the introduction of the anal plate into the ring of

[1] Ref. 39, p. 59.

radials did not affect the basals of dicyclic crinoids" in the same manner as in the monocyclic. While in the latter, when the plate is represented, the orientation of the basals is slightly disturbed, in the dicyclic forms it remains unaltered. The anal plate of the latter rests invariably upon the trunkated upper face of the posterior basal; while in monocyclic crinoids it is supported by the basals *a* and *e* (Nos. 10 and 12), or occasionally by *a* and *x* (No. 8).

This statement leads one to believe that no widening of the posterior basal took place upon the introduction of the anal plate in the dicyclic form, but Nos. 15–18 in Fig. 1 show a decided widening of that plate. Overlooking this inconsistency and the fact that trunkation of the posterior basal is in itself an alteration, we are still unenlightened as to why alteration is demanded in the one case and not in the other, as no explanation of an alternative phenomenon is given. Neither is any reason given, other than the position of sutures, for the markedly different positions of enlargement in basal plates of the four-, three-, and two-basal hexagonal forms. By reading between the lines one is able to supply various explanations, yet they are not the explanations of the writers, nor what is needed and demanded by the conditions of the problem. Furthermore, no reasons nor illustrations are given showing why the abnormal specimen of *Teleiocrinus umbrosus*, by which the theory was apparently confirmed, was oriented with the smaller basal in the left anterior interray. The questions in the writer's mind are: Why should the stimulus of enlarging the anal area in the quadripartite form cause enlargement of the right side of the posterior basal and not of the left or of both sides as well? Why should the same stimulus in a dicyclic crinoid have no effect upon the adjacent basal plates? Why should the same stimulus cause the enlargement of the left anterior basal in the equibasaled, tripartite form, and of the left side of the right anterior basal in the equibasaled, bipartite form, derived therefrom? What was the nature of the change in shifting factor *x* from basal *c* to basal *d*? How could such changes take place without disturbing the orientation of any plate, compound or simple? What were the reasons for the orientation assigned to the abnormal specimen of *Teleiocrinus umbrosus*? These questions have led the writer to investigate the evolution of the basal plates in the monocyclic Crinoidea, and the result of this investigation will be stated in the latter part of this study.

REVIEW OF CERTAIN PHYLOGENETIC CHARACTERISTICS IN MONOCYCLIC CAMERATA

In this review the phylogenetic characteristics of the various groups of monocyclic Camerata will be considered, for it is in this order that the succession is better understood and that the evolution of the basal plates is the most complex. There exist in this order two great groups, separated structurally but not phylogenetically according to the outline of the basal cup, and therefore according to the presence or absence of an anal plate in contact with and trunkating the posterior basal. The first of these groups possesses an anal plate in apposition with the posterior basal, and has in consequence a hexagonal basal. The second group, in which plates of the anal series are either present or absent but not in contact with the posterior basal, has a pentagonal base. In considering these facts, questions of descent and relationship necessarily arise.

In the ontogenetic development of the external skeleton in the living *Antedon*[1] so many of the phylogenetic steps found in fossil crinoids are illustrated, that it may well be looked upon as a key to their methods of development and perhaps to their interrelationships. Leaving out of consideration the earlier embryo-logical stages, let us follow in detail the methods of plate intercalation and development after the formation and contact of the basal and oral plates (Fig. 2).

About the time of the attachment of the pentacrinoid larva, the basal plates assume a regular, trapezoidal outline, the lower part of each being an acute-angled triangle with its apex distally directed (Fig. 2, No. 1). The sides of the lower triangle are bordered by a somewhat thickened edge of solid, transparent stereom, the presence of which indicates that the plate has received its full proportionate increase in that direction.[2] Even after the plate

[1] *Antedon*, while more highly specialized in its larval development than some of the other modern crinoids, is chosen for comparison with the Camerata because it is the best known of any of the genera in which the larval development has been studied.

[2] Ref. 11, p. 729.

edges are thus defined, the plates steadily increase in size, apparently by interstitial growth.[1] The adjacent borders of the plates, however, do not come into absolute contact, as a thin lamina of sarcode is interposed between them until the sutures are closed by anchylosis. The upper margins of the basals have at this time no distinct border,[2] but are still growing by the process of branching and anastomosis (see p. 501, plate growth).

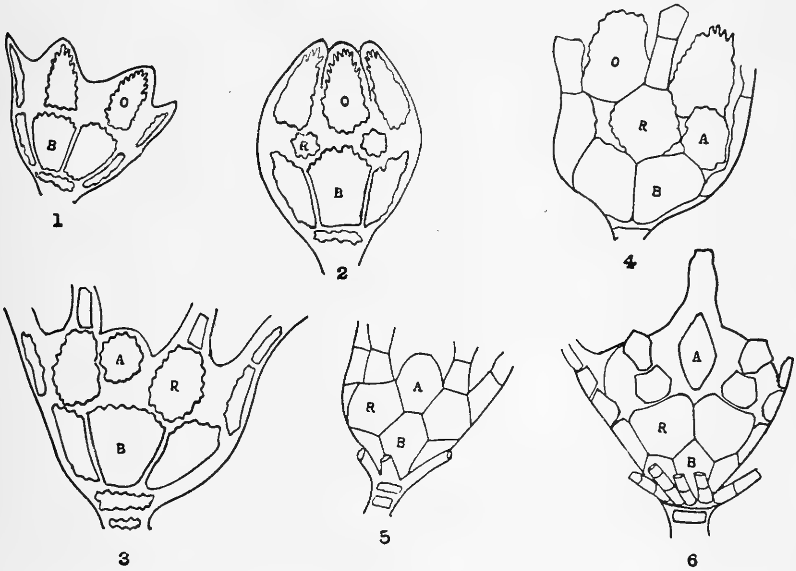


FIG. 2.—Formation of the dorsal cup and migration of the anal plate in *Antedon rosaceus:* 1, 2, after Thomson; 3–5, after Carpenter; 6, original from specimen in Oberlin College Museum; *o*=orals; *b*=basals; *r*=radials; *a*=anal.

Shortly after the fixing of the pentacrinoid and the opening of the cup, a third series of plates, the radials, make their appearance in the space left by the beveling off (absorption) of the adjacent lateral angles of the basals and orals (Fig. 2, No. 2),[3] the beveling being caused apparently by the encroachment of the radials.[4] About the period of the development of the second radials (costals) a forked spicule makes its appearance between the upper parts of the posterior radials. This plate gradually increases in the regular

[1] Interstitial growth: ref. 35, p. 538.

[2] Ref. 11, p. 729, Pl. 41, Fig. 1, *b*.

[3] Ref. 35, p. 539.

[4] Ref. 11, p. 729.

way (see p. 502), until it develops into a round, cubiform plate, the anal plate (Fig. 2, No. 3).[1] The radials, with the anal plate between, now form nearly a complete circle, resting on the basals and separating them completely from the orals.[2] Although greatly enlarged, the radials are still subquadrangular in outline, the proximal angle occupying the enlarged portion of the interbasal suture, and the distal angle, now trunkated, supporting the narrow costals.[3] Considerable space still exists between the adjacent radials, except where they are in apposition with the anal plate (Fig. 2, No. 4), and these spaces are filled only with sarcodic substance.[4] The anal plate from proximal growth now comes into apposition with the posterior basal, and the two are mutually trunkated. Upon further development the radials meet, and their margins assume the finished appearance previously noted in the proximal portion of the basal plates. The posterior radials, especially the right, however, show marked asymmetry, owing to the non-development of the sides adjacent to the anal plate (Fig. 2, No. 5). Growth in the radials does not cease upon their meeting, and as the basals do not now further enlarge, the radials and the anal are forced by contact with each other to extend themselves in an oblique direction, thus enlarging their distal perimeter, and increasing the diameter of the tegmen.

The anal plate by this time has reached its full development and, being more firmly attached to the visceral mass than to the adjacent radials,[5] is gradually lifted out of the cup by the extension of the anal tube. The space left by the withdrawal of the anal is gradually filled by lateral growth from the adjacent radials, which, however, do not immediately come into contact. Before the anal is completely withdrawn from the radial cycle, however, the posterior radials meet below it, and, as withdrawal continues, corresponding and continuous enlargement of the radials fills the re-entrant angle, and gives to the plates their bilaterally symmetrical outline (Fig. 2, No. 6).

About this time a very remarkable change takes place in the tegmen. The oral cycle, like the basal one, does not partake of

[1] Ref. 35, p. 529 (anal).
[2] Ref. 15, p. 314 (radianal).
[3] Ref. 11, p. 729.
[4] Ref. 11, p. 729.
[5] Ref. 11, p. 732.

the pronounced enlargement noted in the radial cycle, its diameter being neither increased by growth of its component parts nor augmented by their separation from one another; but, as the ventral disk expands, the orals become separated from the radials upon which they were previously superimposed and are carried upward and relatively inward and the costals and lower distichals are incorporated into the cup. The space now existing between the radials and orals generally remains as a simple, membranous perisome, traversed by the five ambulacral canals; but, in some specimens of *Antedon rosaceus*,[1] and in other modern crinoids, well-defined groups of interradial plates develop in the angles between the brachials. When these plates appear in the cup they are known as interbrachials, and in the tegmen as interambulacrals. Further tracing of the development of the basals and the orals and consideration of stem formation are not here necessary, although they may at times be referred to in the following discussion.

In tracing the phylogeny of the Batocrinidae and Actinocrinidae, the anal plate is found as a constant characteristic and the base throughout the series is hexagonal. Complete incorporation of the ambulacral grooves has taken place in the tegmen, and the arms are incorporated in the cup up to and often beyond the second distichals. In *Tanocrinus*, a genus probably closely related to the ancestors of the Batocrinidae,[2] five basals are present; the anal plate separates the posterior radials, and is in apposition with and trunkates the posterior basal.

In *Xenocrinus*, *Comprocrinus*, and *Abacocrinus* only four basals are present, the anterior pair being obviously united and somewhat reduced in width. In the other genera of the Batocrinidae and Actinocrinidae there are three equal basals, the basal sutures meeting the antero-lateral radials and the anal plate. Why the third basal suture meets the anal plate will be considered later (Plate III).

The Melocrinidae, while not showing as complex a basal evolution as that shown in the hexagonal Camerata, are interesting in showing the absence of an anal plate in contact with and trunkating the posterior basal, and in some genera an absence of all plates of

[1] Ref. 35, p. 540. [2] Ref. 6, p. 164.

the anal series. The base throughout this family is pentagonal, and the basals number either five, four, three, or one. When five basals are present the basal sutures meet the radials in the normal manner. When four basals are present either the anterior or left anterior suture is missing, and when only three basals are present the sutures meet the anterior, left-anterior, and right-posterior radials.

The Calyptocrinidae have throughout a pentagonal base and only four basal plates, and the anal plates are entirely missing.

In considering these families the question arises as to whether the base has been pentagonal throughout its whole phylogenetic history or whether there has been a hexagonal stage, as in the Batocrinidae and Actinocrinidae.

The Platycrinidae and Hexacrinidae are characterized by having the ambulacral grooves and lower brachial plates but slightly incorporated in the calyx. The orals in the simpler forms are well developed, and the base is either pentagonal or hexagonal. In the Platycrinidae no anals have been positively determined, and the base is pentagonal. Throughout this group there are ordinarily but three basals, five in youth and sometimes but one in age. Two of the basals are large, the third smaller. In the *Hapalocrinus*,[1] the smaller basal is the right-anterior one, and the basal sutures meet the anterior, right-anterior, and the left-posterior radials, as in *Stephanocrinus*. In the other genera of Platycrinidae the left-anterior basal[2] is the smaller, and the basal sutures meet the anterior, left-anterior, and right-posterior radials. In the Hexacrinidae there are usually three, or two, equal basals, sometimes only one.[3] The base is hexagonal and the anal plate well developed. The basal sutures in the three-basal forms meet the antero-lateral radials and the anal plate; in the two-basal forms the sutures meet the anterior radial and the anal plate.

A discussion of the monocyclic Inadunata as a whole cannot now be undertaken, but certain species of Larviformia which in their development illustrate very clearly, even diagrammatically,

[1] Ref. 21, pp. 94–110.

[2] Exceptions are noted on p. 507 in the description of Fig. 5, No. 6.

[3] Ref. 6, p. 158.

some of the slighter morphological changes found in the Camerata will be considered in the discussion of morphological principles.

Having noted the more conspicuous changes through which the basal cup has passed, a detailed study of the processes involved in these may be undertaken.

DETAILED STUDY OF PROCESSES ACTIVE IN PLATE EVOLUTION

The processes active in the evolution of crinoid plates, especially the basals and radials, may be divided into two broadly separated though often co-operating groups: (1) those which do not *necessarily* modify the relation of contact and position of the plates; and (2) those which do modify these relations. The discussion of the first group of processes includes: (*a*) symmetrical growth; (*b*) symmetrical reduction; and (*c*) anchylosis. The second group includes: (*a*) reduction and compensating growth; (*b*) enlargement and compensating reduction; (*c*) plate division; (*d*) plate migration; (*e*) plate interpolation; and (*f*) anchylosis.

I. CHANGES NOT PRIMARILY MODIFYING THE RELATIONS OF PLATE CONTACT AND POSITION

a) *Symmetrical growth.*—Plate growth in the Echinoidea and Crinoidea[1] is due to the deposition, by amebod cells, of crystalline calcium carbonate, or calcium and magnesium carbonate[2] in reticulate pattern in the mesenchyme. Three, or perhaps more, of the ameboid calciferous cells fuse by means of pseudopodia into a plasmodium or reticulate tissue.[3] There the pseudopodia meet, the protoplasm forms a small calcareous nodule (intracellular secretion, according to Theel; extracellular, according to Semon), which gradually increases along the pseudopodia, forming a triradiate spicule. By further branching and anastomosis, the branches of the spicule meet and fuse at the tips of their processes (Fig. 3, No. 3), thus building up a hard tissue (stereom), showing a strongly

[1] Although no observations have been made upon the early details of plate deposition (stereom formation) in the Crinoidea, the growth of the plate from the primary spicule on so closely parallels that in the Echinoidea that there can be no doubt concerning the method of formation.

[2] Composition of crinoid skeletons: ref. 25, p. 31; ref. 14, p. 488; ref. 17.

[3] Stereom formation: ref. 34.

reticulated structure (Fig. 3, No. 4) when sectioned in any direction. The co-ordination of deposition is such that each plate acts optically and mineralogically as a single crystal of calcite, without other planes of weakness than the cleavage planes developed by crystallization. The margins of the plates are at first rough with sprouting spicule branches (Fig. 2, No. 2, R), but later, upon coming into mutual contact, become smooth (Fig. 2, No. 5). Growth by branching and anastomosis gives way to interstitial growth,[1] and the increase in size is more gradual. Each plate, as

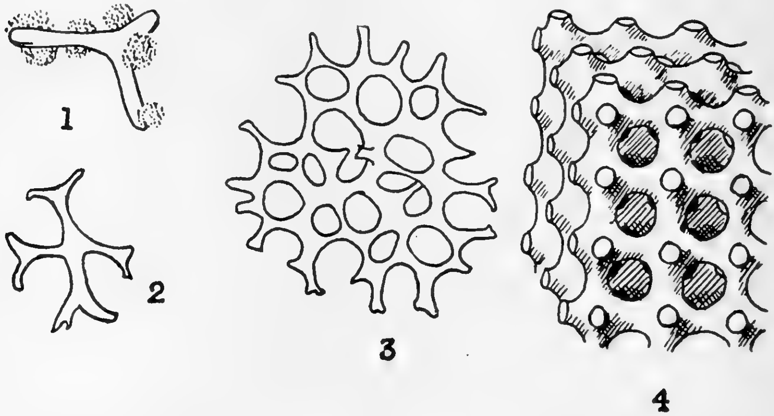


Fig. 3.—Stereom formation: 1, formation of the triradiate spicule by the fusion of seven calciferous cells; 2, basal from a larva of *Antedon* on the sixth day; 3, basal on the tenth day; 4, ideal representation of regular, reticulate stereom. (1, after Theel; 2, 3, after Bury; 4, after P. H. Carpenter.)

it now enlarges, is carried relatively outward and away from the adjacent plates, and in the basal cycle not only away from the adjacent plates, but also away from the axial canal, as is shown by growth lines whenever present. When growth of the plates is symmetrical, each plate in a cycle is the equivalent in size and shape of every other plate in that cycle, and has the same angles with reference to the central axis of the cup as the other plates in the cycle.

b) Reduction of parts by absorption.—This also is a function of ameboid cells, which are similar in appearance to the calciferous

[1] Ref. 35, p. 538.

cells, but take the calcareous salts into solution and transmit them to the deposition cells.[1] When reduction by proximal or distal, or proximal and distal, absorption is symmetrical throughout a cycle of plates, the relation of parts is not disturbed, unless the reduction

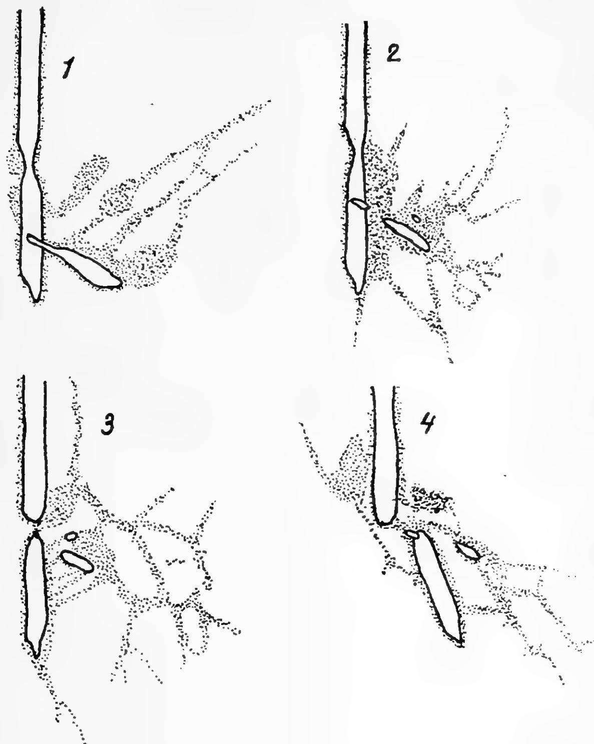


FIG. 4.—Stereom absorption; absorptive cells operating upon the posterior end of a calcareous rod in a mature pluteus: 1, one portion of rod separated, the second partially cut; 2–4, advancing stages up to the nearly completed absorption of portion one, the separation of portion two (after Theel).

of the cycle is complete, thus bringing previously separated cycles into apposition with each other.

c) Anchylosis.—Anchylosis is the uniting of apposed plates by an unbroken deposit of stereom in the sutures, and is, as far as we know, an ontogenetically repetitive process, taking place only

[1] Ref. 34, pp. 349–351.

between plates and not between their formative cell groups. The intrasutural deposit is formed through the activity of the ameboid, calciferous cells, and the firmness with which the plates are united depends upon the amount of stereom deposited. In youth the deposit is slight, the plates are easily separated, and the sutures are usually discernible as external or sometimes as internal grooves. In age, however, much variation exists, for the extent of deposition depends upon the stage of development reached by the group and upon the vitality of the individual. In some cases immature (incomplete) anchylosis is apparently an adult characteristic and the plates are easily separated.[1] In other cases the deposit is as strong as the stereom of the plates, and fracturing results as readily in the plates as in the old suture plane. Again, in cases where firm union is the rule, as in the Camerata, lowered vitality, or other physiological disturbance, sometimes results in the partial or total inhibition of anchylosis. Such abnormalities, or reversions, are of great value in determining the position of sutures otherwise untraceable, and will be more fully considered under the topic of delayed anchylosis.

From the foregoing definition of anchylosis the conclusion is drawn that any suture or group of sutures appearing in the primitive basal cup may be lost through anchylosis, and the following discussion will show the actual and possible combinations due to simple anchylosis alone.

In order to facilitate this description and the tabulation of the variations to be cosidered, the convention of lettering the basal plates from the posterior to the right-posterior, in an anticlockwise direction, has been adopted, the letters separated by dashes making up the basal formula. The letters from *a* to *e* denote the plates and the dashes the intervening sutures; a dash over a letter shows trunkation of that plate, while the absence of a dash between the letters denotes the absence of the suture between those plates. Thus, *a—b—c—d—e—* is the formula for the simple, pentagonal base while $\bar{a}$—*b—cd—e—* shows a hexagonal base with the posterior basal trunkated and the anterior pair of basals united.

[1] Ref. 1, p. 29; ref. 10, pp. 36, 37.

From a study of Figs. 1 and 9 it will be seen that eight types of basal modification, by the reduction in number of the basal plates, occur in the Camerata during the Paleozoic era. The primitive base (*a—b—c—d—e—*), Fig. 1, No. 1, appears in the Ordovician, but it probably originated long before that time. The four-basal type (*a—b—cd—e—*), Fig. 1, No. 2, appears in the Ordovician, becomes abundant in the Silurian, and disappears before the close of the Devonian. The three- inequi-basal type (*ab—c—de—*), Fig. 1, No. 3, makes its appearance in the Ordovician, increases in the Silurian, reaches its climax in the Devonian, and disappears in the Mississippian. The three- inequi-basal type (*ea—bc—d—*), Fig. 1, No. 6, is present during the Silurian, Devonian, and Mississippian, but never becomes very prominent. The one-basal type (*abcde*), Fig. 1, No. 5, occurs at various times during the Paleozoic period, but not as a generic or specific characteristic. The hexagonal, five-basal type ($\bar{a}$*—b—c—d—e—*), Fig. 9, No. 6, is present in the Ordovician. The hexagonal, four-basal type ($\bar{a}$*—b—cd—e—*), Fig. 1, No. 8, appears first in the Silurian (Richmond) and disappears during the Silurian. The three- equi-basal type (*ab—cx—de—*)[1], Fig. 1, No. 10, appears in the Silurian, increases in the Devonian, reaches its climax in the lower part of the Mississippian, and then disappears. The two- equi-basal type (*abc—xde—*),[1] Fig. 1, No. 12, is introduced in the Kinderhook and becomes extinct in the lower part of the Pennsylvanian.

Possible combinations of the primitive five-basals: Since Wachsmuth and Springer have assumed that all crinoids having an unequally tripartite base have the smaller basal in the left-anterior interray, it may be well to consider what combinations may be expected from anchylosis of the primitive five-basals. These combinations are explained below and illustrated in Fig. 5.

Fig 5, No. 1, illustrates the primitive basal cup of pentagonal outline, represented by the formula *a—b—c—d—e—*, and found in *Glyptocrinus*, *Schizocrinus*, *Stelidiocrinus*, and young individuals of *Platycrinus*.

Fig. 5, No. 2, shows a common Ordovician and Silurian type of reduction (*a—b—cd—e—*), in which the two anterior basals are

[1] Formula based upon Wachsmuth and Springer's theory.

anchylosed. In this group there are five possible combinations: *ab—c—d—e—*, *a—bc—d—e—*, *a—b—cd—e—*, *a—b—c—de—*, and *ea—b—c—d—*. Of these combinations, *a—b—cd—e—* has been the only one described in the four-basal Melocrinidae; however, the writer has found the *a—bc—d—e—* (No. 2*a*) combination in the following specimens in the Springer collection: of eight specimens of *Melocrinus calvini* from Calloway County, Missouri, four

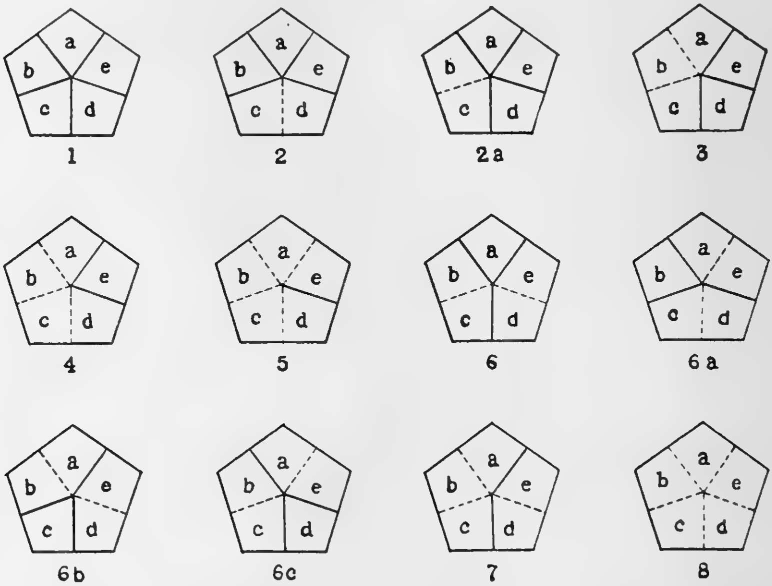


Fig. 5.—Diagrams illustrating types of the possible combinations due to anchylosis of two or more of the primitive five-basals.

could be properly oriented[1], and these showed the *bc* anchylosis (Pl. II, No. 4), as did two specimens of *M. obconicus*? Hall, and one of the type specimens of *M. roemeri*. The other four-basal forms of the Melocrinidae(?) and the Eucalyptocrinidae[2] have the *a—b—cd—e—* type of base.

Fig. 5, No. 3, illustrates a type in which three adjacent basals have been anchylosed (*abc—d—e—*). Here again five combinations

[1] In orienting these specimens the anal tube was used as the reference point.

[2] This orientation of *Eucalyptocrinus* is strictly arbitrary, as no indices for proper orientation have as yet been discovered.

are possible: *abc—d—e—*, *a—bcd—e—*, *a—b—cde—*, *b—c—dea—*, and *c—d—eab—*. Of these combinations one, the *abc—d—e—* combination, is found in *Zophocrinus*, as figured. This orientation does not agree with Bather's interpretation of the genus,[1] but is based upon the discovery of the anus in a large number of specimens studied by the writer in the Springer and Walker Museum collections.

Fig. 5, No. 4, shows the anchylosis of four adjacent plates (*abcd—e—*), leaving but one free plate. Here, however, any plate of the five might have been the free plate, and five combinations are possible: *abcd—e—*, *a—bcde—*, *b—cdea—*, *c—deab—*, and *d—eabc—*. Of these combinations none have been discovered.

Fig. 5, No. 5, illustrates one of five possible combinations in which only one suture exists (*abcde—*). Combinations 4 and 5 seem too asymmetrical from a structural viewpoint to occur as either generic or specific characters, but might appear in cases of delayed anchylosis, in which complete anchylosis is the normal result.

Fig. 5, No. 6, illustrates the simple tripartite combination (*ab—c—de—*), in which two pairs of basals are anchylosed. Of the five possible combinations of this type four are now known: *a—bc—de—*, in *Allagecrinus americanus*;[2] *b—cd—ea—*, in *Storthingocrinus*[3] and *Hyocrinus* (No. 6, *a*)[4]; *ab—c—de—*, in *Sybathocrinus* and the Platycrinidae (No. 6, *b*); *bc—d—ea—*, in *Hapalocrinus*[5] and *Stephanocrinus*[6] (No. 6, *c*). The fifth combination (*ab—cd—e—*) has not yet been discovered.

Fig. 5, No. 7, illustrates one of the five possible combinations in which three- and two-basals are anchylosed, as *abc—de—*, etc. Of these only one is known, *abc—de—* in *Mycocrinus*,[7] as figured.

Fig. 5, No. 8, shows the complete type of anchylosis (*abcde*). While this formula recognizes but one type of complete anchylosis,

[1] Ref. 6, pp. 150, 151.

[2] This combination was found recently, by the writer, in two specimens of *Allagecrinus americanus* in a large collection of that species made by Professor Weller at Louisiana, Missouri.

[3] Ref. 3, p. 426.

[4] Ref. 6, p. 153.

[5] Ref. 21, pp. 95–105, Pls. 9, 10.

[6] Ref. 19, pp. 212, 351.

[7] Ref. 28, p. 110, Pl. 7, Fig. 4.

the type may have been derived by the simultaneous anchylosis of the five primary plates, or from the closure of the remaining sutures in any of the thirty possible combinations given above. Dealing here with results alone, we see that thirty-one possible modifications of the five primary basals are obtainable through simple anchylosis.

[*To be continued*]

EXPLANATION OF PLATES

PLATE I

Teleiocrinus umbrosus Hall. Abnormal specimen cited by Wachsmuth and Springer as confirmation of their theory

No. 1.—Oblique view of posterior interray, showing absence of anal plate and one of the first interbrachials, and the reduction of the right-posterior basal. Basal formula, *ab—cd—e—*; formula of posterior interray, *0—1—3—4—2—*.

No. 2.—View of right-posterior interray, showing normal arrangement of interbrachials *1—2—2—2—*, and reduction of right-posterior basal.

No. 4.—Posterior view.

No. 6.—Tegmen, showing position of anal tube.

Teleiocrinus umbrosus Hall. Springer collection; normal specimens

Fig. 3.—Posterior view, showing normal posterior interray and normal base. Basal formula, *ab—cd—ex—*; formula of posterior interray, *A—2—3—4—1—*. To be compared with Nos. 1 and 4.

No. 5.—Tegmen, showing position of anal tube in another specimen; to be compared with No. 6.

PLATE II

Glyptocrinus decadactylus Hall. Springer collection, specimens having a pentagonal base

No. 1.—Basal view, showing normal pentagonal base with five basals. Basal formula, *a—b—c—d—e—*.

Chicagocrinus inornatus Weller (type). University of Chicago Paleontological Collection, No. 10787

No. 2.—Basal view, showing anchylosis and reduction of antero-lateral basals and compensating enlargement of postero-lateral basals. Basal formula, *a—b—cd—e—*.

Melocrinus calvini Wachsmuth and Springer. Springer collection

No. 3.—Posterior view.

No. 4.—Basal view of same specimen, showing anchylosis and reduction of sinstro-lateral basals and compensating enlargement of posterior and right-anterior basals. Basal formula, *a—bc—d—e—*.

Stephanocrinus angulatus Conrad. University of Chicago paleontological Collection, No. 10787

No. 5.—Basal view, showing anchylosis and reduction of right-posterior and posterior and sinstro-lateral basals, and compensating enlargement of right-anterior basal. Basal formula, *ea—bc—d—*. Note reduction of right-posterior and left-anterior radials.

Platycrinus subspinosus Hall. Springer collection

No. 6.—Basal view, showing normal *Platycrinus type of anchylosis.* Basal formula, *ab—c—de—*. To be compared with No. 5.

Abacocrinus tesselatus Angelin. Springer collection, specimens having a hexagonal base

No. 7.—Basal view, showing asymmetry of posterior radials, enlargement and trunkation of posterior basal, and anchylosis and reduction of antero-lateral basals, coupled with compensating enlargement of postero-lateral basals. Basal formula, $\bar{a}$*—b—cd—e—*.

Melocrinus sampsoni M. and G. (type). University of Chicago paleontological collection, No. 6958; probably *Actinocrinus chouteauensis* S.A.M.

No. 8.—Basal view showing reappearance of anterior basal suture. Basal formula, *ab—c—d—ex—*.

Batocrinus. University of Chicago paleontological collection No. 9082

No. 10.—Basal view of normal specimen. Basal formula, *ab—cd—ex—*.

No. 11.—Basal view of abnormal specimen, showing reappearance of anterior basal suture. Basal formula, *ab—c—d—ex—*.

Actinocrinus multiradiatus. University of Chicago paleontological collection No. 8959

No. 9.—Basal view with base removed, showing asymmetry and reduction of posterior radials. Compare with Nos. 7–14.

Steganocrinus pentagonus Hall. Springer collection

No. 12.—Basal view of normal specimen, showing asymmetry and reduction of posterior radials. Basal formula, *ab—cd—ex—*.

No. 13.—Basal view of abnormal specimen, showing loss of the antero-lateral and posterior basal sutures and the reappearance of the anterior and left-posterior sutures. Basal formula *bc—dea—*; factor *x* may or may not be present.

No. 14.—Basal view of another abnormal specimen, showing loss of right-anterior basal suture and reappearance of anterior suture. Basal formula, *ab—c—dex—*.

No. 15.—Basal view of abnormal specimen, University of Chicago paleontological collection, No. 8979, showing loss of anal plate. Basal formula, *b—cd—ea—*. See Plate III.

PLATE III

Steganocrinus pentagonus Hall

No. 1.—Posterior view of abnormal form of Pl. II, No. 15.

No. 2.—Tegmen of same specimen, showing position of anal tube.

No. 3.—Posterior view of normal specimen in Springer collection. To be compared with No. 1.

Hexacrinus elongatus Goldfuss. Springer collection

No. 4.—Basal view of normal form. Basal formula *ab—cd—ex—*.

Note reduction of posterior radials.

Hexacrinus anglypticus Goldfuss. Springer collection

No. 5.—Basal view of abnormal form, showing loss of posterior basal suture and reappearance of left-posterior suture. Anchylosis of anterior basals normal. Basal formula, *b—cd—ea—*; factor *x* may or may not be present.

No. 6.—Basal view of another abnormal specimen, showing loss of right-anterior basal suture and reappearance of anterior suture. Basal formula, *ab—c—dex—*.

Talarocrinus patei M. & G, Springer collection

No. 7.—Basal view of normal specimen. ×2. Basal formula, *abc—dex—*.

No. 8.—Basal view of abnormal specimen, showing reappearance of left-posterior basal suture. ×2. Basal formula, *a—bc—dex—*.

No. 9.—Basal view of another abnormal specimen, showing reappearance of left-anterior basal suture. ×2. Basal formula, *ab—c—dex—*.

No. 10.—Basal view of another abnormal specimen, showing loss of posterior basal suture and reappearance of left-posterior and right-anterior sutures. ×2. Basal formula, *bc—d—ea—*. Factor *x* may or may not be present.

Pterotocrinus cirnarius Lyon, Springer collection; Tegmen figured by Wachsmuth and Springer, ref. 39, Pl. LXXIX, Figs. 7*a*, 7*b*

No. 11.—Basal view, showing great reduction of anal plate, and asymmetry of posterior radials. Basal formula, *abc—dex—*.

Dichocrinus inornatus W. and Sp. Springer collection

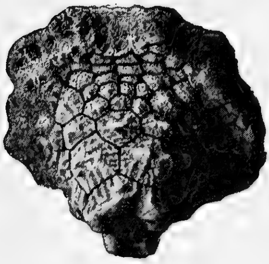
No. 12.—Lateral view of normal specimen. ×1½.

No. 15.—Tegmen of normal specimen showing flexible condition of anal tube and interambulacral areas. ×2.

Platycrinus symmetricus W. and Sp. Springer collection

No. 13.—Lateral view, showing similarity to No. 12. ×1½

No. 14.—Tegmen of young specimen, figured by ref. 39, Pl. LXIX, Fig. 1*c*. Note flexible condition of anal tube and interambulacral areas, and general similarity to No. 15. ×2.



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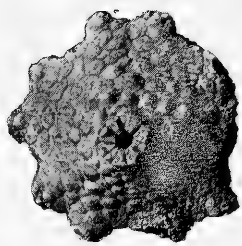

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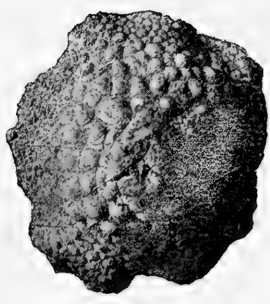

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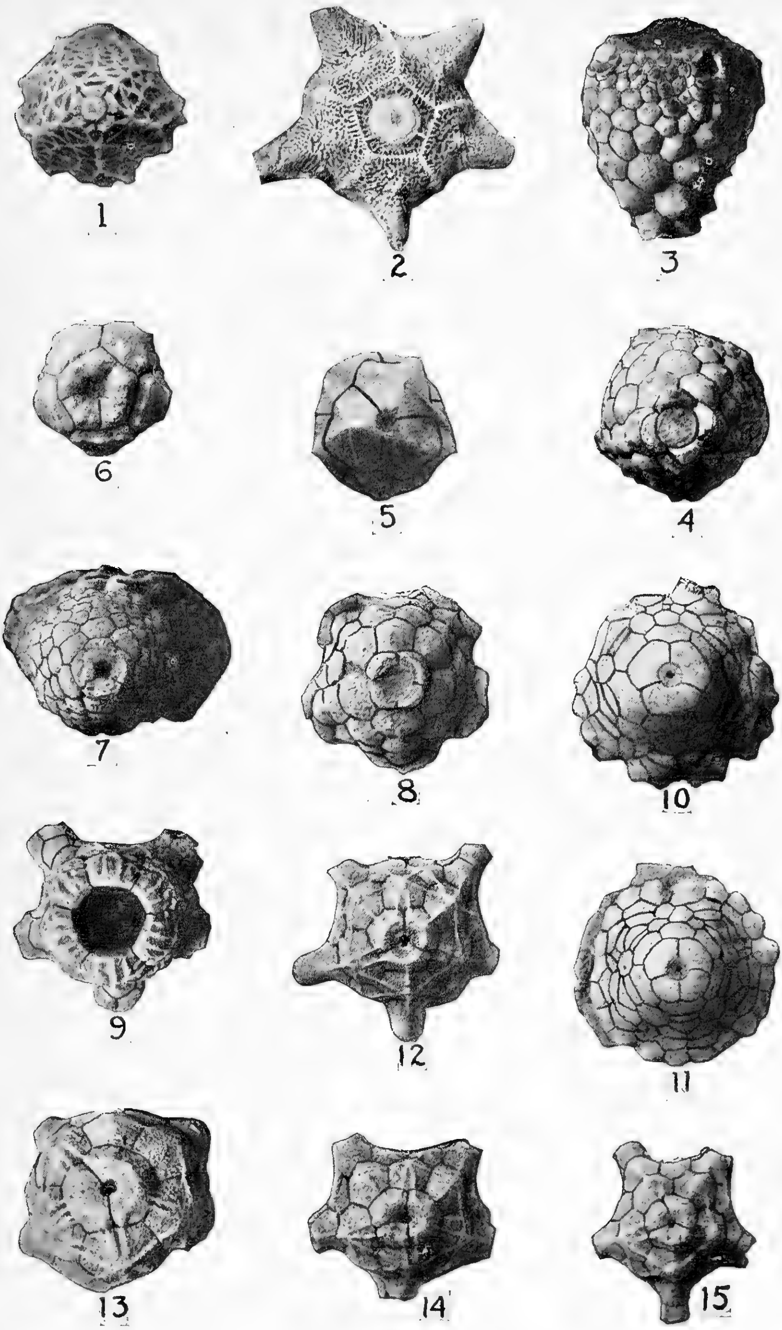
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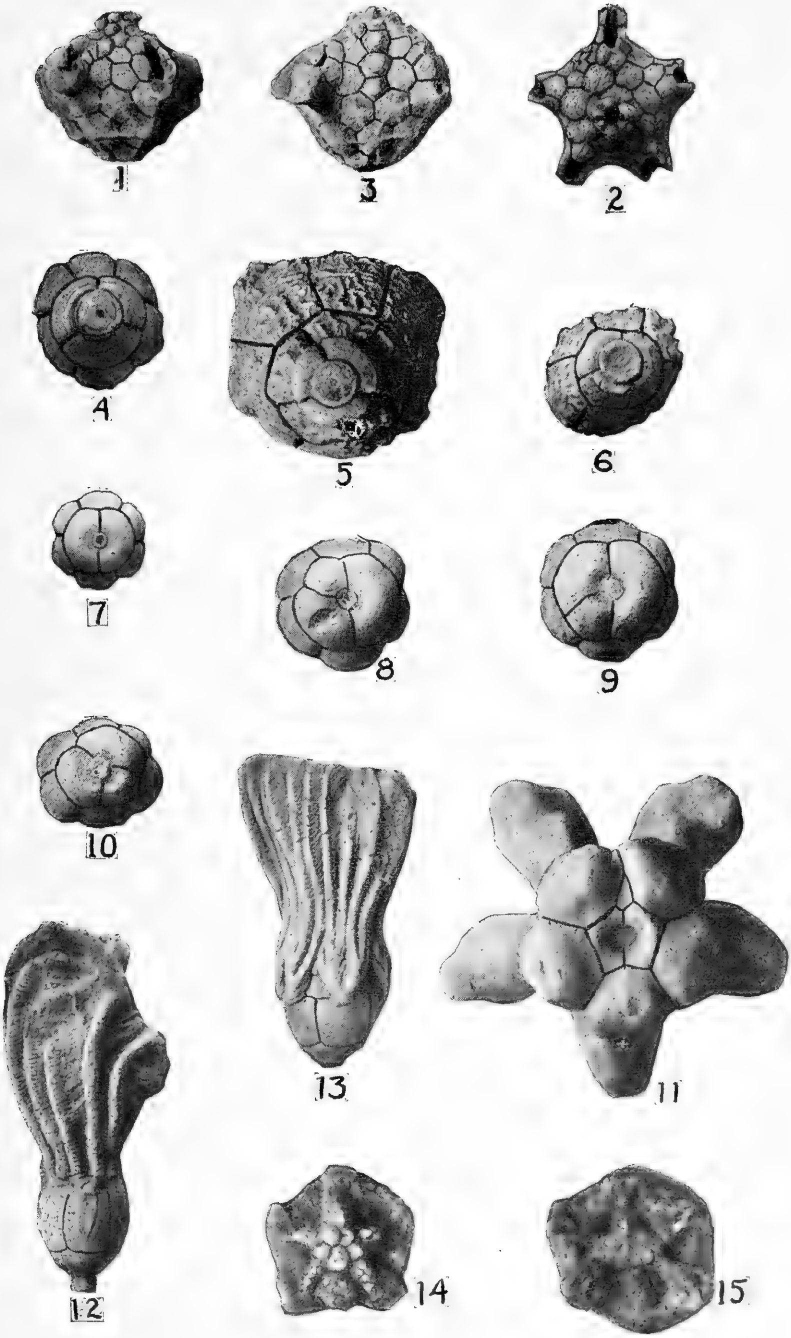
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VARIATIONS OF GLACIERS. XX[1]

HARRY FIELDING REID
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The following is a summary of the *Nineteenth Annual Report* of the International Committee on Glaciers.[2]

THE REPORT OF GLACIERS FOR 1913

Swiss Alps.—Sixty-one glaciers were measured in 1913; a larger proportion were retreating this year than in 1912. The Rhone Glacier, however, has grown in thickness, throughout, with an increase of velocity and an advance of the tongue.

Eastern Alps.—The summer of 1913, like its predecessor, was very wet, especially on the north side of the Alps; the conditions during both summers must have influenced the glaciers in 1913. Of the 37 glaciers observed 8 were advancing, 4 were stationary, and only 25 continued their retreat. The increase in the number of advancing glaciers is certain, and the retreat of the glaciers of the Eastern Alps has diminished; it is doubtful if the retreat can now be said to be the prevailing condition.

Italian Alps.—In the Piedmont Alps the snowfall has been too heavy to permit of good observations, but the glaciers are apparently retreating. Careful photographic surveys have been made of three of the large glaciers on the south side of the Mount Blanc massif; these glaciers are retreating; but the snowfall in the higher regions has increased, so much so in places as to cause a marked change in the appearance of the mountains. In the Monte Rosa group the observed glaciers were retreating. In the Lombard Alps some glaciers were making slight advances, some slight retreats. On the whole, the large glaciers of the Italian Alps were retreating, but a number of the smaller ones were slightly advancing or were in a doubtful condition.

[1] Earlier reports appeared in the *Journal of Geology,* Vols. III–XXIII.

[2] *Zeitschrift für Gletscherkunde,* IX (1914), 42–65.

Swedish Alps.—But one glacier, the Mikka, was observed, and it showed no change.

Norwegian Alps.—All the 16 glaciers examined in the Folgefon and the Jostedalsbrae were retreating with one exception. On the other hand, in the Swartisen, the Okstinderne, and the Frostisen, 7 glaciers were advancing, one retreating, and two were stationary.

Russia.—Observations in the Caucasus and in Turkestan have laid the basis for the determination of future changes. One glacier in the Caucasus was retreating and two were stationary.

Canada.—No observations have been recorded in the last two years;[1] but during the few years before 1910 the Illecillewaet, the Asulkan, the Victoria, and the Yoho glaciers were all retreating. Shortly before 1909, however, the Asulkan made an advance.

Himalaya.—The greater part of the information collected refers to variations which occurred some years ago. The positions of the ends of many glaciers were determined in 1906, but later observations are not available. At that date there was evidence that the glaciers were generally retreating.

New Zealand Alps.—Here also observations are scanty. For about ten years after the middle of the nineties, several of the larger glaciers advanced. Later conditions have not been reported.

REPORT ON THE GLACIERS OF THE UNITED STATES FOR 1914

Mr. F. E. Matthes sends me the following information:

> The snowfall during the winter of 1913–14 in the Sierras was so heavy that the glaciers were still completely covered at the end of September; the snow extended even beyond some moraines which encircle the glaciers at a short distance. These moraines are recent; the youngest is comparable to the moraines which marked the advance of the Alpine glaciers at the end of the eighteenth and the beginning of the nineteenth centuries. Historical evidence is not available to determine the actual time when these moraines were formed; but the presence of big trees (*Sequoia Washigtoniana*) near the glaciers may supply the information; for their rings of growth contain a trustworthy record of the climatic fluctuations of the last three thousand years.

[1] The last report on the Canadian glaciers in this series was in *Variations of Glaciers*, XIII, report for 1906. See *Journal of Geology*, XVI (1908), p. 665.

Professor Lawrence Martin sends me the following information regarding the Alaskan glaciers:

College Fiord.—Miss Keen visited Prince William Sound during the summer of 1914 for the exploration of the Harvard Glacier, and made careful observations of the variations of a number of other glaciers.[1] She found that the Harvard Glacier is 18 miles long, or about 28 miles if the Brunonian Glacier tributary is included. It rises at an elevation of about 7,500 feet. The eastern side of the end of Harvard Glacier seems to have retreated slightly between 1910 and 1914, but the western edge near Radcliffe Glacier was still advancing. There was no observable change in Downer, Baltimore, and Smith glaciers. Bryn Mawr may have retreated slightly; the barren zone at its northern border was widest, but the evidence was conflicting, for a shrub north of the glacier was being overturned at the time of Miss Keen's visit. Vassar Glacier was more crevassed in 1914 than in 1910, but had not advanced appreciably; Wellesley Glacier had retreated slightly; Yale Glacier seems to have advanced a little; Barnard had a slight forward movement.

Harriman Fiord.—The recession of Barry Glacier, observed in 1913, continued in 1914. The total recession of different parts of the ice front, from 1910 to September 25, 1914, was 3,000–7,000 feet. Cascade Glacier was nearly independent of the Barry in 1914. Of the other ice tongues in Harriman Fiord the Baker Glacier advanced at least 1,000 feet between 1910 and 1914, and spread considerably at both borders. The Harriman and Roaring glaciers seem to be still advancing. A small unnamed ice mass on the slopes of Mt. Muir moved forward slightly. The Surprise, Cataract, Serpentine, Toboggan, and Dirty glaciers were unchanged.

Eastern Prince William Sound.—The Valdez Glacier, continuing its long-maintained recession, melted back about 200 feet from 1909 to August 10, 1914. Shoup Glacier advanced very slightly. Columbia Glacier, the largest ice tongue in Prince William Sound, is also the most interesting, for it has continued the slow forward movement that has been in progress since before 1908. Miss Keen found that the eastern border advanced 1,500 feet between 1910 and September 30, 1914, and spread laterally; in other parts the advance was less, being perhaps 1,300 feet on Heather Island. Photographs of Childs Glacier, by Robert Sewall, show that in July, 1914, its northern border was retreating.

Southeastern Alaska.—It was reported in the Juneau papers that Norris Glacier, in Taku Inlet, had made a considerable advance. A photograph of the Taku Glacier, taken about 1907, shows a distinct advance since 1890.

Dr. Martin has tabulated the snowfall and temperature as recorded at several Alaskan stations. He finds not only great differences in different years, but the years of maximum snowfall

[1] *Bulletin of the American Geographical Society*, XLVII (1915), 117–19.

at the various stations are different, so that it is not safe to draw any detailed conclusions about the snowfall in the mountains from the records at the stations; though the general trends are the same. The annual snowfall at Killisnoo, somewhat more than one hundred miles southeast of Muir Glacier, between 1891 and 1896 was about twice as great as it has been since then; but the glaciers do not show corresponding variations. Temperature records have been kept at Sitka, with two short intermissions, since 1828. The average temperature for the five months from May to September in the years 1828–77 and in the years 1906–13 differs by only one-tenth of a degree Fahrenheit. The average temperature at Juneau for the same months during the years 1906–13 is about 2° F. higher than during the years 1883–96. It does not seem possible to infer any definite relations between temperature and glacier variations from these records.

The United States Geological Survey has published a map of a portion of the Chugach Mountains, northeast of Prince William Sound, on a scale of about one inch to the mile (Port Valdez District, Alaska; sheet 602 B). It shows a large area of glaciers and snow-fields. Parts of the Columbia, Shoup, and Valdez glaciers appear on it. Unfortunately the contours are not carried over the glaciers, but the altitudes of a number of points are indicated so that marked future changes in the thickness of the ice will be determinable. Other new maps of Alaskan glaciers cover the Haganita-Bremner region, northeast of the Copper River Cañon,[1] the Bering Glacier, and the western border of the Malaspina Glacier at Icy Bay,[2] and part of the Kenai Peninsula.[3] An excellent topographic map, on the one-inch scale, showing all the glaciers and their relations to the mountains and rivers, accompanies M. C. Campbell's *Popular Guide to the Glacier National Park*.[4] Pamphlets containing popular accounts of the glaciers of Mount Rainier and of Glacier National Park have been issued by the Department of the Interior.[5]

[1] *Bull. U.S. Geol. Surv. No. 576*, Plate I.

[2] *Bull. U.S. Geol. Surv. No. 592*, Plate IV.

[3] *Ibid.*, Plate VIII.

[4] *Bull. U.S. Geol. Surv. No. 600.*

[5] *Mount Rainier and Its Glaciers*, by F. E. Matthes; *Glaciers of Glacier National Park*, by W. C. Alden.

Reviews

Climates of Geologic Time. By Charles Schuchert. Carnegie Institution of Washington, Publ. No. 192, pp. 263–98, Figs. 87–90.

There has been a progressive advance, in late years a most rapid one, from the conception of a former hot, dense, vaporous earth atmosphere, the natural corollary of the Laplacian hypothesis. Knowledge of glacial climates, which had its beginning in studies in the Alps early in the eighteenth century, has grown until not only has there been demonstrated a world-wide lowering of temperature with glaciation of much of the Northern Hemisphere in recent geologic time, but there has been proved as well a number of such glacial periods in earlier times. The cold climates which have periodically affected the earth more or less widely since the beginning of geologic history have been of short geologic duration. The data at hand indicate at least four well-marked glaciations: (1) earliest Proterozoic, shown by the widespread "slate conglomerates" at the base of the Lower Huronian in Canada; (2) latest Proterozoic, marked by thick, widespread tillites beneath the Lower Cambrian of Southern Australia, and by the Gaisa formation of Northern Norway, both now thought to be latest Proterozoic instead of Lower Cambrian; (3) Permian, abundantly proven by tillites in many parts of the world, mostly between latitudes 20° N. and 40° S.; and (4) Pleistocene, the deposits of which mantle much of the Northern Hemisphere. Less well-marked cold periods seem to have occurred (5) at another part of the Proterozoic, for the glacial materials of this age in South Africa represent neither the earlier nor the later part of the era; (6) in the Lower Devonian of South Africa, shown by the Table Mountain series, and (7) in the early Eocene, indicated by deposits in the San Juan Mountains of Colorado. The greatest reductions of temperatures, so far as known, varied between the hemispheres.

Guided by the postulate that the living things of sea and land always have been affected by climatic conditions much as now, climate variations are to be observed in the succession of plants and animals recorded as fossils. In addition, the color and general character of the sedimentary deposits afford light on climatic conditions at the time of their deposition. In spite of widespread glaciation at certain periods, the Proterozoic era had, in the main, a rather warm, equable climate. This is shown by the enormously thick limestone deposits (50,000 feet in Canada), abundance of large Archaeocyathinae, widely distributed graphites, and presence of coal. The Cambrian, with an abundance of shallow-water life, had a uniformly warm temperature which continued into the Ordovician and Silurian. The red shales, gypsum deposits, salt beds, and scant, depauperate fauna of the late Silurian indicate aridity and possible coolness, the latter expressed perhaps by local glaciation (South Africa). The deposits of Northern Europe in the Devonian probably marked a cool, somewhat arid climate, and the great change in the life-forms in the Middle Devonian may be further evidence of the same thing. The climate of the middle and later part of the Devonian was warm; that of the Carboniferous, warm-temperate to subtropic. The great variety of marine life, abundance of reef corals in high latitudes, extensive coal deposits, subtropical flora, and large-sized insects, all suggest this. The adverse climate of the Permian is clearly shown in the glacial tillites, red shales, salt and gypsum deposits (to thickness of 3,300 feet), and depauperate, scanty fauna. The sweeping change in the types of life seen in the Triassic is most convincing proof of climatic severities at this time. Large trees (to 8 feet diameter), and their absence of rings, luxuriant ferns, and thick deposits of limestones in high latitudes, all suggest warmth. The late Triassic-Lias probably saw a reduction of temperature, for of the Triassic ammonites (1,000 species) none passed into the Jurassic, the insects were uniformly dwarfed, and the corals, both numerically and geographically, were very much restricted. The Jurassic was a period of remarkably warm, equable climate. The wide distribution and variety of ammonites (15,000 species), their presence with corals and marine saurians in very high latitudes, and the very cosmopolitan, luxuriant floras are to be noted. The Comanchean-Cretaceous marks the introduction of hardwood forests and may indicate a cooler climate than the Jurassic; but the presence of magnolias in Greenland and Alaska shows at least warm-temperate conditions there. The Cretaceous is distinguished by a remarkable deployment of the immense land reptiles and very thick limestone deposits. Climatic conditions in the Tertiary are not sharply different from those of the Cretaceous. Middle and late Eocene floras show many tropical marks, Oligocene faunas are varied and large sized, especially the foraminifers (nummulites), the Miocene shows a distribution of warm-temperature plants in Spitzbergen and Grinnell Land, but the late Miocene was, at least in many places, cooler. The Pliocene was rather warm but undoubtedly became colder toward the beginning of the Pleistocene when glacial conditions reached full expression.

The author concludes that the marked climatic variations of the past are primarily due to periodic changes in the topography of the land surface, modified by the variations in the amount of heat stored in the oceans, and the change in the composition of the atmosphere which conditions the storage of solar radiation. Supplementary notes with quotations from original descriptions of pre-Permian tillites and a bibliography of the subject are appended.

R. C. M.

Oceania. By P. MARSHALL. Handbuch der regionalen Geologie, 5. Heft, Band VII, Abteilung 2. Heidelberg, 1912. Pp. 36, figs. 10.

Oceania, limited on the west by the Marianne, Pelew, and Caroline islands, on the east by the Sandwich Islands, is a region measuring about 8,400 miles east and west, and 4,200 miles north and south. Most of the islands are small, aggregated in rather well-defined groups or lines, and within the limits of each group the geological and physical structures are somewhat uniform. With the exception of the largest only, the islands are volcanic or composed of coralline limestone, and almost every island is fringed by coral reefs. The basin of the Pacific is of great, and nearly uniform, depth (2,500–3,000 fathoms), but in the west part of Oceania the ocean depths are far less regular. Very deep troughs are found subparallel to some of the island chains and their connecting submarine ridges, and the location of the shallows and basins is suggestive of important structural relations. The island chains seem to define at least four mountain ranges which are seen to converge toward Northern New Zealand, a region therefore of great structural importance. The true border of the Pacific basin segment of the earth's crust is marked by a fairly definite line, indicated by the submarine elevations, areas of raised coral rock, and the distribution of andesitic rocks. This line passes through the Kermadec, Tonga, Fiji, New Hebrides, and Solomon islands, and is noteworthy as the belt of present volcanic activity. Triassic fossils in New Zealand and New Caledonia indicate their coastal connection in the past, and the present faunal and floral distribution is strongly suggestive of the former existence of a continental area limited by the island line mentioned. Coral growths of the Pacific generally imply considerable subsidence, though in places this has been superseded by elevation. A brief description of the physical character and geology of each of the island groups, so far as known, comprises the central part of the paper. A bibliography of the subject is appended.

R. C. M.

Geology of the Gold Belt in the James River Basin, Virginia. By STEPHEN TABER. Virginia Geol. Surv., Bull. No. VII, 1913. Pp. 271, figs. 23, maps 2, pls. 8.

The gold mines are localized mainly in Goochland and Fluvanna counties. Free gold occurs in quartz veins which cut pre-Cambrian quartzites, schists, and gneisses. The gold seems to be associated with granite intrusions, possibly of Cambrian age.

The author suggests that this district illustrates the formation of quartz veins by the force of crystallization. The value of the gold produced in this region amounts to about $6,000.00 per annum.

T. T. Q.

Pre-Cambrian Algonkian Algal Flora. By CHARLES D. WALCOTT. Smithsonian Misc. Coll., LXIV, No. 2, 1914. Pp. 153, pls. 19.

Fossil algal flora, produced by blue-green algae, are found in the Algonkian formations of the Cordilleran region. Walcott describes and figures 8 new genera and 12 new species of algae from the Belt series.

Before the discussion of the algal remains, there is a discussion of the continental conditions and sedimentation of Algonkian times. From Robson Peak, British Columbia, to Arizona and southern California, a distance of over a thousand miles, there is a marked Algonkian-Cambrian unconformity. Preceding this advance of the Cambrian sea, the Algonkian was a time of continental elevation and of largely terrigenous sedimentation in non-marine bodies of water; also there was some subaerial deposition. Marine sediments accumulated along the shores of the continents, but they are now far buried, and everywhere lost to our knowledge. This unknown marine life, preceding the Cambrian invasion, belongs to what the author calls "Lipalian" time. Red sandstones and shales in the west suggest an arid and, possibly, a cold climate. The thick limestones in the western interior are explained as having been deposited from non-marine waters by algae.

T. T. Q.

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THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY

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THE PRE-WISCONSIN DRIFT OF NORTH DAKOTA

A. G. LEONARD
North Dakota Geological Survey

Considerably over one-half of North Dakota is covered by Wisconsin drift, which is found east of the Missouri plateau and also occupies a belt of country along the eastern margin of the plateau. The western border of the Wisconsin drift is marked by the wide, massive Altamont Moraine which crosses the state diagonally from northwest to southeast and has a width in places of 20 miles. West of this moraine there is an older drift sheet which extends from 70 to 130 miles beyond the Wisconsin drift and in North Dakota covers an area at the surface of approximately 19,000 square miles. The border of this older drift crosses the Montana boundary about 30 miles north of the Northern Pacific Railroad. This older drift undoubtedly underlies the Wisconsin drift of eastern North Dakota, but with possibly one exception it has not been observed in outcrops or recognized in wells.

East of the Missouri River the pre-Wisconsin drift, while covered in many places by outwash silt from the Altamont Moraine, is present in Emmons, Burleigh, eastern McLean and Mountrail, and perhaps in Williams and Divide counties. West of the Missouri River the older drift covers most of Morton, Dunn, and McKenzie counties, a corner of Stark, and all of Mercer and Oliver counties. In this area west of the river outcrops are not uncommon, and thus the region is the most favorable in the state for the study of the older drift sheet.

The following account of some of the features of the pre-Wisconsin drift is based on observations made during the course of field work for the North Dakota Geological Survey, a portion of the time in co-operation with the United States Geological Survey, in Morton, Dunn, McKenzie, Burleigh, and other counties during the years 1909 to 1914 inclusive.

The older drift west of the Missouri is in most places thin and has undergone great erosion. The deposit perhaps never had any considerable thickness in this region except locally, where it forms moraines, and much of the glacial material which was formerly present has been swept away by streams. The drift throughout much of the area is thus represented by bowlders and gravel, the coarser materials left behind when the finer débris, such as clay and sand, was carried off. There are extensive tracts where little or no glacial material is present and where only an occasional bowlder or a patch of gravel indicates that the ice sheet once covered this region. The western margin of the older drift is therefore poorly defined, and the mapping of it is based largely on the distribution of glacial bowlders and gravel.

As would be expected from the foregoing characters, the pre-Wisconsin drift has not, except in certain restricted areas, affected the topography to any large extent. The region is one of many streams and mature drainage, in striking contrast with the area of the Wisconsin drift, with its few streams, numerous lakes, and youthful topography.

PRE-WISCONSIN DRIFT OF BURLEIGH COUNTY

East of the Missouri River in Burleigh County, between the river and the Altamont Moraine, the older drift is present, but the occasional outcrops appear to indicate that it forms only a thin veneer over the underlying rocks, seldom exceeding 8 or 10 feet in thickness. It outcrops in the bluffs of the Missouri River 3 miles northwest of Bismarck, where 10 feet of till is found, and in the cut at the east end of the Northern Pacific bridge it attains a thickness of 15 to 20 feet. The bowlder clay appears in a number of the cuts along the Minneapolis, St. Paul & Sault Ste. Marie Railroad north of Bismarck, here generally associated with water-laid drift. It also outcrops at several points on Apple Creek, where it shows a thickness of 10–12 feet.

DRIFT IN MORTON COUNTY

West of the Missouri River in Morton County the glacial drift is represented almost wholly by gravel and bowlders, the latter occurring in great numbers. These bowlders, which are mostly granite, thickly cover the surface in many localities, resting directly on the bedrock, and except in rare instances no drift clay is associated with them. In some places they are scattered loosely over the ground, but in many others they form a bed or pavement in which the individual bowlders are in contact with each other. These bowlder deposits or bowlder beds are especially noticeable on the tops of divides and on upland areas. The bowlders vary in size from 6 or 8 inches to several feet in diameter, large ones measuring 8 and 10 feet being seen occasionally.

MORAINES OF LITTLE HEART RIVER BASIN

The most interesting and notable occurrence of glacial till in Morton County is found in the basin of the Little Heart River where the drift has been heaped up into morainic hills. During the Glacial Period this basin was probably occupied by an ice lobe of the continental glacier, and this lobe formed the belt of morainic hills which nearly encircles the broad valley plain and deposited more or less drift in the preglacial valleys of the Little Heart and its tributaries. As the ice

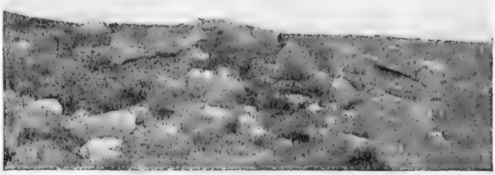

FIG. 1.—Bowlder-covered moraine hill of the pre-Wisconsin drift, Little Heart Basin, northeastern Morton County.

melted, the waters flowing from it deposited much outwash silt in the form of valley trains sloping away from the moraines. A number of the morainic hills have been partially buried by the outwash silt and rise like islands from the level plain of the valley train. The morainic belt of bowlder-covered hills and ridges is found near the base of the slopes on either side of the two valleys tributary to that of the Little Heart River (Fig. 1). Moraines cross the valley in three places and one belt of ridges and hills continues unbroken along the south side of the valley of the South Branch for a distance of 12 miles. The cultivated fields extend up to the moraine and end there where the soil becomes too rocky and the slopes too steep for cultivation.

FIG. 2.—Pre-Wisconsin till overlying Fort Union beds on Tobacco Garden Creek several miles above its mouth, McKenzie County.

DRIFT IN MC KENZIE COUNTY

Near the western boundary of North Dakota the pre-Wisconsin ice sheet reached 35–40 miles south of the Missouri River and thus covered the greater part of McKenzie County which lies between the Yellowstone, Missouri, and Little Missouri rivers. The older drift left by this ice sheet is well shown in many places in this

FIG. 3.—Pre-Wisconsin till resting on stratified sand and gravel on Tobacco Garden Creek, near its mouth.

region and the glacier also caused important drainage changes. The best exposures are found on Sand Creek, a short tributary of the Missouri River several miles east of Tobacco Garden Creek, on Tobacco Garden Creek, and on Clear Creek, a tributary of the latter.

FIG. 4.—Pre-Wisconsin drift resting on Fort Union sandstone, valley of Clear Creek, a tributary of Tobacco Garden Creek, northeastern McKenzie County.

Near the mouth of Tobacco Garden Creek appears 58 feet of till in a cut bank. It is yellowish gray or drab in color, contains many small bowlders, and rests on Fort Union beds (Fig. 2). Not far from here is seen 18 feet of bowlder clay overlying 15 feet of well-stratified sand and gravel (Fig. 3).

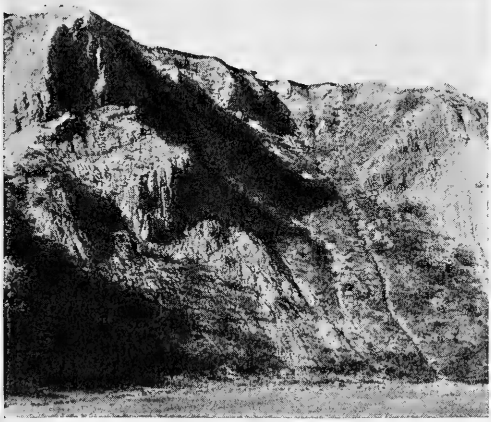

FIG. 5.—Pre-Wisconsin drift exposed on the tributary of Sand Creek, northeastern McKenzie County.

The valley of Clear Creek was partly filled with drift and there are many good outcrops of bowlder clay in the frequent cut banks along the stream where from 30 to 40 feet and over of till is exposed (Fig. 4). The greatest thickness found along this creek was in Sec. 36, T. 152 N., R. 97 W., where in a high bluff 100 feet of dark gray till overlies 100 feet of soft Fort Union sandstone. This outcrop lies within the morainic area to be described later, which probably accounts for the exceptional thickness of the pre-Wisconsin drift at this point.

Another excellent drift section occurs in this same morainic area 3 miles west and one-half mile south of Charlson, or 5 miles south of the Missouri River on a tributary of Sand Creek (Fig. 5). Here the following section appears in the steep bluff which rises abruptly from creek-level:

	Ft.	In.
Sandy clay and soil	2	
Sand and clay in alternating bands	8	
Gravel		8
Sand and clay in alternating layers	3	
Gravel, coarse		8
Sand	2	4
Gravel	7	8
Till or bowlder clay, dark gray in color, and containing large numbers of pebbles and bowlders imbedded in the tough, hard clay. A large proportion of the bowlders and pebbles are composed of compact limestone and the till contains considerable blue shale (Pierre ?). Thickness of till exposed above the creek	61	
	85	4

The sand and gravel forming the stratified drift of the foregoing section are light yellow in color. The drift hills just back of the bluff rise 50–60 feet above the top of section, so that the total thickness of the drift above creek-level is from 140 to 150 feet.

BOWLDER BED ON THE MISSOURI RIVER

An interesting bowlder deposit belonging to the pre-Wisconsin drift is found along the Missouri River just above water-level, 2 miles below the Nesson Ferry and one-half mile below the mouth of Tobacco Garden Creek (Fig. 6). This bed of bowlders shows a thickness, above the normal stage of the river, of 12–14 feet and its depth below water-level was not determined. The deposit is well exposed along the water's edge for a distance of nearly 100 yards, and scattered bowlders and ferruginous gravel occur at intervals for another 200 yards. Overlying the bowlders is 15 feet of gravel, which is overlain in turn by silt and fine sand extending to the top of the terrace, 100 feet above the river. The bowlder bed is composed of bowlders of all sizes, those from 2 to 3 feet in diameter being quite common, though those less than 1 foot in diameter are most abundant. One sandstone bowlder measured 14 feet in length, another was 9 feet long, and another 4 feet. Granite, limestone, petrified wood, and sandstone bowlders are found, together with other kinds of rock. The interstices between the coarser materials are filled with gravel and sand, and the whole deposit is cemented into a rather firm, indurated mass. It is very ferruginous and brown from the limonite forming the cementing material, and in many places the bowlders are firmly held by the iron cement and sand, which serve as a matrix in which the bowlders are imbedded; when the latter weather out their shape is preserved in the matrix.

FIG. 6.—Bowlder bed on the Missouri River near mouth of Tobacco Garden Creek, McKenzie County.

While some of the bowlders of this deposit may have been brought here by floating ice, it is probable that most of the deposit was left here by the pre-Wisconsin ice sheet when it advanced south of the river. The finer materials of the drift, if they were ever present, have been carried away, leaving the gravel and bowlders, which were subsequently cemented by the iron of the surface waters.

MORAINE OF THE PRE-WISCONSIN DRIFT

Mention has been made on a previous page of the moraines of the Little Heart River Basin, and in McKenzie County a much more extensive moraine of the pre-Wisconsin drift forms a prominent topographic feature of the region. It lies in the northeastern part of the county, east of Tobacco Garden Creek, where it extends on the upland from the edge of the Missouri Valley bluffs north of Charlson in a southwesterly direction to the valley of Timber Prong Creek in Secs. 14 and 15, T. 151 N., R. 97 W. It has a length of 16 miles, an average width of 2 miles, and its area is about 30 square miles. This moraine shows well from Charlson, where its ridges and hills are seen rising from 100 to 150 feet above the flat plain in the foreground (Fig. 7). Within the morainic area the surface is rough and hilly and the ground is thickly strewn with bowlders. The topography is typically morainic, with numerous irregular hills and ridges, while scattered among the hills are great numbers of hollows or kettle-holes, some containing water and others dry. Many of the hills rise 50–125 feet above the bottom of the kettle-holes.

FIG. 7.—Small lake in the moraine of the pre-Wisconsin drift near Charlson, northeastern McKenzie County.

Where this moraine crosses the valley of Timber Prong Creek it forms a dam, which holds back the waters of the upper valley and forms a lake known locally as Dimick Lake. This moraine lake is very irregular in shape and has an area of between two and three square miles.

North of the Missouri River another morainic belt occurs which may be part of the pre-Wisconsin moraine just described as extending southwest from the vicinity of Charlson, though it is perhaps more likely to have been formed by the Earlier Wisconsin ice sheet referred to on another page. It lies from 2–3 miles west of White Earth Creek and with a width of 1–2 miles extends north and south a distance of at least 6 or 8 miles between the Missouri River and the Great Northern Railroad. Fifteen or 20 miles or more west of the Altamont Moraine the railroad crosses a well-developed moraine extending 4 or 5 miles and perhaps more north and south of Temple, and has a width of several miles. This hilly belt lies about 9 miles west of the above-mentioned moraine near White Earth Creek.

CHARACTERISTICS OF THE PRE-WISCONSIN DRIFT

The topography of the older drift and the large amount of erosion it has suffered compared with the Wisconsin till have been mentioned on a previous page, where it was shown that in many places only the coarser materials of the drift—the pebbles and bowlders—remain as evidence that the ice sheet once covered the region. But the color of the pre-Wisconsin till is generally unlike that of the Wisconsin drift. The latter is commonly light yellow to light gray in color as exposed in railroad cuts or along stream valleys, but where the deeper till appears in fresh excavations it is seen to have the blue color of the unoxidized clay. The pre-Wisconsin till, on the other hand, where best exposed on Sand and Clear creeks in northeastern McKenzie County (Fig. 8), is dark gray in color throughout the maximum observed thickness of over 100 feet.

FIG. 8.—The valley of Clear Creek where it cuts through the moraine of the pre-Wisconsin drift, northeastern McKenzie County.

Except in the morainic areas the thickness of the pre-Wisconsin drift is not great. West of the Missouri River it is seldom as much as 8 or 10 feet and generally the thickness is not over 2 or 3 feet or less. The thinness of the older drift is due partly to erosion which has removed much of the glacial material and over a large part of the area left only bowlders or a thin veneer of gravel, but partly perhaps also to the fact that the drift may never have been very thick in this region.

BOUNDARY OF THE PRE-WISCONSIN DRIFT

Chamberlin and Salisbury many years ago noted the presence of an older drift beyond the Altamont Moraine and its approximate boundary was shown on their map.[1] The more detailed work of

[1] "Terminal Moraine of the Second Glacial Epoch," *Third Ann. Report U.S. Geol. Surv.*, pp. 291–402; also Plate XXXV.

recent years has shifted the margin somewhat farther west and south and it is now provisionally located as shown on the accompanying map (Fig. 9).

Glacial drift is found 50 miles south of the mouth of the Yellowstone River, or within less than 15 miles of Glendive, Montana. For a distance of 50 miles east of the western boundary of North Dakota the drift margin extends approximately east and west and lies 30–40 miles south of the Missouri River. North of the Killdeer Mountains the boundary swings sharply to the south, and crossing the Knife River near the western edge of Dunn County it takes a general southeasterly course across the state. The margin of the drift is believed to cross the Northern Pacific Railroad and the Heart River between 2 and 3 miles west of Gladstone. That a lobe of the ice sheet crossed the Heart River at Gladstone is shown by the presence of thick deposits of drift gravels on the upland 1–2 miles south of the Heart and at an elevation of between 100 and 200 feet above river-level. In places the gravel and sand have a thickness of at least 90 feet, and the deposit contains a number of good-sized granite bowlders. A well-defined gravel ridge marks the edge of the drift for 3 or 4 miles in this area south of the Heart River at Gladstone. This ridge rises 30–40 feet above the surface on either side and falls away rather abruptly on the south, while on the north the slope is more gradual.

There is no evidence that the ice sheet extended more than 2 or 3 miles south of the railroad between Gladstone and Richardton, but in this vicinity glacial gravel and a few small bowlders occur that far south. Between the Cannon Ball and Heart rivers glacial bowlders are found as far west as Elgin, or within 12 miles of the western border of Morton County. In general the drift margin between the Killdeer Mountains and the South Dakota line lies from 40–60 miles west of the Missouri River.

Thickness of the ice sheet.—In the vicinity of Berg in northeastern McKenzie County there are twelve or fifteen high buttes, known as the Blue Buttes, which are irregularly distributed over an area of 15 or more square miles. Many glacial bowlders occur on top of these buttes at an elevation of over 2,700 feet above sea-level, or 1,000 feet above the Missouri River only 6 miles to the east.

Since the buttes rise nearly 500 feet above the surrounding upland the ice sheet probably had at least this thickness in order to override them and deposit bowlders on their summits. Another

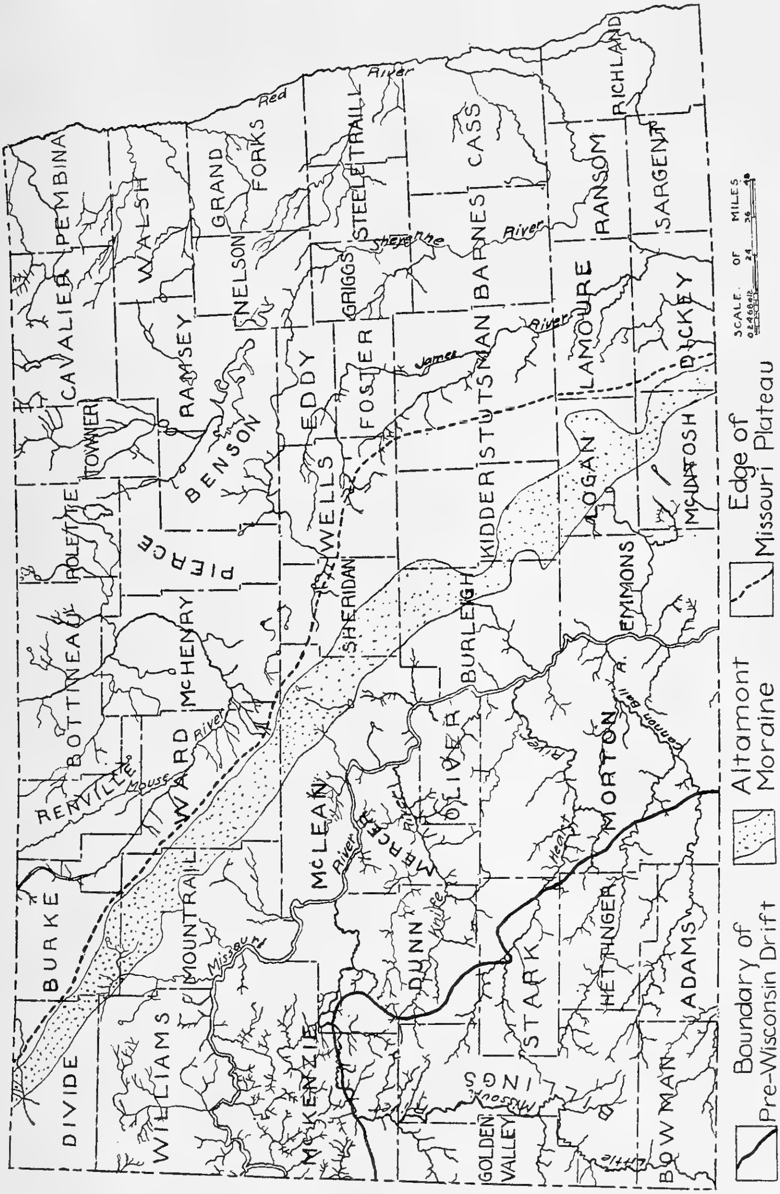

FIG. 9.—Map showing margin of pre-Wisconsin drift and Altamont Moraine in North Dakota

explanation for the presence of the bowlders on top of the high buttes is that the ice upon encountering these obstructions was buckled up as it passed over them. But it seems more probable that the ice sheet which was able to push across the deep valley of the Missouri River and advance 40–60 miles beyond was thick enough to submerge the Blue Buttes and pass on over them. The terminus of the continental glacier was not far from 15 miles south of the Blue Buttes, since the ice advanced only as far as the Killdeer Mountains. Back about 15 miles from the edge the ice sheet therefore doubtless had a thickness over the upland plain of considerably over 500 feet. The ice which filled the Missouri River Valley must have had locally a thickness of 1,000 feet or over.

Age of the older drift.—That the drift west of the Missouri River is much older than the Wisconsin drift is evident from the great amount of erosion it has undergone. Over much of the region the finer materials of the till have been swept away, leaving only bowlders and gravel. The older drift also differs in color, being considerably darker than the Wisconsin. This pre-Wisconsin drift has commonly been regarded as Kansan and there is perhaps more reason for referring it to the invasion of the Kansan ice sheet than any of the other early ice invasions.

The drift north of the Missouri River and west of the Altamont Moraine appears to be younger than the drift south and west of the river. It has undergone less erosion and resembles the typical Wisconsin till in color. Calhoun believes that the drift of northeastern Montana is of Wisconsin age, and on his map this drift is shown as extending to within about 40 miles of the North Dakota line.[1] The extra-morainal drift north of the Missouri River in Williams County is undoubtedly continuous with the drift sheet west of here in Montana, in which case it is probably of Wisconsin age, and belongs to the Early Wisconsin stage.

If this view is correct, there are three drift sheets in North Dakota—the Late Wisconsin east of the Altamont moraine, the Early Wisconsin west of the moraine and north of the Missouri River, and the Kansan drift west and south of the river.

[1] Fred. H. H. Calhoun, "The Montana Lobe of the Keewatin Ice Sheet," *Prof. Paper No. 50, U.S. Geol. Survey*, 1906, pp. 52–57.

EVOLUTION OF THE BASAL PLATES IN MONOCYCLIC CRINOIDEA CAMERATA. II

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PART II

2. CHANGES PRIMARILY MODIFYING THE RELATIONS OF PLATE CONTACT AND POSITION

The second series of changes, those which modify the primary position and relation of the basals and radials, will now be considered. These are: (*a*) reduction and compensating growth; (*b*) enlargement and compensating reduction; (*c*) plate division; (*d*) plate migration; (*e*) plate interpolation; and (*f*) anchylosis.

a) *Reduction and compensating growth.*—Reduction, or the diminution in size of a plate, may be either a function of the absorptive ameboid cells (see p. 502), or due to inhibited growth (atrophy). That is, the absorption of a fully outlined plate may take place, as in the absorption of the anal and oral plates in *Antedon*, or a continuous diminution in development to a former standard of size may result in the atrophy and final disappearance of a plate, as in the great reduction of the basals in *Pisocrinus quinquelobus*[1] and the disappearance of the first costal in some specimens of *Eucalyptocrinus rosaceus*[2] and *Alloprosallocrinus conicus*.[3] Atrophy in plate growth may be due either to plate contact, which inhibits the free branching and anastomosing type of development, or to some deep-seated morphological change. The simplest form of inhibition in plate development is that shown in the normal growth of plates after coming into mutual contact. It is the process which

[1] Ref. 5, p. 27.

[2] Ref. 28, p. 90, Pl. XI, Figs. 6, 7.

[3] In *Alloprosallocrinus conicus* the writer has found that the apparent anchylosis of the costal plates (see ref. 39, p. 407) is due to the complete reduction of the first costal.

gives to the plates their polygonal outline and must not be considered a form of atrophy. Plate contact does, however, produce atrophy when the accelerated growth of one plate causes the reduction in size of some adjacent plate. This type of inhibition may be termed superficial atrophy, and is apparently the type just illustrated in the absorption of the first costal in *Alloprosallocrinus*. Atrophy of the other type is apparently the result of marked internal changes which appear on the exterior in the reduction of skeletal parts. This form of inhibition may be termed deep-seated atrophy, and is the type illustrated in the drawing together of the posterior radials in *Pterotocrinus* upon the reduction of the anal plate (Pl. III, No. 11.)

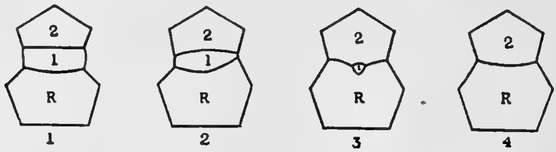

Fig. 6.—Figures showing the reduction of the first costal in *Alloprosallocrinus conicus:* 1 and 2, from specimen No. 9350; 2 and 3, from specimen No. 9357, in the University of Chicago collection.

With the decrease in diameter of a plate in a closed cycle there must be (1) a compensating increase in the diameter of some plate or plates in the same cycle, or (2) a decrease in diameter of some plate or plates of the apposed cycle; otherwise the symmetry of the cup will be distorted. The first principle is clearly demonstrated by the increase in diameter of the first interbrachial plates in *Amphoracrinus*[1] upon the gradual reduction of the proximal portion of the second anal plate. The second principle is clearly demonstrated in the reduction of the apposed compound basal and radial of *Zophocrinus*.[2]

This form of change might be confused with vertical plate-splitting followed by anchylosis of the parts to the adjacent plates if the change were a sudden mutation and no knowledge of the ontogenetic development obtainable; otherwise the phylogenetic succession would show the factors involved. If the reduction of a

[1] Ref. 32, p. 197. [2] Ref. 6, p. 151.

plate in a closed cycle is asymmetrical, the growth of one of the laterally adjacent plates will be greater than that of the other, and will, on completion of the reduction, occupy the entire area of the missing plate. This process is shown nearing completion in the reduction of the antero-lateral radials in *Catillocrinus*,[1] and the consequent enlargement of the left posterior and anterior radials, and in *Mycocrinus*[2] in the reduction of the left anterior and dextro-lateral radials. In *Pisocrinus* the principle is diagrammatically shown in both basal and radial cycles, where, by the reduction of two basals and three radials, three basals, two radials, and the radianal are greatly enlarged (Fig. 7, Nos. 1–4).

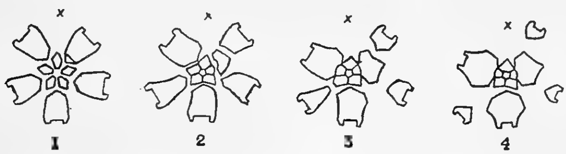

Fig. 7.—Diagrams illustrating reduction and compensating growth in *Pisocrinus:* 1, hypothetical, ancestral stage; 2–4, based upon specimens in the University of Chicago collection; x = position of first anal plate.

b) *Enlargement and compensating reduction.*—Plate enlargement, as we have seen, is due to the activity of the ameboid calciferous cells. In normal, symmetrical development the growth of the young plates is for a short time more rapid than that of the body wall, but upon plate contact the increased enlargement of both plates and body wall is theoretically balanced. If, however, a plate increases more rapidly than the adjacent plates, and is not controlled by the inhibiting influence of symmetrical development, and its accelerated growth is not compensated for by growth of the body wall, this growth must be compensated for in some other manner. Accelerated lateral increase of this type in a cycle plate demands then either (1) the decrease in diameter of some adjacent plate or plates in the same cycle or (2) the increase in diameter of some adjacent plate or plates in the apposed cycle and (3) distortion of the horizontal outline of the calyx or various combinations of the first two of these secondary developments may occur.

[1] Ref. 6, p. 149, Fig. LXII. [2] Ref. 28, p. 110, Pl. 7, Fig. 4.

Accelerated increase of an interpolated plate between cycles or plate groups demands: (1) the decrease in size of some adjacent plate or plates, as in the decrease in size of the dextro-lateral radials in *Pisocrinus* (Fig. 7), upon enlargement of the radianal, or (2) distortion of the cup.

c) *Plate division*.—This process is the splitting of a plate into two (perhaps more) parts, either during or after the formation of the primary, formative cell group. Division of a cell group is due to cell separation, and may or may not be accompanied by cell division. Division of the plates when they are once formed is due to the action of the absorptive, ameboid cells. Division differs essentially from intercalation, in that a fundamentally distinct cell group is demanded for the interpolated plate. But no matter how division may take place, apparent evidences of division in the plates of fossil crinoids must be very carefully investigated before too much significance is attached to the opinion that division and not interpolation has taken place.

Division due to absorption is only known to occur during the absorption of the supporting rods in echinoid larvae,[1] and in the reduction of the radianal in *Antedon*.[2] Division or duplication is assumed by Bather[3] in the formation of the paired, proximal interbrachials in Actinocrinidae, yet all evidence from the work on crinoid larvae shows duplication and not division to be the process involved. Horizontal bisection is assumed by Bather[4] in ten genera of monocyclic Inadunata, not including those in which bisection of the right-posterior radial only occurs. However, when it is noted how closely the development and migration of the radianal in the larvae of modern crinoids parallels the development and migration of the radianal in the Flexibilia,[5] there is good reason to believe that bisection of the right-posterior radial has not occurred, but that the radianal and subradials are primary or interpolated (secondary) plates. Vertical splitting seemed beyond question in

[1] Ref. 34, pp. 349–54.

[2] Ref. 27, pp. 52, 53, Pl. 5, Fig. 11.

[3] Ref. 3, p. 34, fifth notice.

[4] Ref. 6, pp. 112, 144.

[5] Ref. 16, p. 332, 333.

the formation of the compound, left-posterior radial in *Anomalocrinus*,[1] yet Springer[2] has shown it to be an abnormality, *due perhaps to plate fracture*.[3] There are, it is true, certain conditions surrounding apparent cases of plate division which lead us to believe that division and not interpolation has occurred. If, for example, two plates of the same cycle occupy the approximate area of one plate in that cycle, if they mutually fulfil the requirements of but one plate in that cycle, and if in the obliteration of the intervening suture a plate would be formed indistinguishable from the other four undivided plates in that cycle or from the morphologically undivided equivalent of that plate in a closely related ancestral genus, division would seem the only logical conclusion. But this conclusion is by no means proved. In the light of phylogenetic and ontogenetic development as ascertained from fossil crinoids division is very uncertain, for we cannot see the process taking place. Furthermore, if division had occurred anchylosis of the parts to the adjacent plates might take place and either complete absorption with compensating enlargement or migration would have to be called upon to explain the appearance of the new suture. Thus, no matter how carefully we attempt to ascertain the fact that division has occurred, the factor of interpolation will usually appear as an alternative. Only through careful observation, in modern larval development, of plates not destined to obliteration in the adult stage can this process be satisfactorily determined.

d) *Plate migration*.—Any shifting which brings a plate, as a unit, into a new relation of contact and position with plates of the adjacent cycles, or of adjacent plates in the same series, may be termed a migration. For simplification in the discussion, the different types of migration may be broadly separated into two divisions: simple migrations, or those unattended by movements of the sarcode; and complex migrations, or those dependent upon movements of the sarcode. Of the simpler forms, three types occur: portional migration, cell-group migration, and simple plate migration.

[1] Ref. 37, Part III, p. 221; ref. 40, p. 152.

[2] Ref. 32, p. 213.

[3] The italics are the writer's.

If the absorption or atrophy of one side of a plate and the growth on the opposite side are approximately equal, the plate would appear to be shifting as a whole, although actually stationary in part. This type of migration may be called portional migration, and is the type illustrated in the shifting forward of the postero-lateral basals in *Xenocrinus* and sometimes in *Eucalyptocrinus* and *Callicrinus*.

One form of cell-group migration involving the approximation and fusion of two groups into one would occur, if in the previous development of phylitic compression of characters anchylosis were to be carried back into the embryonic period. Thus, anchylosis which appeared as an adult character in early times might appear as an embryonic character in a later stage of development, and cause fusion of the formative cell groups. It is suggested that this type of fusion might be responsible for the interradial development of the two larger infrabasals in *Antedon*.[1] That cell groups as such may migrate in response to physiological stimuli from changed environment without any such evolutional change is also possible, and experimental evidence has been obtained to substantiate this hypothesis.[2]

Simple migration, after plate formation, without tortion or other movement of the sarcode, seems from the very nature of plate growth (see p. 501) to be impossible. This opinion is apparently substantiated by the system of migration of the anal plate in *Antedon*, and of the radianal in *Promachocrinus*[3] and *Hathrometra*,[4] and by the development of the posterior radials in *Antedon* upon the introduction of the anal. Equal spacing of the radials and the anal in the hexagonal stage of *Antedon* is not apparent; on the contrary, the space separating the postero-lateral and antero-lateral radials is much greater than that separating the postero-lateral radials and the anal. As the plates increase by branching and anastomosis, the adjacent margins of the anal and the postero-lateral radials meet and assume a finished appearance (Fig. 10) before the postero-lateral and antero-lateral radials meet. Forward shoving of the postero-lateral radials into this unoccupied

[1] Ref. 8, pp. 288, 289.
[2] Ref. 26, p. 90.
[3] Ref. 16, p. 332.
[4] Ref. 24, pls. 8–12.

area by growth pressure would be expected, but it does not occur. On the contrary, the posterior radials either assume an asymmetrical outline as in *Antedon*, most of the hexagonal Camerata (Pls. II-III), and many of the Fistulata, or the continued widening must be compensated for by accelerated growth of the sarcode in the posterior region. Since no better opportunity for simple plate migration could be conceived, and since it does not in this case occur, there is little reason for believing in its existence.

Complex migrations consist of plate shiftings induced by accelerated growth, tortion of the body wall, in either local or broad areas, which distorts the normal space and contact relation of plates. This form of migration is diagrammatically shown in the carrying up by elongation of the anal tube of the anal in *Antedon*, and of the radianal in *Promacocrinus* and *Hathrometra*. Where the anal and radianal, being more firmly attached to the viscera than to the adjacent plates, are bodily lifted out of the cup into the tegmen by the accelerated growth of the hind-gut, this process is the one which undoubtedly explains the migration of the radianal in all fossil crinoids. A more common form of complex migration, and one shown in many groups of crinoids, is that which results in the formation of biserial from uniserial ossicles in the arms.

e) *Plate interpolation.*—This process may be defined as the interpolation of some plate or plates, of primary or secondary derivation, between any plates forming the primitive crinoid cup and its appendages. It is one of the most common forms of evolution found in the crinoidea, and may be broadly separated into two groups: primary interpolation, or the development of primary or secondary plates *in situ* from a primary or secondary formative cell group; and secondary interpolation or migration. Only the first type need here be considered, as plate migration has already been discussed. Primary interpolation is the only known method by which additional stem ossicles appear; the new ossicles developing either between the base and the adjacent stem ossicles, as in the Inadunata and Camerata, or between other stem ossicles, as in the Flexibilia. In the development of cirri, primary interpolation is the rule, the interpolation taking place at the proximal end of the appendage. Here too belong the development of the perisomic[1] interbrachials, of the ambulacrals between the orals and interambulacrals, and of the peculiar plates appearing between the basal and radial cycles of *Acrocrinus*.[2] Interpolation in the basal cycle is known in but two genera. In *Sagenocrinus* and *Homalocrinus* the radianal is incorporated in the basal cycle, and in *Sagenocrinus* especially it assumes the appearance of a basal plate. Interpolation in the basal cycle, being well established in at least two instances, seems very rare, yet this may be due entirely to our lack of knowledge, for the evolution of the radianal plate in the Flexibilia leads one to believe that it appeared in its primitive state in the basal cycle.[3] A discussion of interpolation in the radial cycle has been purposely omitted in the preceding citations, as it belongs more properly in a discussion of the origin of the anal plate, where it will be fully considered.

It appears then that every cycle of plates excepting the infrabasals, and every series excepting the brachials, are affected by interpolation, and even in the brachial series Clark[4] has evidence which points strongly to interpolation. There is then a possibility that every plate cycle and series may be subject to interpolation, but this point is not of immediate consequence and need receive no further attention.

Interpolation in the calyx may demand (1) a reduction in some adjacent plate or plates of the same cycle or group, with or without oblique development of the plates,[5] as in the reduction of the posterior radials and oblique development of the radial cycle in *Antedon* upon interpolation of the anal plate; (2) an increase in diameter of some adjacent plate or plates in an apposed cycle or group, with or without trunkation, depending upon the alternating or superimposed position of the interpolated plate, as in the enlargement and trunkation of the posterior basal in some of the Camerata

[1] Ref. 16, p. 339.

[2] Ref. 39, pp. 805–10, Pl. 53, Figs. 1–3, 4–9, and 10*a*, *b*.

[3] Ref. 31, p. 493, Pl. 5, Fig. 9.

[4] Ref. 13, p. 119.

[5] Oblique development is here used in reference to the displacement of either the proximal or distal ends of a plate, from the vertical axis of the cup and not from the planes of pentamerous symmetry.

and Fistulata upon interpolation of the anal plate, and broadening of the radials without trunkation upon interpolation of interbrachials, as in many of the Camerata; (3) increase in the body wall, as is shown in the lengthening of the calyx of *Acrocrinus* upon interpolation of the extra plates between the basals and radials; (4) interpolation of an extra plate in an adjacent cycle or group to satisfy the demands of plate alternation; (5) deformation of the cup; (6) various combinations of the first four effects named.

f) Anchylosis.—The process of anchylosis is provisionally placed under this group of processes, because of its intimate association with certain modifications of plate contact and position which cast some doubt upon the propriety of assuming it to be a result and not the cause of those modifications. This fact is shown in the following section.

ANCHYLOSIS: ITS ANTECEDENTS AND CONSEQUENCES

1. ANCHYLOSIS AND REDUCTION

Anchylosis is the most potent factor operative in the obliteration of sutures, and while it has been discussed as a simple ontogenetic process, its antecedents and results have not been considered. The expression "reduction and anchylosis," so commonly used in the description of brachials, means anchylosis following and depending upon reduction, but whether or not this usage is morphologically correct is not clear to the writer. Anchylosis may take place without reduction, or reduction without anchylosis, although the former is not common. Anchylosis may perhaps be either preceded or followed by reduction, but the writer is inclined to believe that when anchylosis is preceded by reduction the reduction is phylogenetic, and that in ontogenetic development anchylosis is followed by reduction. That is, plates which will appear in the adult as a reduced anchylosed unit are in ontogenetic development up to the time of anchylosis the equivalent of the other plates in the same cycle or series, and with anchylosis inhibition of growth causes the reduction of the compound plate. This inhibition of growth may be due either to deep-seated atrophy in local areas or to local superficial atrophy.

The first change of interest in anchylosis of basals is the change of plate outline, from the pentagons through a heptagon to a hexagon. With lateral anchylosis of two basal plates, the pentagons of the basals are merged into a heptagon, with a re-entrant angle where the supported radial interlocks with the supporting compound plate. Upon further development, absorption decreases the angle of the radial plate, causing it to assume, first a lower angle, then a proximally convex outline, and finally, by complete absorption, a straight angle. At the same time, by increased deposition along the adjacent basal margin, the re-entrant angle of the heptagon is gradually filled, the filling comforming throughout with the reduction of the inserted angle. The final step is the change of the heptagon to a hexagon.

At some time either before, during, or after anchylosis, a remarkably persistent reduction of the compound plate or its component parts occurs. This reduction is parallel to the line of sutural closure, and is sometimes accompanied by reduction in the proximal diameter of the directly supported radial. From the principles set forth in the discussion of reduction and compensating enlargement, either compensating enlargement of the adjacent plates must take place or distortion follow the reduction. When only one pair of basals is anchylosed, as in the *Xenocrinus*, etc., and the *Calyptocrinidae*, the reduction is bilaterally symmetrical; the basals adjacent to the reduced plates are equally enlarged, and the reduction is apparently not due to deep-seated causes and affects only the basal plates and the proximal margin of the apposed radials (Pl. II, Nos. 2, 7). When two pairs of plates are anchylosed, as in the Stephanocrinidae, Pentremitidae, and Platycrinidae, the problem is not so simple, for on one side the compound basals are mutually apposed, and the intervening suture meets the center of the proximal margin of the radial. If the reduction of the compound basals is asymmetrical and occurs only on the sides opposed to the simple basal, no distortion in symmetry is necessitated. If, however, the reduction is symmetrical, there must be a distortion in symmetry of the cup, for there is no basal to enlarge where the compound plates are mutually opposed. In the Platycrinidae the reduction is asymmetrical, and is perhaps due to superficial atrophy.

The simple basal is in general symmetrically enlarged, and the base is occasionally a regular pentagon.

In the Stephanocrinidae and Pentremitidae the reduction of the compound basals is bilaterally symmetrical, and is usually accompanied by reduction of the radials directly supported by the compound plates. This reduction is compensated for on the anterior side by lateral growth of the simple basals and the radials obliquely supported by it. On the posterior side, however, distortion has taken place. If absorption had caused the reduction, either plate shoving or shrinkage of the sarcode would be necessary to keep the plates in contact; but plate shoving is apparently impossible, and shrinkage of the sarcode improbable. Upon comparison of the ornamentation in the reduced and unreduced radials in *Stephanocrinus*, another change seems to have taken place. The neural ridges of the reduced radials are fused, forming a single broad ridge, which apparently indicates that the underlying nerves are in closer relation than in the other radials. The reduction seems, then, to have been caused by the inhibition of lateral expansion in the sarcode in the reduced areas, and not to absorption, and is a very good example of deep-seated atrophy. In the three-basaled, hexagonal Camerata, anchylosis and reduction of the basals are complicated by the appearance of the anal plate, and cannot now be considered.

2. DELAYED ANCHYLOSIS

In many genera, especially of the hexagonal Camerata, anchylosis takes place at such an early period in development that no trace of the immature forms with unanchylosed basals is preserved. The only hope, then, of locating the missing suture is by delayed anchylosis, or characteristics of ornamentation. Ornamentation has, however, received so little study, and the subject is so broad, that the writer cannot at present give it adequate consideration. Examples of delayed anchylosis, however, are not unknown, and a number of cases will be cited in the latter part of this paper. Delayed anchylosis is simply a nascent stage of anchylosis, due to the inhibition of activity in the ameboid calciferous cells. It may appear in the form of internal or external grooves, or in its completeness as an unchanged suture. In the latter case, it is in the Camerata always accompanied by the inserted angle of the apposed radial. In the pentagonal Camerata the reappearance of a suture or group of sutures would unhesitatingly be described as cases of delayed anchylosis. In the hexagonal forms, however, doubts might arise concerning the reappearance of the anterior suture in the three-basaled genera and of the right-anterior suture in the two-basaled genera, since such reappearance would, according to Wachsmuth and Springer, indicate the presence of six basal plates (pp. 492–93). There might also be some question as to whether these reappearances are due to delayed anchylosis or resorption; but until more light can be thrown upon the problem of sutural reappearance by reabsorption of the intrasutural deposit, these abnormalities may well be ascribed to delayed anchylosis.

3. ANCHYLOSIS AND THE PHYLOGENETIC REAPPEARANCE OF SUTURES

Anchylosis of the basals, as far as we now know, is an ontogenetically repetitive process, confined to plates and not taking place as a result of cell-group fusion. The basal sutures are always present in ontogenetic development, and constitute phylogenetically a plane of weakness in the compound plate. This is apparently not true of the infrabasals, at least in modern forms, as is shown in the interradial development of two of the infrabasals in the embryo of *Antedon*. Atavistic reappearance of sutures, by delayed anchylosis, is a possibility, but the cenogenic or phylogenic reappearance of a suture lost through anchylosis is another question. The skeleton of the Echinoderm is deposited in the midst of living tissue and remains under the full control of the ordinary processes of growth, reabsorption, and modification by living tissue.[1] The partial or total absorption of plates, the shifting of sutures, and the reabsorption and modification of the basals in the formation of the centro-dorsal are sufficient evidence of this statement. It seems possible, then, that under the conditions of physiological disturbance (loss of vitality) common in the paracme of development,[2] failure of anchylosis or reabsorption of the intrasutural deposit might take place, and the sutures reappear as phylogenetic

[1] Ref. 7, p. 350. [2] *Ibid.*, p. 350.

characters; but we have no evidence of such a reversion, and, until such evidence is brought forward, theories of descent demanding the reappearance of lost sutures should be carefully scrutinized.

DEVELOPMENT OF THE INTESTINE AND THE CONSEQUENT ZONES OF POTENTIAL WIDENING

"In all the Echinoderm classes it is the digestive tube that controls any departure from pentamerous radial symmetry." This statement by Clark[1] may perhaps be too sweeping in extent, especially when we consider the potency of atrophy and compensating hypertrophy (p. 533) in distorting symmetry; but the fact that the digestive tube is one of the most powerful factors in distorting symmetry cannot be too strongly emphasized. The most striking and therefore the most widely known effect of this power is that shown in the various distortions of the mouth and ambulacral grooves by excessive growth of the hind-gut. These tegminal distortions have been so frequently described that there is no necessity of reviewing them here; distortions produced by the intestine in the basal and radial cycles have, however, received too little attention.

In the development of the digestive system in *Antedon* the gastric sack is elongated horizontally into a form somewhat resembling the human stomach, having a large end into which the funnel-shaped oesophagus opens, and a small end with a caecal termination, which is the potential intestine. Upon further development the intestine is also horizontally prolonged, and coils to the right, around the stomach, in the space left for it by the enlargement of the calyx;[2] before the coil is completed, however, the anal appears and the intestine directs itself toward that plate. The pressure exerted by the intestine upon the anal tends to keep separated the posterior radials and prevents the right-posterior radial from encroaching upon the anal.[3] Soon, however, the intestine turns upward and carries the anal with it into the tegmen. The thrust exerted by the outward growth of the intestine which displaces the anal and also the radianal (see p. 538) must not be con-

[1] Ref. 16, p. 152.

[2] Ref. 12, pp. 227–28.

[3] Radianal. See Ref. 16, p. 333.

sidered as a gentle pressure, nor the displacement of these plates as a gentle process, due only to their much closer association with the intestine than with the surrounding plates.[1] The outward push of the intestine is in proportion to the strength of the calyx walls a powerful force, capable of inhibiting plate growth and of greatly distorting the relations of plate contact and position.

In the recent works of Springer and Clark attention has been called repeatedly to the remarkable parallel between the ontogenetic migrations of the radianal in modern crinoids and its phylogenetic migration in fossil forms. Since the migration of the radianal in recent forms is caused directly from its intimate association with the hind-gut in its upward growth, there can be no doubt that such an association existed in the ancient crinoids, and that the tendency for shifting the radianal gradually increased and the association became so firmly established that the radianal is now completely withdrawn from the cup in individual development.

The radianal in the early Flexibilia is incorporated in the basal cycle below the right-posterior radial, and probably appeared in that position in the ancestors of the Flexibilia.[2] The outward push of the developing intestine was then directed obliquely to the right against the radianal and in the succeeding stages shoved and pulled this plate upward and to the right into the posterior interradius and out of the cup. Furthermore, in *Sagenocrinus*[3] it permitted such an enlargement of the radianal that the right margin of the posterior basal was shoved to the center of the posterior interray. This change is of especial interest in the study of basal plate evolution, as it shows one method of obtaining a posteriorly directed basal suture, such as is exhibited in all genera of Camerata having a hexagonal, tripartite base.

This apparent digression from the subject of basal plate evolution in the Camerata—a group in which, as far as we now know, a radianal plate never appeared—is for the purpose of bringing clearly to mind the powerful effect of the growing intestine and the presence of zones of potential weakness in the calyx. These zones of weakness lie along the posterior interradius in the radial cycle

[1] Ref. 11, p. 732.

[2] Ref. 31, p. 439, Pl. V, Fig. 9.

[3] *Ibid.*, Pl. VII, Fig. 18.

and along the right-posterior radius in the basal cycle, and it is to the latter zone that especial attention is called. Wachsmuth and Springer have noted this zone of potentiality in but one instance (description of Fig. I, No. 7, of this paper), although it seems the only zone of potentiality in the basal cycle which can logically be accounted for. Pressure from the end of the developing hind-gut must from the necessity of its position be directed obliquely to the right against the posterior interradius, and any lateral pressure of the gut must be directed against the right side of the calyx, the two combining to shove the right side outward and away from the left side. Thus the stress produced by this shove would naturally fall along the right-posterior basal suture, as this is the nearest suture or plane of expansion adjacent to the posterior interradius within the zone of pressure exerted by the hind-gut.

ORIGIN OF THE ANAL PLATE

Comparison of the cup and tegminal structures in the Batocrinidae and Platycrinidae shows that a very long period of time must have elapsed, or very rapid evolution have taken place, before such a highly specialized form as *Tanaocrinus* could have originated from any of the early Platycrinidae. Since *Tanaocrinus* is an early Silurian (Richmond) genus, relationship can be established with the Platycrinidae only through Ordovician or pre-Ordovician ancestors; therefore, if *Tanaocrinus* is related to the Platycrinidae, it must have been derived from a form having a simple, pentagonal, five-basal cup. The primary step in the evolution of this form into *Tanaocrinus* would be the introduction of the anal plate into the radial cycle, thus giving to the cup its hexagonal outline, and inducing in the basal-plate cycle a remarkable series of modifications. The questions then arise: How do we know that the anal was a secondary and not a primary plate? At what period in the ontogenetic development of the Camerata was it interpolated in the radial cycle? Where did it originate? And what changes followed its interpolation? It is generally agreed that the anal plate in the hexagonal Camerata is of secondary origin. If this is true, the statement just made concerning the ancestry of *Tanaocrinus* is undeniable, for by eliminating the secondary plates of that genus and restoring the orals an ideal larval or ancestral form will appear. If, however, the anal plate is a primary plate in the radial cycle, a different line of descent is indicated.

In the ontogenetic development of the skeleton in the living *Antedon* the anal plate is interpolated after the basals and orals have formed closed cycles, and before the radials are laterally in contact. As the anal expands by lateral and proximal growth, it comes into contact with the posterior radials and the posterior basal; but this happens before the distal margins of the basals are completed and while the radials are still separated from each other. Since growth in the anal plate and the posterior radials does not cease upon their coming into contact, shoving of the posterior radials in the direction of the unoccupied lateral areas might be expected. This, however, does not occur. On the contrary, the crowding results in a partial inhibition of growth in the apposed margins, and a marked asymmetry results in the outline of the posterior radials, especially in the right-posterior radial. If comparison is now made between *Antedon* in this stage of development and the early Camerata having a hexagonal base, a striking similarity is seen in the development of the basals, radials, and the posterior side of the calyx. The posterior radials in both forms are asymmetrical and narrower than the anterior radials, and the asymmetry is due to the diminution of the posterior side of the plates, the distance between the center of the radial facet and the plate margin being less in the posterior half than in the anterior half. If comparison is then made between the relative position of axial lobes and radial plates in pentagonal and hexagonal Camerata, a further distortion is noted in the hexagonal forms. The lobes of the canal in the pentagonal forms occupy an interradial position, while either two or three of the lobes in the hexagonal forms occupy a radial position. These facts show that there is a distorting factor present in the posterior side of the cup. When it is considered that pentamerous symmetry is the rule in Echinoderms, and that sutural symmetry based upon the hexamerous plan only appears in the basal cycle with the appearance of the posteriorly directed basal suture, there seems to be no other alternative than that the anal plate is the distorting factor, and that it has developed secondarily in the radial cycle, or has migrated into that position.

The origin of the anal plate is as yet an unsettled question, but there are several possibilities which may well be considered. It may have originated as a secondary plate in either the basal or oral cycle. It may have developed as one of a brachial series, or an interbrachial cycle, or it may have originated as a separate plate in the radial cycle. Origin in the basal or oral cycles is clearly out of the question, for we know of no plates in either cycle from which it could have originated. Assumption of origin as a brachial, which is Bather's explanation for the origin of the anal plate in the Fistulata,[1] is without foundation in the Camerata.

Origin as one of an interbrachial series of the ordinary type is also improbable, for although these interbrachials are present in *Tanaocrinus*, *Xenocrinus*, and *Compsocrinus*, they are clearly formed at a later stage of development. Origin as a first interbrachial, that is, one of an interbrachial series interpolated between the radial plates, has been seriously considered by Carpenter[2] in a comparison of *Xenocrinus*, and some of the dicyclic Camerata, with *Antedon* and *Thaumatocrinus renovatus;* and while such a cycle may have existed and the lateral plates have atrophied, there has been found no record of such a cycle in the monocyclic Camerata. This, however, does not preclude the idea that the anal series may have been so interpolated, and that the lateral plates which appear in some of the dicyclic Camerata have been the result of reduplication.[3] Let us examine the ornamentation in the anal series of *Compsocrinus* and *Xenocrinus*, and see if this may not throw some light upon the question. Bather, in calling attention to the anal ridge in the Reteocrinidae, *Glyptocrinus*, etc., says, "The *anal* ridge is connected with the ridges that unite the posterior basal to the right- and left-posterior radials, and this indicates that an axial cord passed up it to govern the motions of the anal tube."[4] That this ridge does so indicate the presence of an anal nerve seems beyond question, for in comparing the ornamentation in *Xenocrinus* and *Compsocrinus* with the nervous system of

[1] Ref. 4, pp. 319–31.

[2] Ref. 10, pp. 38–46.

[3] Ref. 16, p. 338.

[4] Ref. 6, p. 119.

Thaumatocrinus a striking similarity is discovered. In *Thaumatocrinus* the interradial arms are innervated by secondary branches of the axial cord, which originate slightly above the point of bifurcation of the basal cord, quickly join, and pass up the interradial arms, while the main branches pass up to the radials (Fig. 7, No. 2). In *Xenocrinus* and *Compsocrinus* (Fig. 8, No. 1) the anal nerve ridge arises at the point of bifurcation of the axial trunk ridges in the posterior basal, and there can be little doubt that the branching of the underlying nerves took place in the same manner as they do in *Thaumatocrinus.* The parallel here is so close that the writer was at first inclined to the belief that the interpolation of the anal series in the Camerata is of the same type as the interpolation of the interradial arms in *Thaumatocrinus.* In *Thaumatocrinus*[1] the "interradial" radials appear very early in the ontogenetic development as narrow plates separating the radials and gradually increase to the size of the true radials. An objection to this form of development has been stated by Bather, on the ground that no primitive genera have been found in which the anal plate appears as a narrow linear plate.[2] This objection, however, is not formidable, for the change may have been a discontinuous mutation, or may have taken place during periods of retreat of the sea. Ulrich believes that most mutations have so taken place, for he says in the "Revision of the Paleozoic Systems": " . . . . almost invariably we deal with the nearly finished product of a process of mutation that was begun and established before the new phase invaded areas now accessible to the student of fossil faunas."[3]

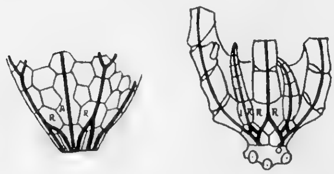

FIG. 8.—Diagram showing the course of the radial and anal ridges in *Compsocrinus* and the branching of the nerves in *Thaumatocrinus:* 1, *Compsocrinus harrisi* (based upon Wachsmuth and Springer); 2, *Thaumatocrinus renovatus* (after Carpenter); course of nerves based upon dissection by the writer.

[1] See Ref. 16, p. 337.

[2] Ref. 3, fifth notice, p. 37.

[3] Ref. 36, pp. 498–501.

The logical sequence of events based upon the *Thaumatocrinus* theory would be the interpolation of the anal plate in the radial cycle and serial development of the succeeding anals. But when this sequence of events is applied to the pentamerous, monocyclic Camerata difficulty is immediately encountered. Either these forms have lost their true anal plate and the anal now appearing in them is the homologue of the second anal in the hexagonal Camerata, or they have developed along a different line of evolution from the hexagonal forms. But before taking up these questions let us examine this theory of interpolation more closely.

Stratigraphically the pentamerous base precedes the hexamerous base, and it seems scarcely possible that a hexagonal form which could give rise to both *Glyptocrinus* and *Tanaocrinus* could have been living in the ocean basin during pre-Ordovician and Ordovician times, and that only those forms having lost the anal plate should have migrated into the epicontinental seas during the Ordovician, while those having the anal plate were withheld until Silurian (Richmond) times. This is apparently carrying the theory of selective action too far to be believed. Again, the embryological evidence shown in *Thaumatocrinus* may not be reliable. We have noted that the radianal in *Promacocrinus* originates to the left of the right-posterior radial; furthermore, we know that the radianal appears in the more primitive crinoids in a subradial position. There has been not only a progressive upward shifting of the radianal in these groups, but there has been apparently a progressively upward shifting of its point of origin. Embryology does not repeat all the ancestral characteristics step by step and then eliminate them in a different fashion in producing the various genera and species; certain characters which are gradually being eliminated phylogenetically are probably, in Crinoidea, the result of a progressively increasing inhibition of plate development in the larva, which ends in the complete obliteration of the plate.[1] Since embryology does not repeat all the ancestral stages, and does in this case permit of changes in the position of origin of a plate, there is a possibility that the "interradial" radials in *Thaumatocrinus* did

[1] For a more complete discussion of this phase of development based upon a wide series of observations, see Ref. 23, Chap. III, "Recapitulation."

not originate in the position in which they now originate, and too much dependence should not be placed upon this character. The evidence presented by fossils is fixed, although often wrongly interpreted, and until stronger evidence is submitted it is well to hold closely to that presented in the stratigraphic succession.

Stratigraphically the pentamerous base preceded the hexamerous base, and when we consider with this the evolution of the two-basaled, hexagonal Camerata, a more logical theory of development for the anal plate is presented. In this short-lived group we have a very rapid evolution from some platycrinid stock. The anal plate in *Platycrinus* originates in the posterior interray between the distal margins of the radial plates, while the anal plate in *Dichocrinus* projects above the level of the radials and costals and bends sharply inward toward the anal tube; its distal portion is reduced, and, if it were separated from the enlarged proximal portion and slightly modified, could not be distinguished from the anal in *Platycrinus*. Enlargement and downward growth of the anal seems then to have occurred, and a different theory is offered for the interpolation of the anal plate.

This theory for the appearance of the anal plate is, then, that the anal plate is of secondary derivation; that it was interpolated phylogenetically after closure of the radial cycle, but ontogenetically after the basal had formed a closed cycle and before the radials had come into contact. The cup in this stage of development is in a flexible condition, and readjustments can readily be made. Development of the anal plate in this position requires no true migration to come into contact with the posterior basal; portional migration, or proximal growth with distal inhibition in the younger stages, will produce the *Tanaocrinus* type of anal, while distal growth alone is necessary to produce the *Glyptocrinus* type of anal. The stimulus which kept the radials apart and permitted this downward growth of the anal plate was the demand for room on the part of an enlarging hind-gut, and it is this stimulus which has caused some of the most remarkable changes in crinoid evolution. Additional plates in the anal series were probably added as needed, for protection of the anal tube, and no slipping downward of a completed series of anals is required. In considering this change we must remember that we are not dealing with a completed model in which the plates are of fixed and unchangeable size, and in which every change of plate position must be accompanied by an entire readjustment of the adjacent plates; we are dealing with a growing organism in which there is a certain amount of flexibility in adjustment by plate growth.

If this theory for the interpolation of the anal plate is correct, the first anal plates of *Glyptocrinus*, *Platycrinus*, and *Dichocrinus* are homologous; and in further developing the theory for the evolution of basal plates this view will be followed.

[*To be concluded*]

DIFFERENTIATION IN INTERCRUSTAL MAGMA BASINS

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Dr. N. L. Bowen's comprehensive article on "The Later Stages of the Evolution of the Igneous Rocks," issued as a supplement to the last volume of this *Journal*, will be hailed with satisfaction by all petrologists, and indeed with gratitude by those who have the misfortune not to be chemists. It contains the first serious attempt to deal with the problem of magmatic differentiation directly from the standpoint of experimental knowledge. In demonstrating how the course of crystallization may be changed by the sinking of crystals, or the straining away of liquid from crystals, or the formation of zoned crystals in isomorphous groups of minerals, the author scarcely goes beyond actual laboratory experience, and his conclusions accordingly carry a great weight of authority. When he proceeds to construct on this basis a general theory of differentiation, the element of hypothesis is necessarily introduced, and, as the author recognizes, his argument can no longer command unquestioning acceptance. It is a very interesting contribution to a discussion which is not likely soon to be closed.

I wish to make a few remarks upon one of the subsidiary issues, which, however, touches the main theory at numerous points, viz., Bowen's predilection for differentiation *in situ* as opposed to differentiation prior to intrusion. That an appreciable settling down of crystals may take place after intrusion is not to be denied, but I think that the experience of any field geologist goes to show that it is a rare and exceptional incident. Daly has given a list of about thirty stratified sills and laccolites in which such "gravitative" differentiation is believed or conjectured to have occurred, but probably a critical examination would dispose of many of the examples cited. In some, such as the Loch Bordan mass in Sutherland, there is not a gradual transition but a sharp boundary between the several rock types. Bowen remarks that the upper acid magma, remaining fluid after the lower basic portion has wholly crystallized, may come to have an intrusive relation to the latter. This would be sufficient to explain veining of the one rock by the other; but, where an overlying sheet is separated from an underlying one by a surface of discontinuity, I can see no explanation but that of distinct intrusions. Nor is this explanation necessarily excluded even when no sharp division is seen, for, under appropriate conditions, a transitional zone may result from partial admixture. The Sudbury laccolite is probably a case in point, though I must confess to only a limited personal examination of the mass. I found no indication of a regular "composition gradient" in either norite or granophyre, considered separately, while the transitional zone between them has all the characters of a hybrid rock. The sulphide ore I leave out of count, as doubtless representing a magma immiscible with that of the norite. The clear instances of gravitative differentiation in sills and laccolites of which I have direct knowledge are all in rocks which must represent very unusually fluid magmas, such as the analcime-bearing intrusions of Permian age in Scotland. They are the kind of exceptions which help to prove the rule: viz., that in an intrusive body of moderate size a prohibitive viscosity soon puts a stop to the settling down of crystals. Doubtless a laccolitic mass of very large dimensions retains its fluidity longer, but it is obviously in a great intercrustal reservoir that the most favorable conditions for this action will be realized.

Bowen would apply the conception of differentiation in place to the plutonic rocks of Skye; but the facts, as I see them, absolutely negative such a hypothesis. The peridotite is not found at the base of the gabbro, but enveloped in the midst of it. The granite breaks through the gabbro, and, where any approach to a stratiform arrangement is apparent, does not overlie, but underlies, the basic rock. In one part the granite has been so chilled against the gabbro that its margin and the offshoots from it assume the characters of a spherulitic rhyolite. I infer that the gabbro was, in this place, not only solid but cold when the granite was intruded. The large gabbro laccolite itself is made up of numerous irregular sheets, showing differences in composition and structure, and often visibly cutting one another. In the peridotite this composite structure is more strikingly exhibited, and it can be detected in places in the granite, which is a much more uniform rock. The several component sheets are not disposed in an orderly fashion in accordance with their various densities. Add to this evidence the fact that peridotite, gabbro, and granite all make smaller separate intrusions, some much too far away from the main complex to have any direct connection with it, and it will appear beyond dispute that the differentiation which yielded these various rocks was effected prior to their intrusion, and therefore in some large reservoir at a deeper level.

Bowen does not refuse the conception of a deep-seated magma basin stratified according to density; but he seems to think it an absurdity that, on that hypothesis, the earlier intruded magmas should be drawn from the lower levels (p. 73). I will try to remove his objections. I have already urged[1] that in order that such a basin may have a considerable degree of permanence, as it obviously has, we must suppose some approach to thermal equilibrium between it and the surrounding crust. This implies a temperature gradient within the basin approximately like the normal gradient in the earth's crust of the region. It implies, further, what I may call a fusibility gradient corresponding with this normal temperature gradient. Now, the separation and sinking of crystals, as pictured by Bowen, goes with a cooling-down of the magma, which terminates in complete solidification. Any intrusions drawn from the basin must therefore be consequent upon *remelting*. The occasion of this I presume to be a gradual rise of the isothermal surfaces, which must accordingly become more closely spaced. In other words, reheating implies a temperature gradient steeper than that to which the fusibility gradient is adjusted, and it follows that the lowest layers will first become fluid. I have not attempted to develop this view of the matter, and should welcome criticism; but Bowen's zeal for differentiation in place has caused him to pay little regard to the possibilities of this alternative.

I am wholly in accord with Bowen in the conviction that alkaline and calcic rocks are derived from the same primitive magmas

[1] See especially *Compte Rendu XII Congr. Géol. Intern.*, Toronto, 1914, pp. 205–8.

(p. 59). My belief has been, and is, that the differentiation of these two great classes of magmas from the common stock and the separation of them—in general in a horizontal sense—constitute the first and most important steps in the evolution of igneous rocks. Why the chemical differentiation should so consistently follow these lines has been a difficult problem, and it is the more gratifying to be offered at least a partial answer to the question. Stated broadly, Bowen's ideal scheme of differentiation leads first to a series of calcic rock types and subsequently, if continued, to an alkaline series. There are qualifications of this rough statement which I do not go into here; but in general it appears that, if a separation can be brought about at a certain well-defined stage of the progressive differentiation, it will be a separation between calcic and alkaline. This separation, I hold, has actually been effected on a grand scale, and I have sought the immediate cause of it in the action of crustal stresses squeezing out the residual fluid.

A discussion of this suggestion from the chemical point of view would be instructive, but here Bowen disappoints expectation. He dwells on particular cases in which separation has not taken place at the stage specified, but at a somewhat earlier stage; and he throws doubt upon the existence of any general regional distribution of alkaline and calcic rocks, such as Iddings demonstrated long ago. The fact that, among the younger rocks of North America, alkaline types characterize the Atlantic slope and calcic the Pacific, he would explain by supposing that erosion has exposed deeper levels on the western side of the Rocky Mountains than on the eastern. He forgets that the contrast of petrographical facies holds good for the lavas as well as for the intrusive rocks. Moreover, the fact that lava flows still cover vast areas on the western side, while on the eastern they have mostly been removed, makes it difficult to accept his statement about the relative amounts of erosion.

As regards the association of calcic rocks with regions subjected to powerful lateral thrust, nothing would be gained by traversing old ground again, but to Bowen or any other unbeliever I will offer just one consideration. If we examine those crystalline schists which are admittedly of igneous origin, together with foliated igneous gneisses, we find that they belong almost exclusively to the calcic branch. A few exceptions there are, and must be. A nepheline syenite may be intruded in a line of faulting during the time of movement, as in the Langesundsfjord; or it may be crushed and metamorphosed long afterward by stresses with which it has no genetic connection, as at Loch Borolan; but these are isolated and incidental occurrences. The matter is easily brought to the test. In Grubenmann's classification, based solely on chemical composition, the crystalline schists and gneisses of igneous origin are contained in six of the twelve groups. The calcic rocks are in Groups I, III, IV, and V, which correspond with granites, diorites, gabbros, and peridotites. They include a rich variety of types, and collectively make up enormous tracts of the earth's crust. To complete his classificatory scheme the author has been able to produce various types of alkaline rocks, which scantily furnish forth Groups VI and VII, but most of them are little more than petrographical curiosities. In respect of the total bulk of all known occurrences, these alkaline crystalline schists as a whole are quite insignificant as compared with any single type in the calcic division.

The striking disparity here noted is only one consideration among others which points to a peculiar distribution of alkaline and calcic igneous rocks in relation to crustal stresses. If anyone seriously believes that such things are matters of chance coincidence, there is no more to be said. It is to be hoped rather that chemists, as well as geologists, will recognize here a real significance, and will lend their help in the attempt to explain the facts, not to explain them away.

STRATIGRAPHY OF THE SKYKOMISH BASIN, WASHINGTON

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WITH

REPORT UPON PALEONTOLOGY AND PALEOPHYTOLOGY

CAROLINE A. DUROR

STRATIGRAPHY

I. GENERAL AREAL DISTRIBUTION

In general, the rocks of the Skykomish Basin trend in a north-south direction. This is almost exactly true of the igneous and metamorphic terranes. Only the sedimentary Swauk and the tufaceous Keechelus series vary from this general statement, for they show a trend in general west of north but bending northward on their northern prolongation. Dawson has remarked this tendency of all the rocks of the Cordilleran system.[1] The rocks lie in roughly parallel bands in the north, but are replaced southward until the granodiorite entirely takes the place of the earlier series and extends over nearly the entire width of the quadrangle. Igneous rocks greatly predominate in the area, metamorphics and sedimentaries being approximately equal in amount, and both being comparatively small. Volcanics make up a smaller division. These relations will be illustrated by the following classification table:

Snoqualmie granodiorite	130.90
Keechelus andesitic series	32.20
Tye soda granite and Beckler stock	24.15
Easton schist	22.95
Swauk sedimentary series	56.00
Maloney metamorphic series	14.80
Index granodiorite	4.35
Surface outcrop areas	285.35 sq. mi.

[1] G. M. Dawson, "Geological Record of the Rocky Mountain Region in Canada," *Bu Geol. Soc. Am.*, XII (1901), 59.

In the following discussions no effort will be made to subdivide the metamorphic rocks of a sedimentary origin from those of an igneous origin, where these are so intimately associated as to make the subdivision impracticable. However, the schists of the northeastern area are easily kept distinct from the metamorphic series of the northwestern area.

On stratigraphical grounds the rocks readily fall into two groups: (1) the pre-Tertiary, and (2) the Tertiary. The division line between these is the most marked unconformity in the Cascades. We have present a schist, belonging to the pre-Tertiary, which is cut by quartz and igneous rock dikes, making the oldest or basal terrane.

This is called the Easton schist, and it forms the metamorphic terrane in the northeast. No definite idea of its age can be suggested except that it is pre-Ordovician. Fragments of it are included in the Mesozoic batholiths, and it is more complexly folded than the Maloney (Gunn Peak) metamorphic series. The next younger series belongs on paleontologic and correlation evidence to the Ordovician. It is a series of quartzites, schists, and crystalline limestones with associated greenstones, approximately 4,000 feet thick, outcropping in the northwest. Weaver correlates this series with the Cache Creek series as defined by Dawson.[1] It has at least one stage less of dynamic history than the Easton and on lithologic grounds it is believed to be equivalent to Smith's Peshastin series of the Snoqualmie area; but its fossil content identifies it as Ordovician instead of Carboniferous, as the Peshastin is called by Smith and the Gunn Peak by Weaver. Nothing can be said of the remainder of the Paleozoic history of the area. The absence of later Paleozoic and Triassic seems to be general in the region of the Cascade Mountains. In Jurassic time, however, there was a notable period of deep-seated volcanic activity, resulting in the intrusion of the great Sierra Nevada-Cascade granodiorite batholith, possibly the greatest of igneous intrusions.[2] This batholith is represented by two terranes in the Skykomish Basin. The first is the Tye soda granite in the northeast, and the second

[1] G. M. Dawson, *Ann. Rept. Can. Geol. Surv.*, N.S., VII (1894), 37B–49B.

[2] R. A. Daly, *Igneous Rocks and Their Origin* (1914), p. 53.

is the Index granodiorite in the northwest. The Cretaceous is not represented but is known to occur as a marine series farther northward. Following the Mesozoic batholithic intrusion came a positive orogenic movement, corresponding to the Laramie revolution, which left the Cascade area, at the close of the Mesozoic, high above sea-level.

The Tertiary period opened with a period of continental deposition in which the Swauk sandstone was deposited unconformably on the eroded edges of earlier metamorphic rocks. These arkoses consist of mingled fragments of granitic rock and of schist derived from the Paleozoic metamorphic series and from the Mesozoic batholith. Both Smith and Willis consider these arkoses to be lake deposits, but Weaver more correctly designates them as purely continental. They show conglomeratic facies and cross-bedding and vary so markedly in thickness that only the maximum figure of 4,000 feet is of any significance. They are equivalent to the lower Puget of western Washington and, on paleophytological grounds, to the Fort Union of the Montana-Wyoming areas. No definite information is recorded of the late Eocene and Oligocene, the gap being succeeded by Miocene andesitic tuff beds. These are volcanic tuff ejectamenta cut by dike- and sheet-like intrusions of andesitic composition. We have insufficient evidence to suggest where these tuffs had their immediate source, but their chemical resemblance to the Miocene granodiorite suggests forcibly that they were derived from the same magma. In later Miocene a recurrence of deep-seated vulcanism took place, resulting in the injection of the Snoqualmie granodiorite, which is the most important terrane present in the area. This batholith, if its texture is to be accounted for, must have been covered by at least 2,000 feet of rock. In this cover late Eocene and Oligocene may be included. In latest Miocene and in early Pliocene the region was planed to a low relief; a disturbance of isostatic equilibrium followed, which resulted in the arching up of the Cascade Mountains to a maximum height of approximately 8,000 feet. Since this Pliocene uplift, canyons some 5,000 feet deep have been cut in the granodiorite, a fact bearing witness to the severity of erosion experienced by the area.

In the Pleistocene the Skykomish Basin was eroded by valley glaciers, and the only discernible post-Tertiary volcanic history is recorded in a thin layer of ash, probably drifted from Mt. Rainier by prevailing southwest winds. Post-Pleistocene time has not lasted long enough seriously to change the aspect of the topography left by glaciation.

II. PRE-TERTIARY HISTORY

PRE-MESOZOIC

The pre-Mesozoic is represented by two divisions, one of which is considerably older than the other, and on lithologic grounds is referred to an equivalency with the Easton schist. The later division has experienced at least one stage less of metamorphic history and is of known Ordovician age, on the evidence of fossils obtained from a cherty phase of the limestone lens outcropping in Lowe Gulch (D 2), two miles west of Grotto. No evidence of the exact age of the Easton schist has been put forth and none can be suggested for the Skykomish Basin. It comprises extremely metamorphosed and crumpled rocks generally derived from sediments. This structural condition of the rocks precludes any estimate as to their original thickness, but does enable one to infer that they are of considerably greater age than any other Paleozoic division which is much less dynamically disturbed.

MALONEY

The Maloney comprises a series of metamorphosed rocks including quartzites, limestones, and schists of sedimentary origin cut by basic igneous rocks, usually best described as greenstones, which are later in age than the Maloney, but which on the evidence of their extreme metamorphism are considered to be also of Paleozoic age. The name Maloney is applied to a series formerly believed to be equivalent to the Peshastin series, which is called Carboniferous in age. The evidence on which this correlation is made is presented in an earlier paper.[1] Subsequent identification of fossils found in the limestone lenses shows the formation to be Ordovician in age, and therefore the name Maloney is suggested.

[1] Warren S. Smith, "Petrology and Economic Geology of the Skykomish Basin, Washington," *School of Mines Quarterly*, XXXVI (1915), 157.

Miss Caroline A. Duror, in another part of this paper, has identified the following fossils as of Ordovician age: *Rafinesquina deltoidea* and *Illaenus americanus.* This is the first recorded evidence of the presence of Ordovician strata in the Cascade Mountains of Washington, and both fossils are the first of their kind of Paleozoic age to be found there. With this Ordovician series begins the definitely known geologic history of the Skykomish Basin. It was a period during which the area stood approximately at sea-level, as evidenced by the fact that the limestone lenses carry marine fossils. The presence of quartzite shows that probably the area was not deeply submerged, but more probably was near the continental margin. There is no record of the post-Ordovician Paleozoic.

MESOZOIC

There are no Mesozoic deposits at present, though there is evidence that they must have existed. The sole known event of the Mesozoic in the Skykomish Basin is the intrusion of batholithic igneous rocks whose structural relations identify them as Mesozoic, though there is no other positive evidence of their age. But it is altogether probable that the batholiths were intruded as a part of the great Sierra Nevada intrusion identified in California and Oregon as of Jurassic age. Daly, Smith and Calkins, Russell, Weaver, and others assert this probability. The granodiorite of which this batholith is composed is granitoid in texture, and such a texture can be established only under a thick cover of superjacent rock. This cover was removed in post-Jurassic time, leaving the batholith uncovered at the end of the Mesozoic. Russell[1] and Smith[2] have described sedimentary rocks of Cretaceous age, from Whatcom County to the north, and it is therefore inferred that removal of the 2,000 feet or more of the cover of the Jurassic batholith was toward the north. The series, as described by Smith, under the name Pasayten, begins with a conglomerate in which

[1] I. C. Russell, "Cascade Mountains in Washington," *20th Ann. Rept. U.S.G.S.*, Part II (1898), p. 114; G. M. Dawson, "Geological Record of the Rocky Mountains in Canada," *Bull. Geol. Soc. Am.*, XII (1901), 84.

[2] Smith and Calkins, "Cascade Mountains in Washington," *20th Ann. Rept. U.S.G.S.*, Part II (1898), p. 114.

granitic bowlders predominate, is 6,000 feet or more thick, and is dynamically disturbed. The Mesozoic closed with a period of severe orogenic disturbance, as evidenced by the structural relations

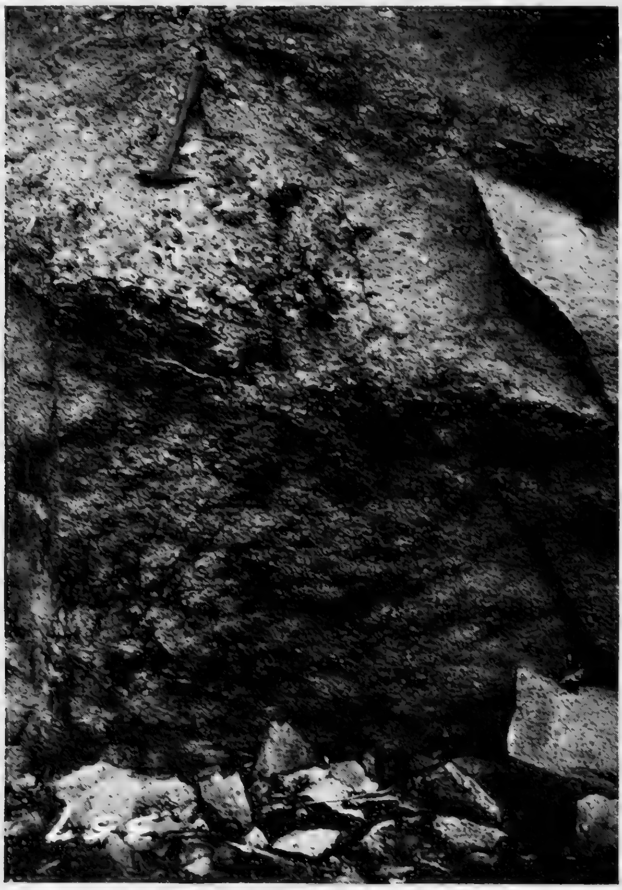

FIG. 1.—Swauk arkose series. Conglomeratic facies

of Tertiary rocks. This unconformity is very marked, because the earliest Tertiary sedimentaries lie at distinct angular unconformity on the pre-Tertiary rocks, a break which is well described by Smith and Calkins in the Snoqualmie area.[1] The pre-Tertiary

[1] G. O. Smith and F. C. Calkins, *Folio U.S.G.S.*, 1906, 2.

disturbance left the area adjacent to the Skykomish Basin on the east in a condition sufficiently elevated to make the earliest Tertiary a period of erosion.

III. TERTIARY

EOCENE

In the Skykomish area the Eocene was a period of sedimentation during which 4,000 feet of arkoses, shales, and conglomerates were deposited. About the middle of the series there are two shale formations which yield a considerable flora. The series is directly continuous with the Swauk series of the Snoqualmie quadrangle, and is also related to it on paleontologic grounds. It outcrops in a belt several miles in width, striking approximately N. 45° W. in the Eagle Creek-Beckler and the Foss River valleys. The dips vary; in the measured section, half a mile south of the Great Northern Railway, the base of the series lies nearly level, with increasing dip to the east as one goes east, and to the west as one goes west, until the top of the series stands vertical. It is an anticline whose basal beds rest unconformably on Easton schist, and whose roof is a part of the Keechelus andesite series.

Miss Duror's appended report is made on the flora collected from two horizons about 600 feet apart vertically, the lower being 1,100 feet from the base of the Swauk. Fossils numbered F 831, F 831+50, and F 844 are from the upper beds; those numbered F 865 from the lower. With the latter is associated a coal bed some 14 inches thick on which slopes have been driven in the hope of finding minable coal.

The sandstones and conglomerates are cross-bedded and the fragments usually angular and never assorted (Fig. 1). It has been considered a fresh-water lake deposit. In the light of the recent developments of stratigraphy it may better be classed as in part purely continental and in part deposited by streams, probably in deltas. The shales, and particularly those carrying complete specimens of *Sabal*, could only have been laid down *in situ* and must have been formed in shallow water—probably in a swamp. None of the series bears evidence of deposition in deep water, and both the angular condition and the considerable size of the fragments forbid their having been transported for any great distance.

Correlation.—Knowlton has done the paleontologic work on the continental Eocene of Washington. He has made the determinations both for the Eocene (Puget) of western Washington and for the Eocene (Swauk, Teanaway, and Roslyn) of eastern Washington. Continual reference is therefore made to him as an authority. The original report on the Swauk[1] showed 25 species belonging to the following genera: *Lygodium*, *Sabal*, *Myrica*, *Comptonia*, *Populus*, *Quercus*, *Ficus*, *Cinnamomum*, *Prunus*, *Diospyros*, *Zizyphus*, *Celastrinites*, *Phyllites*. Of these genera, *Sabal*, *Populus*, and *Ficus* are reported by Miss Duror from the Skykomish Basin, and both *Sabal* and *Ficus* are index fossils of the lower Eocene (Puget), as stated by Knowlton: "The following genera have been found in the lower beds but not at all in the upper: *Cladophlebis*, *Lastrea*, *Siphonites*, *Ficus*, *Eucalyptus*, and *Aralia*."[2] Turning to the western area we find that the Puget formation consists of some 10,000 feet of arkoses and intercalated carboniferous shales representing the Eocene. Besides the above named, Knowlton describes *Quercus*, *Juglans*, *Rhamus*, *Populus*, and *Laurus* from that series. Of these Miss Duror reports *Juglans*, *Populus*, and *Laurus*, and the presence of *Ficus* and *Sabal* correlates the Swauk with the lower Puget (Carbonado). Miss Duror's report further proves the equivalency in age of the Swauk with the Fort Union of Montana, North Dakota, and Wyoming.[3] The Swauk sedimentary series may then be correlated with the lower Puget of western Washington, with the Swauk (lowermost Eocene) of eastern Washinton, and with the Fort Union areas farther east.

MIOCENE

Keechelus.—This series of rocks of volcanic origin comprises tuffs, sheets, and dikes usually of andesitic but less frequently of dacitic composition. The tuffs predominate strongly and form beds of unknown but considerable thickness widely distributed in the Skykomish Basin. They overlie the Swauk sandstone, and the

[1] *Folio 106, U.S.G.S.*, 1904, p. 5.

[2] *Folio 54, U.S.G.S.*, 1899, p. 3.

[3] A. G. Leonard, "Cretaceous and Tertiary Formations," *Jour. Geol.*, XIX (1911), 541–43.

dikes have baked the sandstones. The Keechelus is therefore post-Swauk in age. Contrariwise, the Keechelus series has been indurated and otherwise metamorphosed by the Snoqualmie batholith to the southward; in the Snoqualmie area the Keechelus series is underlaid by a sedimentary series of sandstones and water-laid pyroclastics (Ellensburg) which contains flora called Upper Miocene by Knowlton.[1] The Keechelus series in the Skykomish Basin, being really continuous and lithologically identical with the series of the southern area, is therefore considered Miocene in age. As has been pointed out by Smith and Calkins, a striking chemical similarity exists between the Keechelus andesite and the subjacent body of granodiorite. Both fall into the same chemical classification—tonalose. It is immediately inferred that the two rocks are consanguineous, or, in other words, that the andesitic pyroclastics were blown out from a magma that later solidified as the Snoqualmie granodiorite. We must assume 2,000 feet or more of cover, and it is suggested that this Keechelus series may very well have provided at least a part of the cover which has later been removed by processes of erosion. No estimate can be made of the thickness of the Keechelus series. It is undoubtedly widely variable and probably had a thickness of several thousand feet.

Snoqualmie granodiorite.—Into the Keechelus series was intruded one of the younger of the known great batholithic intrusions. It has a known length of major axis of about thirty miles and is approximately two-thirds as broad. Throughout, this terrane is a massive, fresh, granitoid igneous rock which has been discovered by erosion to a vertical depth of 5,000 feet or more. It has, as was seen above, metamorphosed rocks of late Miocene age, and has sent apophyses into them, and therefore must itself be Miocene or later in age. To account for its holocrystalline nature and for the fact that it has been peneplaned, uplifted, and maturely dissected, it seems necessary to put the date of its intrusion as near that of the Keechelus as possible. The age is therefore given as late

[1] G. O. Smith and W. C. Mendenhall, "Tertiary Granite in Northern Cascades," *Bull. Geol. Soc. Am.*, XI (1900), 224; G. O. Smith and F. C. Calkins, *Folio 139, U. S. G.S.*, 1906, p. 8.

Miocene, in accordance with Smith's interpretation.[1] The only metamorphic effects experienced by this rock are the slight clouding of feldspars and the formation of a system of joints. There is a southernmost corner of another batholith, or, more likely, of a subjacently connected continuation of the same batholith, north of Grotto, and it is probable that these Tertiary batholiths form the core of the Cascade Range throughout the northern half of the state. Daly has correlated several of his batholiths with the Snoqualmie batholith.

PLIOCENE

There is no stratigraphic evidence of Pliocene history. It is physiographic rather. We infer that the Snoqualmie batholith had a cover in excess of 2,000 feet in thickness. This cover was removed and the entire area reduced to one of low relief in late Miocene and post-Miocene time. In the Pliocene the area was uplifted with a broad arch of north-south trend and with certain minor warpings of transverse trend. Subsequent to this uplift, but still in the Pliocene, the area was maturely dissected by steam action. This process of peneplanation, uplift, and mature dissection is evidence of the very considerable duration of the Pliocene.

PLEISTOCENE

This is the age of glacial occupancy, when glaciers of the alpine type filled the valleys to a depth of several thousand feet and flowed down to their confluence with the Piedmont glacier of Puget Sound. Evidence has been put forward by many writers of two periods of glacial advance in the Puget Sound Basin, but of course the last alpine glacier to occupy the valley would have destroyed all evidence of any previous glaciation, and it can only be said that the Skykomish Basin was maturely dissected by glaciers of the alpine type in Pleistocene time. Comparatively little time has elapsed since the glaciers withdrew from the valley. The only stratigraphic evidence of this period is the accumulation to a depth of several inches of a volcanic ash which has only a

[1] G. O. Smith and W. C. Mendenhall, "Tertiary Granite in the Northern Cascades," *Bull. Geol. Soc. Am.*, II (1900), 201–28.

slight soil covering at present—an evidence of recent volcanic activity in the near-by volcanic cones.

RÉSUMÉ

Eocene time witnessed the accumulation of 4,000 feet of arkose sandstone. This was orogenically disturbed so that it now dips at considerable angles. In the Miocene a series of volcanic tuffs and andesitic intrusives were derived from a magma which approached the surface and cooled as a batholith in late Miocene. Pliocene saw the formation, uplift, and mature dissection of a peneplane. The Pleistocene was a period of glaciation lasting nearly to the present, in which the Skykomish area was maturely dissected by ice erosion.

IV. STRUCTURE

A glance at the map shows the tendency of all formations to trend north-south. Only the Swauk arkose series deviates from this tendency, and even this formation tends to assume a normal relation in its northward outcrop. The great igneous terrane (Miocene batholith) has its major axial trend in a direction parallel to the north-south axial trend of the Cascade Range.

JOINTING

There are two known systems of joints of considerable importance and one or more of less prominence. The first two strike N. 45° E. and N. 70° E., respectively, and the lesser system strikes N. 80° W. It is suggested that these joints are the result of pressure exerted by orogenic forces in raising the Cascade peneplane to its present position. If this pressure were exerted continuously in an east-west line from the Pacific side, we should anticipate a set of joints striking N. 45° E. and a lesser set striking N. 45° W.[1] At least one important set of joints does strike N. 45° W. in the Cleopatra Mine. But it is necessary to postulate a change in the direction of application of the force to account for the system of joints striking N. 70° E. and N. 80° W.[2] It seems possible that such a change may have taken place in the direction of application

[1] A. Daubrée, *Géologie expérimentale* (1879), pp. 316 f.

[2] G. F. Becker, "Finite Strain in Rocks," *Bull. Geol. Soc. Am.*, IV (1893), 23.

of orogenic pressure, and this change may account for the transverse warping of the surface of the peneplane which is noted elsewhere. The importance of the development of these structural relations has an important influence on ore deposition (Fig. 2).

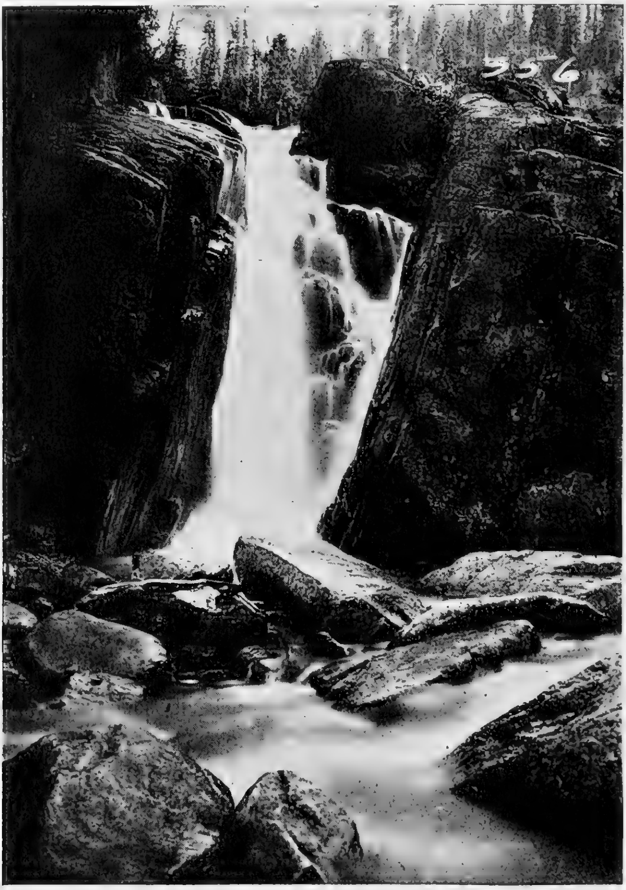

FIG. 2.—Kimball Creek. Note jointing. Rock: granodiorite

REPORT ON THE FLORA OF THE SWAUK SERIES

The flora of the beds is of Fort Union age. The material examined yields fifteen genera and nineteen species, of which two are new; the other seventeen species have been recorded from

Fort Union beds. Three ferns are represented by abundant specimens of *Asplenium* and *Pteris* in the shales of F 831 and F 831+50.

GENUS *Asplenium*

Asplenium magnum var. *intermedium* var. *novum* (Duror) (Fig. 3)

Knowlton: "Fossil Flora of Yellowstone Park," extract, *Mono. XXXIII, U.S.G.S.*, 1899, Part 2, p. 667; Pl. LXXIX, Figs. 8, 8*a*.

Heer: *Flora Foss. Arct.*, Vol. IV, "Ostsibriens," Taf. XX (*A. whitbiense*).

This form is so named because it is intermediate in character between *A. magnum* (Knowlton) and *A. whitbiense* (Heer). The frond is not pinnate, but the lobes are cleft one-half to one-third of the distance to the rachis. The margin of the lobes is entire. These lobes are one and one-half to twice as long (along midvein) as broad and come to a rounded point. Secondary veins come off at an angle of about 45°, members of each pair being almost opposite. Each secondary bears eight to ten pairs of tertiaries, which are generally once forked. A few rare cases of simple secondaries and still fewer twice-forked secondaries were observed. The variety differs from *A. magnum* of Knowlton in possessing almost deltoid instead of ovate lobes and in being rather larger. This form is separated from *A. whitbiense* of Heer, because here most secondaries fork once only, and because Heer's form has true pinnules—the form being bipinnate. There is no suggestion that this form is fully even once pinnate.

FIG. 3.—*Asplenium magnum* var. *intermedium* var. *novum*. (¼ natural size.)

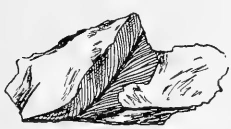

FIG. 4.—*Pteris pennaeformis*. (½ natural size.)

GENUS *Pteris*

Pteris pennaeformis (Heer) (Fig. 4)

O. Heer: *Fl. Tert. Helvetiae* (1855), p. 38; Taf. XII, Fig. 1*a–d;* Miocene age.

Lesquereux: *Tert. Flora* (1878), p. 52; Pl. IV, Figs. 3, 4, *Pseudopennaeformis*, Lower Lignitic age.

The Cascade specimens are quite similar to that figured by Heer, except that here only that part of the pinnae with entire margins is seen. Secondary veins are seen to fork twice, as in Heer's Fig. 1*e*, though from his description he found such nervation rare.

GENUS *Sabal*

Sabal powelli (Newb.)

Newberry: *Proc. U.S. Nat. Mus.*, V (March 21, 1883), 504.
Later Extinct Floras of North America, p. 30; Pl. LXIII, Fig. 6; Pl. LXIV, Figs. 1–19; Tertiary (Green River group) age of Wyoming.

Palms are represented in these beds, chiefly in F 831+50 and in F 865, by numerous perfectly preserved specimens of this type. In some cases both upper and lower surfaces of the petiole of one leaf were preserved. The forms agree in all respects with Newberry's type.

GYMNOSPERMAE

Gymnospermae are represented by countless fragments of *Glyptostrobus*, *Sequoia*, and *Taxodium*—this last in greatest abundance. The greatest number of these forms is found in the shales of F 831+50.

FIG. 5.—A, *Sequoia nordenskioldii;* cone in cross-section (natural size). B, *Asplenium cascadia*. C, *Taxodium distichum miocenum*. (½ natural size.)

GENUS *Glyptostrobus*

Glyptostrobus ungeri (Heer)

Heer: *Flora Tert. Helvetiae*, I, 51; Taf. XIX, XX, Fig. 1; Taf. XLIX, Fig. 50. Newberry: (G. *Europaeus* Brogn.): 1. *Annals N.Y. Nat. Hist.*, IX (1868), 43.

2. *Illus. Cret. and Tert. Plants* (1898), Pl. XI, Figs. 6–8*a*.

3. *Later Extinct Floras of N.Am.*, p. 24; Pl. XXVI, Figs. 6–8*a;* Pl. LXV, Figs. 3–4.

No cones of this species were found, but the general form of these fragments is like the Figs. 1*e* and 1*a* of Taf. XX, and of Fig. 50 of Taf. XLIX of Heer. They also resemble quite closely those from Birch Bay, Washington, figured by Newberry (see 3 above) on Plate LV. Those were of Fort Union age.

GENUS *Taxodium*

Taxodium distichum Miocenum (Heer), Fig. 5, C; Fig. 7, D.

Heer: *Miocene Baltische Flora* (1869), p. 18; Taf. II, III, Figs. 6, 7.
Newberry: *Later Extinct Floras of N.Am.*, p. 22; Pl. XLVII, Fig. 6; Pl. LI, Fig. 3, in part; Pl. LII, Figs. 2, 3, 4; Pl. LV, Fig. 5.
Lesquereux: *Tertiary Flora* (1878), VII, 223; VIII, 73.

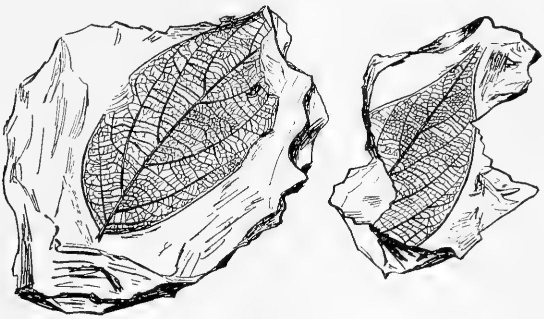

FIG. 6.—*Laurus cascadia* var. *leve*. (½ natural size)

FIG. 7.—A, B, B¹, *Laurus cascadia*. C, *Sequoia nordenskioldii*. D, *Taxodium distichum miocenum*. (½ natural size.)

The Cascade specimens are quite typical. The form is Greenland Miocene or basal Eocene in age.

Genus *Sequoia*

Sequoia nordenskioldi (Heer) (Figs. 5, A, 7, C, 8, B)

Heer: *Flora Foss. Arct.*, II ("Miocene Spitzbergens," 1870), 36; Taf. II, Fig. 13*b;* Taf. IV, Figs. 1*a*, *b*, 4–38.
Newberry: *Later Extinct Floras of N.Am.*, p. 20; Pl. XXVI, Fig. 4.

Sequoia nordenskioldi is represented by a few leafy branches occurring with the *Taxodium*, but in addition by a handsome cone. The cross-section is given in Fig. 5. The form is referred to *S. nordenskioldi* rather than to *S. langsdorfii* because the leaves are very little if at all narrowed before they join and run down the stem. The cone is almost identical with that of Heer (*op. cit.*, Taf. IV, Fig. 4*a*), except that these dimensions are 20×22 mm., not 16×13 mm., as Heer gives, and that here no leaves remain on the branch. This cone is not as elongate as in *S. langsdorfii.*

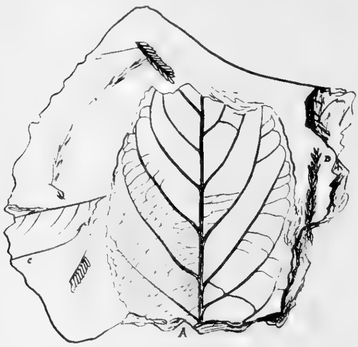

FIG. 8.—A, *Pterospermites whitei.* B, *Sequoia nordenskioldii.* C, *Sapindus obtusifolius.* (½ natural size.)

Dicotyledons

There are no identifiable monocotyledons found in these beds. Dicotyledons are represented by ten fairly well-preserved forms, and by fragments of many more. The genera are: *Ficus*, *Juglans*, *Hicoria*, *Laurus*, *Magnolia*, *Populus*, *Protoficus*, *Pterospermites*, and *Sapindus.*

Genus *Ficus*

Ficus ungeri (Lesq.)

Lesquereux: Supplement *Ann. Rept.*, 1871, p. 7; Fig. 1.
Hayden Survey, VII (1878), 195; Pl. XXX, Fig. 3.

Numerous fragments in F 831+ 50 beds are referred doubtfully to this form. The open-bowed secondaries in almost opposite pairs and the "very entire" margin are identical. Noted from Green River group, Middle to Upper Eocene.

Ficus sp. ? (Knowlton)

Knowlton: *Rept. on Fossil Plants Associated with Lavas of Cascade Range* (Western Oregon) (1898), p. 46; Pl. III, Fig. 1.

In shales (F 831+50) a specimen very similar to Knowlton's figure, in the roundly notched margin, and the 45° angle of emergence of the secondaries, was found. Here also no base or tip was to be seen.

Genus *Hicoria*

Hicoria (Carya) *antiquorum* (Newb., Knowlton)

Newberry: *Ann. N.Y. Lyc. Nat. Hist.*, IX, (April, 1868), 72.
Illust. Cret. and Tert. Plants (1878), Pl. XXIII, Figs. 1–4.
Lesquereux: *Later Extinct Floras of N. Am.* (1868), p. 35, Pl. XXXI, Figs. 1–4.
Tertiary Floras (1878), VII, 289; Pl. I, Figs. 1–5; Vol. VIII, Pl. I, Fig. 2.
Knowlton: *Tertiary Plants of N.Am.* (1898), p. 117.
Fossil Flora of Yellowstone Park, etc.

This form is found in the sandy F 844 beds. It is referred to these species rather than to *Juglans nigella*, because the teeth are here rounded, as in *Hicoria*, and the secondaries are less prominent than in *J. nigella.* The leaf narrows gently toward the base and joins the stem (midvein) by a quarter-inch long winged "petiole." The form is noted by Newberry and by Knowlton from Eocene beds (*Planatus*) at the mouth of the Yellowstone River.

Genus *Juglans*

Juglans acuminata (Heer)

Heer: *Flora Tert. Helvetiae*, p. 88; Taf. CXXIX, Figs. 2–8.
Flora Foss. Arct., VII, "Grönlands," 761; Taf. LXXV.
Knowlton: "Fossil Plants from Kukak Bay," *Alaskan Exp.*, IV (1904), 152; Pl. XXXIII, Fig. 3.

The form is identified from fragments only, but these are rather numerous. The entire margin and the angle of the midrib and secondaries are very similar in these specimens and in Heer's figures, but show considerable dissimilarity to Knowlton's type, where the angle between the midrib and secondaries is larger and where the latter are alternately long and short and bowed. The form, according to Heer, "is spread through the whole Tertiary and possesses many synonyms."

Genus *Laurus*

Laurus cascadia N.Sp. (Figs. 6 and 7, A, B, B[1])

This specific name is given to several excellently preserved specimens in the shales of F 831. There is variation among the forms, but hardly more than to permit of naming of two varieties. The leaf is ovate lanceolate, coming to a sharp slender tip, and slightly unsymmetrical at the obtusely pointed base. There are six to eight pairs of strong secondaries, the members not directly opposite, besides a rather faint pair at the base, where the members are opposite. Secondaries come off at an angle of about 70° or less, as in Fig. 7, and are very gently bowed. The tertiaries show a horizontal parallel arrangement all the way across the leaf, so that they do not join the secondaries at right angles, except in the case of the two lower pairs. Fig. 6 shows preserved a fine network of veins between the tertiaries. The margin of the leaf is entire, and the ultimate veins border it in a series of loops. About one-quarter inch of petiole was found (Fig. 6). In Fig. 6 the breadth is 38 mm., the length probably 100 mm. The two pieces figured are not parts of one leaf. In Fig. 7 the dimensions are 32×80 mm., and here A and B are two sides of the impression of one leaf. A small form, very like Fig 6, but not drawn, was about 18×35 mm. *L. cascada* resembles *L. similis* of Knowlton (*Rept. on Fossil Plants Associated with Lavas of Cascade Range of Oregon*, Pl. V, Figs. 1 and 4) merely in the horizontal tertiaries and in the angle of the secondaries. Tip and base are, however, quite different in the two forms. The base of *L. perdita* comes nearest to being as blunt as that of *L. cascadia.*

Laurus cascadia leve var. *nova* (Duror) and *L. cascadia* (type) differ largely, in that the former is proportionately broader and with somewhat heavier veins.

Genus *Magnolia*

Magnolia nordenskioldi (Heer)

Heer: *Flora Foss. Arct.*, VII, "Grönlands," 123; Taf. CVIII, Figs. 2, 3; IV. "Spitzbergens," 82; Taf. LII, Fig. 1.

This reference is made doubtfully on certain fragments from the sandstone of F 844. The size of the leaf, strength, and irregular anastomosing of the secondaries of the veining are correct. The tertiaries, arising at right angles to the secondaries and dovetailing with the tertiaries from adjacent secondaries, are also similar to Heer's figures. The form is noted from the Canadian Miocene—really Eocene.

Genus *Populus*

Populus is represented by numerous more or less fragmentary remains, in which, however, many of the characters are fortunately plainly discernible. Three of Ward's species are believed to be present, besides one of Heer's. The three forms are noted from beds called Laramie, now considered of Fort Union age.

Populus amblyrhynca (Ward)

Ward: *U.S.G.S. Bull. No. 37* (1887), 20; Pl. VI, Figs. 1–8.

Reference of the forms to this species is made with great certainty. In the Cascade form the base is somewhat flatter than in Ward's figure, the identification resting chiefly upon the character of the thick tertiaries sent out from the inner side of the second pair of secondaries. The resemblance is closest to Ward's Figs. 2 and 3 of Pl. VI.

Populus cuneata (Newb.)

Newberry: *Later Ext. Floras*, pp. 31, 64.
Illus. Cret. and Tert. Plants, Pl. XIV, Figs, 1–4.
Lesquereux: *Cret. and Tert. Floras*, p. 225; Pl. XLVI, Fig. 5.
Dawson: "Cret. and Tert. Floras of Brit. Col. and N.W. Terr.," *Trans. Roy. Soc. Can.*, Sec. IV (1882), p. 32.
Ward: *U.S.G.S. Bull. No. 37* (1887), p. 19; Pl. IV, Figs. 5–8; Pl. V, Figs. 1–3.

One specimen was so called because the first pair of secondaries here, as in the figures of *P. cuneata*, leave the midrib about 5 mm. up from the attachment of the petiole.

Populus zaddachi (Heer)

Heer: *Flora Foss. Arct.*, I, 98; Taf. VI, Figs. 1–4; II, 468; Taf. XLIII, Fig. 15*a*; Taf. XLIV, Fig. 6.
Flora Foss. Alaska, p. 26; Taf. II, Fig. 5*a*.
Lesquereux: *Mem. Mus. Comp. Zoöl.*, VI (1878), No. 12; Pl. VIII, Figs. 1–8.

This form is referred to this species because it is remarkable for its larger size. Judging from a fragment, the complete leaf was about 4×6 inches, as is that of Lesquereux in Fig. 8. There are three pairs of secondaries, the lowest very faint, the innermost very strong and straight. The margin is not preserved. Lesquereux notes this form from Upper Miocene, but one of Heer's examples is Miocene of Spitzbergen (equal to Eocene).

Populus artica (Heer)

Heer: *Flora Foss. Arct.*, IV, Taf. XXXII.

The Cascade form is very questionably referred to this species. There is a single smooth, faintly veined leaf from beds F 831+50 whose base is almost cordate but otherwise agrees with *P. artica*, and even similar bases are to be found in Heer's figures.

Genus *Protoficus* (*Saporta*)

Protoficus is represented by many beautifully preserved specimens from shales of F 831+50. They are apparently all of one new species.

Protificus fossi N.Sp. (Figs. 9 and 10)

The leaf is lanceolate, broadest just at the middle; the apex is a short, sharp point; the margin is irregularly, sharply dentate to one-third of the way to the base, then wavy to crenulate. The base is blunt to slightly tapering and not absolutely symmetrical, as seen in Fig. 10. The midrib is straight and moderately strong, with seven pairs of secondaries. The members of each pair are not strictly opposite, except above, where they are strongly bowed outward. The nervation has a palmate aspect, since the two lowest pairs of secondaries come off at the top of the petiole, and the rest only above the lower half of the leaf, or even higher. Six pairs of tertiaries arise from the second pair of secondaries and form loops near the margin. Small nerves extend from these loops into the teeth. All the other tertiaries are at right angles to the midrib in parallel "horizontal" rows. One small specimen measured 11 cm. in length by 4.5 in breadth (Fig. 10); the type (Fig. 9) is 9 cm. in width by 15 cm. in length.

The tertiary veination is similar to that of *Ficus tiliafolia* and there is also something of the same palmate look; but in *Ficus* the gap to the next pair of secondaries is only one-third as exaggerated as here. The margin of *F. tiliafolia*, moreover, is entire.

Protoficus zelleri of Lesquereux (*Bull. Mus. Comp. Zoöl.*, XVI, No. 12 [1888], 50), while described as notably palmate, is more cordate at the base and the border is merely crenulate. This leaf is only 7×5.5 cm.

FIG. 9.—*Protoficus fossi.* ($\frac{1}{4}$ natural size.)

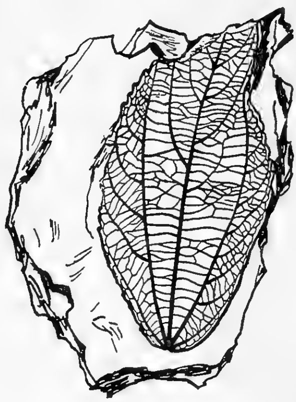

FIG. 10.—*Protoficus fossi.* ($\frac{1}{2}$ natural size.)

Protoficus inequalis (Newb.) (*Proc. U.S. Nat. Mus.* V [1882], 512) is not described as having a gap between the lower end and upper secondaries and is notably unsymmetrical at the base. The margin is merely undulate.

GENUS *Pterospermites*

Pterospermites whitei (Ward) (Fig. 8)

Ward: *U.S.G.S. Bull. No. 37* (1887), p. 94; Pl. XLI, Figs. 5 and 6.

The species from the shales of F 831+50 is in marked contrast to the foregoing *Protoficus*. The identification is rather certain, although the base and tip are wanting. The midrib is not quite so sinuous above as it is in Ward's figures. The form is noted from the Laramie of Montana, now conceded to be Fort Union in age.

GENUS *Sapindus*

Sapindus obtusifolius (Lesq.) (Fig. 8C)

Lesquereux: *Hayden Surv.*, VII (1873), 266; Pl. XLIX, Figs. 8–11; VIII, 235; Pl. XLVIII, Figs. 5–7.
Knowlton: *U.S.G.S. Bull. No. 204*, p. 79.

The form is represented by numerous fragments such as are shown in Fig. 8, C. Better specimens (not figured) show the typical, unequal base and the alternately stronger and weaker secondaries. Similar forms are described by Knowlton from the Fort Union of Montana and North Dakota.

The writer wishes to express her indebtedness to Dr. Arthur Hollick of the New York Botanical Gardens for valuable help and suggestions.

REPORT ON THE FAUNA OF THE MALONEY SERIES

Rafinesquina (Hall) *deltoidea* (Conrad) (Fig. 11, A, B, C, D), *Leptaena deltoidea* Conrad, *Am. Geol. Rept.*, 1838, p. 115.
Strophomena deltoidea Davidson, *Foss. Brachiopoda*, III (1864–71); Pl. XLII, Figs. 1–5; Pl. XXXIX, Fig. 22.
Streptorhyncus (*Strophonella*) *deltoidea* (Hall, 1883), *Sec. An. Rept. State Geol. of New York*, Pl. XLII, Figs. 1–7.
Rafinesquina deltoidea Hall, *Pal. New York*, VII; Part. I, p. 281; Pl. IX*a*, Figs. 1–5. (Same figures as in references above.)

The Cascade specimens are referred with slight hesitation to *Rafinesquina deltoidea*, notwithstanding the fragmentary nature of the material. There is a strong resemblance to *Plectambonites* (*Leptaena*) *sericius* (Sow.) var. *rhombica*, as figured in Davidson's *Fossil Brachiopoda*, V, 169; Pl. XII, Figs. 4–7. However, the remains of the muscle scars, and more especially the concentric wrinkles, stronger near the hinge line, are characteristic of *Rafinesquina*. The alternate striation, such as the Cascade specimens show, is described in both forms, "every fifth or seventh striation markedly stronger." Here generally every fifth striation, though rarely every seventh, and occasionally every second, is emphasized. Such a variation, and another in the profile of the shell, is noted by Professor M'Corq (quoted in Hall, *op. cit.*). In these specimens the most convex shell (Fig. 11, A, B) is not sharply flexed at any one point, while younger individuals, as in Fig. 11, C, show less arching, but a more sudden geniculation. The specimens are partly exfoliated and have a finely punctate surface.

Fig. 11, A, B, and D are of pedicle valves, and Fig. 11, C of a brachial valve. This last specimen is partly an impression of the

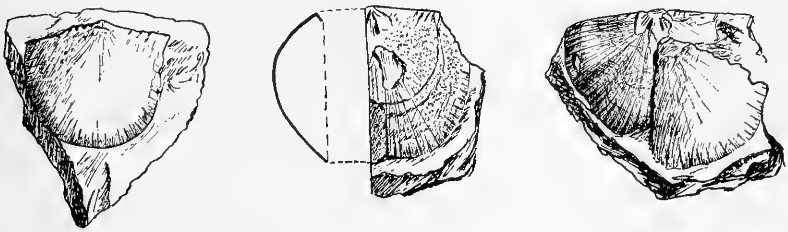

FIG. 11.—*Rafinesquina* (Hall) *deltoidea* (Conrad). A, B, and D, pedicle valves; C, brachial valve.

outer surface of the shell, since the striations show as grooves; but part of the true shell remains where the muscle scars are shown.

Illaenus americanus (Billings)

Billings (1859, quoted; 1865, quoted and figure copied): *Paleozoic Fossils*, I, 329; Fig. 316*a–d*.

Winchell and Ulrich: *Minn. State. Surv.*, III (1897), Part II, 714; Figs. (from above) 20, 21, 22, 23.

FIG. 12.—*Illaenus americanus* (Billings). A, front view; B, top view; C, side view.

A single specimen, the glabella and fixed cheeks, was found associated with the *Rafinesquina deltoidea*. All the features on these parts agree perfectly with Billings' figures. This specimen probably belonged to an animal one inch long, while Billings' forms ranged from two to three inches in length. Naturally, smaller forms have been noted, as in Grabau and Shimer, *Index Fossils*, p. 295, where one and one-fourth inches is given as the entire length.

Fig. 12, A is the front, Fig. 12, B the top, and Fig. 12, C the side view of the one specimen. The dotted line in Fig. 12, B gives the outline of the eye, which was destroyed in uncovering the fossil.

Both of these forms are index fossils of Trenton age. Naturally, they are not restricted to one bed, but in no case have they been recorded as younger than Ordovician.

The writer is indebted to Dr. Shimer and to Dr. Grabau for valuable help and advice.

"PUFF" CONES ON MOUNT USU

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Two days before the eruption of Mount Usu, in southwestern Hokkaido, Japan, the writer arrived at the foot of the volcano. He remained there for twelve days, watching every phenomenon, going without sleep the first five days. The first explosion occurred

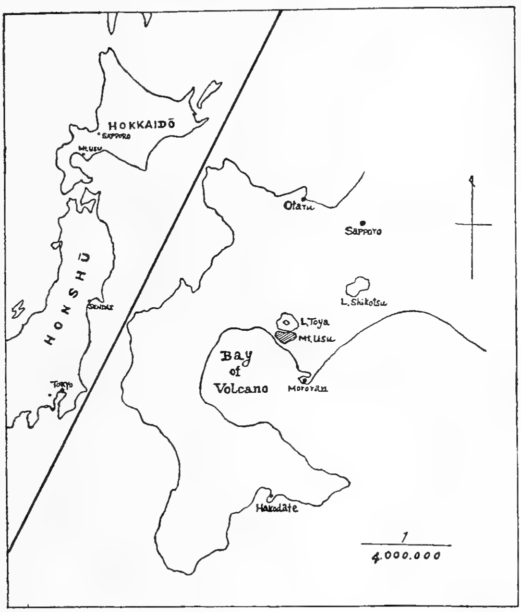

FIG. 1.—Sketch map of southwestern part of Hokkaido

on July 25, 1910, and others followed in rapid succession. Violent eruptions ceased in about ten days and the writer returned to Sapporo on August 7. He again visited the volcano in September and in December of the same year, in May and October, 1911, in

May, 1912, and in May, 1913. Many interesting facts were observed which will be published later in another paper. Here attention is to be called only to certain peculiar cones formed on one of the mud flows.

The main eruption of the volcano caused the formation of forty-five small explosion craters on its northern slope. These craters extend from east to west in two zones along Lake Toya,[1] north of the volcano. During the first few months after their formation innumerable bombs and considerable quantities of sand and ashes were blown from every craterlet. From five of them mud flowed at different times, the flow from a small crater at the southern foot of the parasite cone Nishi-Maruyam being especially interesting. This crater is located on a gentle slope of about five degrees, and is 100 meters in diameter. For twenty days it intermittently threw out columns of hot water, occasionally mingled with mud, to a height of about 60 meters. Approximately two hundred eruptions occurred per day at intervals of from three to thirty minutes. A mass of mud, estimated by the writer at 230,000 cubic meters, spread out in a sheet averaging 1.5 meters in thickness, over an area 200 by 700 meters. It covered a farm, where it destroyed a thousand apple trees and other crops, and pushed three houses in the direction of the lake and finally destroyed them.

The mud consists mainly of plagioclase, hypersthene, augite, magnetite, and hematite, and resembles the material of the sea sand at the west foot of Mount Usu. It differs, however, in also containing fragments, from the size of peas to that of nuts, of compact gray to coarse black andesite. These fragments are not usually exposed at the surface of the mud, having sunk on account of their greater size.

The materials thrown out by the crater were highly heated and sticky at the time of their eruption, and contained a great amount of water and gas. For several months the flow continued steaming, but as time passed and the moisture and gases became exhausted, it ceased, and the mass became harder and harder. A year after

[1] Lake Toya is a depression lake, according to T. Kato (*Report Earthquake Investigation Committee*, Vol. LXII).

the eruption the surface of the flow was so hard that it was difficult to discern footprints upon it, and specimens could be obtained only with the aid of a pointed stick or a hammer. At this time the surface was flat except for low, wavy undulations and very irregular sun cracks.

A year later the writer found the flow covered with thousands of small cones, each of which had an opening which was compara-

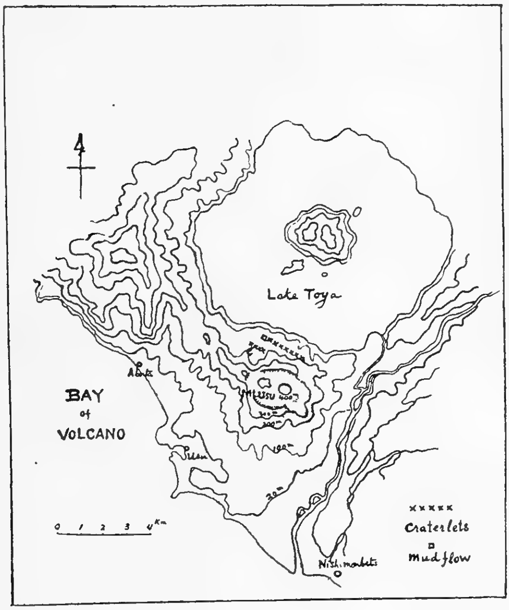

FIG. 2.—Map of Mt. Usu and vicinity, showing the position of craterlets and mud flow here described.

tively large but of no particular shape. The cones were of different sizes, the smallest being 0.5 meter in diameter and 0.1 meter in height while the largest was 3.0 meters in diameter and 1.5 meters in height. They were irregularly arranged on the flow at intervals of 10 to 30 meters, and were either dome-shaped or resembled a common bell with a slope of forty degrees.

The cause which produced these elevations is the same as that which forms small pitted cones when any viscous substance is boiled, namely, the escape of gases or vapors through the mass and the breaking of the bubble at the surface. After the cessation of the mud flow the surface dried and sun cracks were formed. The gases near the surface rapidly escaped through these openings, but those imprisoned near the bottom of the mass were unable to do so, the upper part only having dried out. Later, by the coalescing of the small bubbles, the remaining gases united beneath the surface in reservoirs of greater size. The accumulated pressure finally became great enough to force a passage through the mud to the surface, the sudden escape of the gas forcing the mud upward

Fig. 3.—The largest "puff" cone. Photo taken by the writer, May 16, 1912

to form cones. The other mud flows in this district, being thinner, dried out more rapidly, and no cones were formed.

The writer has been unable to find descriptions of any such phenomenon in the case of other mud flows, although similar elevations occasionally occur on lava flows. He therefore suggests the name "puff cones."

No new cones were formed after the summer of 1912, the greater part of the gas having been expelled. Since that time weathering has begun to reduce the slopes, so that, in all probability, no trace of this fantastic phenomenon will remain after a few years.

ORIGIN OF FOLIATION IN THE PRE-CAMBRIAN ROCKS OF NORTHERN NEW YORK[1]

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INTRODUCTION

Data bearing upon the problem of the origin of foliation in the pre-Cambrian rocks of northern New York have been gathered during the last ten years by the writer while he was engaged in the geological surveys of various quadrangles in the Adirondack Mountain region. In the attempt to explain the origin of the foliated structures of the rocks, examples and analogies from other parts of the world will be introduced, and it is hoped that the conclusions reached may have a wider application than to the Adirondack region alone.

This paper is not much concerned with criteria for the determination of original igneous or sedimentary character of the rocks. The conclusions reached are almost wholly based upon observations made upon rocks which have been generally recognized as quite certainly either igneous or sedimentary. Rocks of rather doubtful origin are frequently met in minor quantity, but these may be disregarded in the present discussion.

The strata all belong to the very ancient Grenville series, including various gneisses and schists, together with crystalline limestone and quartzite. The chief criteria for the determination of their sedimentary origin are: distinct banded structures, often showing alternating layers of widely different composition sharply separated from each other; presence of extensive bodies of limestone and quartzite interbedded with the gneisses; dissemination of graphite flakes through many of the rocks; and the very common occurrence of garnet in many of the rocks, and the less common occurrence of sillimanite.

[1] Published by permission of the Director of the New York State Museum.

The metamorphic rocks of igneous origin, given in regular order of geologic age, comprise the anorthosite series, the syenite-granite series, and the gabbros, all of which show quite varied degrees of metamorphism. All are intrusive rocks and younger than the Grenville. Among the criteria for recognizing their igneous origin are: preservation of original rock textures, such as the porphyritic and the diabasic; relative homogeneity in large bodies; common occurrence of distinct inclusions of older rocks; intrusive contacts, often with dikes from the large bodies penetrating the older rocks; very common occurrence of zircon and zoisite in fresh, well-crystallized grains.

THE GRENVILLE AND ITS FOLIATION

FOLDING OF THE GRENVILLE

Character of the Grenville series.—The Grenville series comprises the oldest rocks of the Adirondack region, and they are, in fact, among the most ancient known rocks of the earth's crust. They consist of a great mass of thoroughly crystallized sediments, such as limestones, sandstones, and shales which have been changed to crystalline limestones, quartzites, and various gneisses and schists. A more or less well-developed foliation is always parallel to the stratification surfaces which are usually distinctly preserved in spite of the crystallization. Granulation is not common. Grenville strata are well represented throughout the Adirondack region, their distribution being very irregular or "patchy" in small to large areas. They are considerably less extensive than the later (intrusive) syenite-granite series, which latter, together with the Grenville, makes up the great bulk of Adirondack rocks. Neither top nor bottom of the Grenville series is known, though thicknesses of from 10,000 to 20,000 feet are actually shown in single sections, and the total thickness is doubtless much greater. Adams and Barlow report a Grenville section about eighteen miles thick in Ontario. The strata are often tilted at high angles or very moderately folded, and sometimes locally contorted. There is a general tendency toward a northeast-southwest strike of Grenville masses in the Adirondacks, but there are many important exceptions.

Grenville series generally regarded as highly folded and compressed.—It has been quite generally assumed by all (including the writer) who have carried on geological work in the Adirondack region that the Grenville strata have been severely compressed and folded as well as thoroughly metamorphosed and foliated by the compression. A few citations from the more recent publications will illustrate the ideas usually held. "There is abundant proof that the rocks have undergone great compression and have been folded and faulted on an extensive scale."[1] The Grenville rocks "have been greatly compressed and intricately folded and plicated."[2] "The old sedimentary rocks have undergone complete recrystallization, entirely obliterating their old textures, and, as a result of severe compression, have had a development of cleavable minerals along certain parallel planes, the mineral particles having a common orientation."[3] "In pre-Potsdam time the pre-Cambric sediments had been tremendously folded and faulted and intruded at great depths."[4] "After the intrusions the whole region was subjected to intense compression and metamorphism when the gneissic or foliated structure of all the rocks was developed."[5]

An alternative hypothesis.—That the Adirondack Grenville strata are more or less folded is admitted at the outset, but, in the light of recent studies, the writer doubts the interpretation of the folded, tilted, and foliated structures as due to intense lateral compression. Certain evident features of the Grenville strata and related intrusives are directly opposed to this interpretation, while all of the structural features may be much more satisfactorily explained in another way. Thus it is conceived that the originally horizontal, or at most only very moderately folded, Grenville strata were much broken up and tilted in masses great and small, and in other cases actually domed, by the irregular upwelling of the great bodies of magma (especially syenite-granite) under only very moderate lateral pressure. This alternative explanation will be

[1] D. H. Newland, *New York State Mus. Bull.*, No. 111, 1908, p. 20.

[2] H. P. Cushing, *ibid.*, No. 145, 1910, p. 9.

[3] *Ibid.*, No. 95, 1905, p. 400.

[4] I. H. Ogilvie, *ibid.*, No. 96, 1905, p. 478.

[5] W. J. Miller, *ibid.*, No. 170, 1914, p. 77.

developed at some length in its application to the Adirondack region.

Evidence against intense folding of the Grenville.—In spite of the assumption of severe lateral compression, no large-scale example of intense folding of the Grenville has ever been positively demonstrated in the Adirondacks, and this in the face of the fact that many hundreds of square miles have been mapped in detail. Describing the Grenville structures of the Elizabethtown–Port Henry quadrangles, Kemp says: "The dips are prevailingly moderate and the ancient sediments appear to have been folded or tilted to only a moderate degree."[1] Regarding the Long Lake quadrangle, Cushing says: "Nearly east and west strikes prevail, and the prevalent dip is southward. This either indicates comparatively little folding, or else isoclinal folding, or else that the foliation does not coincide with the bedding and so does not bring out the folding. It is not possible to demonstrate which of these alternatives is the true one, though the second is very unlikely, and all the direct evidence obtainable is against the third."[2] He also states that in the largest Grenville belt "the dips are so flat that they can seldom be made out with certainty."

The writer[3] has described a structure section in the Broadalbin quadrangle four miles long across the strike of Grenville strata with dips of 20–30° to the southeast. The exposed thickness of Grenville is about 10,000 feet with no repetition of beds due to possible isoclinal folding and no field evidence for profound faulting. Another Grenville section recently described by the writer[4] in the North Creek quadrangle is five miles long with a pretty uniform dip of from 40° to 50°, thus showing a thickness of some 18,000–20,000 feet of strata. There is no evidence of repetition of strata by either folding or faulting. The Grenville is extensively developed throughout this quadrangle, and all the available evidence points to only moderate deformation of the strata either by tilting or slight folding.

[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 85.

[2] H. P. Cushing, *ibid.*, No. 115, 1907, p. 485.

[3] W. J. Miller, *ibid.*, No. 153, 1911, p. 13.

[4] *Ibid.*, No. 170, 1914, p. 15.

According to Cushing, "the foliation strike over much of the Saratoga quadrangle is nearly east-west, and the dips are to the south and rather flat, seldom reaching 45°. As elsewhere, a great monocline of the rocks is suggested, and, as elsewhere, this makes a Grenville succession of enormous thickness, so thick as to suggest caution in the interpretation of the structure, and as to emphasize the probability of the alternative suggestion that the rocks are closely pinched and folded in a series of closed, overturned folds."[1] It is, however, by no means necessary to assume that such common occurrences of monoclinal dips may be due to isoclinal folding. The breaking up and tilting of many blocks or belts of Grenville strata into general parallelism with the upwelling bodies of magma could quite conceivably have taken place under only very moderate lateral compression at most, and, in such cases, monoclinal dips are just what would be expected. This matter will be more fully discussed below.

In the Little Falls, Remsen, Port Leyden, and Lake Pleasant quadrangles, which are also mapped in detail, the Grenville is only sparingly represented, but none of the field evidence points to profound folding of the strata due to lateral compression.

The recent (1913–14) survey of the Blue Mountain quadrangle by the writer has thrown important light on the structure of the Grenville series which is there extensively represented. The great Panther-Snowy mountain mass (altitude 3,900 feet) of syenite occupying the southern portion of the Blue Mountain and the northern portion of the Indian Lake quadrangles is completely bounded on the west, north, and northeast by an unbroken belt of Grenville (mostly limestone) whose strikes and dips show it to lap up on the flanks of the mountain mass of igneous rock for many miles. The curving strike of the igneous rock is also essentially parallel to that of the Grenville. It is evident that we have here a large-scale example of the raising or doming of Grenville over the surface of the great body of uprising magma, the general cover having been removed by erosion, leaving only the circumferential belt of Grenville strata. The higher portions of the syenite now rise fully 2,000 feet above the Grenville. This large-scale tilting

[1] H. P. Cushing, *ibid.*, No. 169, 1914, p. 30.

of Grenville strata is certainly not due to severe lateral compression, nor is there, in any part of the quadrangle, evidence of highly folded or compressed Grenville strata.

In the northwestern part of the Thirteenth Lake quadrangle the writer has examined Chimney Mountain, which is a mass of granitic syenite rising fully 900 feet above a valley on the west. Perfectly bedded Grenville rocks with dip of 50° lap over the whole western face of the mountain of igneous rock, and it seems certain that the tilt of the strata was produced by the rise of the magma.

We are thus led to conclude that none of the published Adirondack geologic maps or available data afford any reason to believe that the Grenville strata were ever profoundly folded or compressed. There is, however, much tilting on large and small scales and some very moderate folding. Such structures may be readily accounted for simply by the irregular intrusion or upwelling of great bodies of more or less plastic magma which broke up, tilted, and lifted or domed the masses of Grenville.

Grenville structure in the Thousand Islands and Ontario regions.— The Thousand Islands district forms the connecting link between the Adirondack and Canadian pre-Cambrian areas, and lies to one side of the region discussed in this paper. Having recently studied the Thousand Islands district, Cushing says: "The Grenville beds are now found for most part in highly inclined condition, dips of less than 45° being relatively rare, while those approaching verticality are common. . . . . It has also been shown that the dip is not everywhere in the same direction, but that, with the general direction of strike to the northeast-southwest, the dip, while prevalently to the northwest, becomes at times southeast. . . . . The highly tilted condition of the rock series, and the changing dips seem certainly indicative of folding."[1] He then describes a prominent belt of Grenville strata which he believes has a synclinal structure. But, accepting the existence of this syncline, does such a structure prove the region to have been subjected to an intense force of compression? Large bodies of granite bound this Grenville belt on either side, and it is quite conceivable that the uplifting effect of the intruding masses, possibly accom-

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 109.

panied by some crowding or squeezing of the Grenville between the igneous masses, may have produced this very structure. Cushing also argues that "the general parallelism of the foliation of all the pre-Cambric rocks" affords "evidence of thoroughgoing compression of much later date" than the granitic intrusions. But, as will be shown below, such parallelism of foliation is not necessarily due to severe lateral compression. It should be said, however, that in the Thousand Islands region the granitic and Grenville rocks do seem to be more strikingly arranged in parallel northeast-southwest belts than is usual throughout the Adirondacks. It is possible that considerable orogenic forces did operate across the area from the Thousand Islands region northward into Canada, where also the parallelism is notable. Recent study of the Canton quadrangle seems to indicate considerable folding there. Adams and Barlow, in their description of the Haliburton and Bancroft areas, state that the batholiths "are elongated or arranged in lines having a prevailing direction of about N. 30° E., to which direction the strike of the rocks (Grenville) lying between the batholiths in general conforms. This direction constitutes, so to speak, the general strike of the country, and shows that its present structure has been determined, not only by the rise of granite magma, but by the presence of a second factor in the form of a tangential pressure, acting simultaneously."[1] But it is not at all certain that this tangential pressure was really orogenic in character. Even a very moderate compressive force, not at all sufficient thoroughly to fold and plicate the rocks, acting upon the rising magmas would readily account for all the structural phenomena now visible.

Variation of foliation strikes.—Even if we grant a very considerable lateral compression in the Thousand Islands–Canadian region, the Adirondack area, fully a hundred miles across and to the southeast, does not necessarily come under the same category. In fact, while parallelism of syenite-granite and Grenville rock belts and foliation are common in the Adirondacks, there are so many important variations from a northeast-southwest strike that any generalization regarding such a strike of the rock belts is of little

[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6,* 1910, p. 16.

significance. A glance at the accompanying sketch map (Fig. 1) will emphasize the fact that various large areas show strikes distinctly out of harmony with a northeast-southwest structure. The unpublished Lake Placid geologic map shows exceedingly variable strikes. Many variations also occur within most of the other quadrangles, more especially the North Creek, Long Lake, and Blue Mountain (unpublished). Within the Lake Pleasant quadrangle, the foliation strikes relatively uniformly northwest-

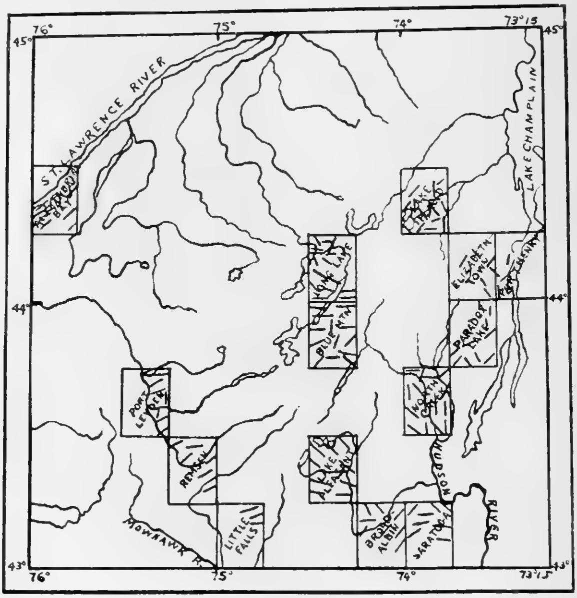

FIG. 1.—Sketch map of the Adirondack region showing generalized strikes of foliation within those quadrangles which have been mapped in detail.

southeast or just at right angles to the assumed force of compression of the region. Papers by Professor Kemp and assistants in the thirteenth, fifteenth, seventeenth, eighteenth, and nineteenth annual reports of the New York state geologist contain many very variable strike observations in the eastern Adirondacks aside from the quadrangles of the accompanying sketch map. It thus seems clear that the Adirondack rocks show strikes which could not possibly have been produced by a severe lateral pressure exerted across the whole region, for any such pressure, great enough to produce close folding, would have produced a high degree of parallelism of strikes throughout the region.

Local contortions.—Local contortions or sharp folds in the Grenville strata are by no means uncommon, being especially prominent in the limestones and closely associated hornblende and pyroxene gneisses. Such plications have usually been regarded as strong evidence for large-scale folding, being thought of as minor folds superimposed upon large-scale folds. Now, in the first place, it is the writer's experience that such local contortions or plications are very largely confined to the limestone beds, which are easily the most plastic of all Adirondack rocks. In the second place, the crowding of a batholithic magma against the invaded Grenville strata, or the catching of a mass of Grenville between two batholithic magmas, would readily account for more or less local contortions or even puckering of strata without any assumption of orogenic or severe lateral pressure exerted throughout the region. The shouldering action of the upwelling magmas must have produced rather severe local pressures. Regarding the Glamorgan batholith of Ontario, Adams and Barlow say that the Grenville rocks forming the periphery on several sides, "being squeezed between this and the adjacent batholiths, are too highly contorted . . . . to display the prevailing dip distinctly."[1] Evidently such structures do not necessarily call for severe regional compression.

Summary.—To summarize, there is no known evidence within the Adirondack region that the Grenville strata have ever been highly folded or severely compressed, while many broad Grenville belts are known to be only very moderately folded, and many masses, large and small, are merely tilted or domed at various angles. Very locally the strata are sometimes contorted or plicated. The structural relations are therefore best explained as having been the result of slow irregular upwelling of the more or less plastic magmas, probably under very moderate compression, whereby the Grenville strata, previously deformed very little or none at all, were broken up, tilted, and lifted or domed. The stratification surfaces of the Grenville were thus swung into general parallelism

[1] Adams and Barlow, *Geol. Surv. Can.*, *Mem. 6*, 1910, p. 15.

with the slow-moving magmatic currents. According to this view, individual large blocks or belts of Grenville strata, or several such blocks or belts separated by intrusive masses, with strike of intrusive masses parallel to Grenville stratification, would be expected to show monoclinal dips; some Grenville masses were shifted around in irregularly rising magmas so as to show various strikes according to directions of movement of the magmas, and hence would not be expected to exhibit monoclinal dips; some Grenville masses were merely domed over bodies of rising magma and would exhibit more or less quaquaversal strikes and dips; while still other Grenville masses were probably bent or even considerably folded into synclines by being caught between bodies of magma upwelling at about the same rate. Isoclinal or close folding on a large scale would scarcely be expected.

In all of this discussion it is important to bear in mind that the Adirondack intrusives occupy a much greater extent than the invaded Grenville rocks, and that, in spite of their intrusive character, they everywhere seem to occupy the position of a fundamental or underlying gneiss. It appears to have been literally true that the Grenville strata were irregularly floated on a vast body of magma, the magma in many places having either arched up or broken through the strata.

ORIGIN OF GRENVILLE FOLIATION

We have just shown that the Grenville strata have never been highly folded or compressed. It is therefore necessary to explain the metamorphism of the strata on some other basis than that of subjection to severe lateral pressure. The old sediments are thoroughly crystallized, and it is certain that they have been reorganized into new minerals under deep-seated conditions; that is to say, they have undergone anamorphic metamorphism. But evidently we are here dealing with a case of essentially static, rather than dynamic, metamorphism.

Origin of parallelism of Grenville foliation and stratification.—The universal parallelism of Grenville foliation and stratification is a fact of prime importance. If the Grenville and accompanying great intrusives had been subjected to compression severe enough to develop the distinct foliation, is it not remarkable that the stratification surfaces have never been obliterated and cleavage developed instead, and also that the stratification and foliation are always parallel? Now, the stratification of the highly crystalline Grenville is remarkably well preserved. Also, unless we assume intense isoclinal folding, so that mineral elongation could everywhere have taken place at right angles to the direction of lateral pressure, the parallelism of stratification and foliation cannot be accounted for by crystallization under severe lateral pressure. We have already shown, not only that there is no positive evidence for such isoclinal folding, but also that there is much positive evidence against any more than the tilting, or, at most, very moderate folding, of the Grenville on large scales.

Again, if the foliation of the Grenville were essentially a dynamic process—that is to say, the result of regional compression after the great igneous intrusions—why should the Grenville be notably less foliated and granulated than the intrusives? (See below.)

We are thus forced to the only alternative conclusion, namely, that the Grenville foliation was developed during the crystallization of essentially horizontal strata under heavy load of overlying material. Those minerals which cause the foliation were elongated during crystallization under heavy downward pressure where conditions of warmth and moisture were also favorable. According to this conception the parallelism of foliation and stratification is precisely what would be expected. It is quite generally assumed that static pressure, that is to say, simple downward pressure, "to the amount exerted in the upper part of the earth's outer crust, appears to have little metamorphic effect."[1] In dealing with the very ancient Grenville, however, it must be remembered that the material now at the surface was once very deeply buried. The thickness of the Grenville series in the Adirondacks is at least some miles and more than likely many miles. Adams and Barlow[2] have recently estimated a thickness of nearly eighteen miles for the Grenville strata in Ontario. It is also definitely known that during pre-Cambrian time the Grenville strata were subjected to tre-

[1] L. V. Pirsson, *Rocks and Rock Minerals* (1909), p. 335.

[2] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 33.

mendous erosion when at least some miles, and quite possibly many miles, in thickness of materials were removed. Thus it seems clear that much of the Grenville rock now visible was once far more deeply buried than any known body of sediments since the beginning of the Paleozoic. Conditions of downward pressure and temperature were, therefore, more than usually favorable for static metamorphism. On the basis of static metamorphism it is not necessary to account for a high degree of metamorphism, because the Grenville series, though thoroughly crystalline, is mostly only moderately foliated with relatively little granulation, and with stratification generally well preserved. It may also be suggested as a possibility that actual crystallization did not begin until an early stage in the intrusion of the slowly upwelling magmas when additional heat for regional metamorphism was supplied.

Evidence from other sources.—Experimental evidence is also suggestive in this connection. Thus, Becker and Day[1] have proved that crystals in general have a strong tendency to grow (or elongate) most rapidly at right angles to the direction of pressure. According to Wright,[2] cubes of glass formed by melting together wollastonite, diopside, and anorthite heated to the state of incipient crystallization under vertical pressure, showed, under the microscope, that the three minerals crystallized with long axes at right angles to the direction of pressure. Experimental evidence, therefore, strongly supports the possible development of elongated crystals in the Grenville sediments under conditions of static metamorphism.

Van Hise has suggested, regarding the parallelism of foliation and bedding in the Grenville series, that "vertical shortening and consequently horizontal elongation below the level of no lateral stress may have *begun* the process."[3] The writer views this as essentially the *whole* process, instead of assuming, as Van Hise did, that foliation parallel to bedding continued to develop under certain peculiar conditions when the rocks were subsequently folded. The explanation of foliation parallel to bedding is greatly simplified when it is not necessary to consider severe compression of the region.

[1] Becker and Day, *Proc. Wash. Acad. Sci.*, VII (1905), 283–88.

[2] F. E. Wright, *Am. Jour. Sci.*, 4th series, XXII (1906), 226.

[3] C. R. Van Hise, *U.S. Geol. Surv., 16th Ann. Rep.*, Part I, p. 773.

Describing the metamorphism of the Shuswap pre-Cambrian series in the Canadian Rockies, Daly says: "It is clear that the Shuswap series has not been seriously affected by dynamic metamorphism. The strata and most of the injected granites were completely or almost completely recrystallized while the strata lay nearly flat. In some localities the effects of dynamic metamorphism have been superposed on those due to previous static metamorphism."[1]

Orientation of Grenville inclusions.—Another fact of importance in connection with the origin of Grenville foliation is the occasional occurrence of well-foliated inclusions of Grenville gneisses variously oriented in the great intrusive bodies. Twenty years ago, in St. Lawrence County, Smyth, noting irregular inclusions of black gneiss in granite, said: "The two foliations, that of the black masses and of the (granite) gneiss, range from parallel with, to perpendicular to, each other."[2] He also noted a similar arrangement of Grenville laminated gneiss inclusions in syenite in Jefferson County. The writer has observed similar phenomena on small and large scales at various localities. Kemp has recently noted inclusions in massive anorthosite and says: "The foliation of the fragments runs in all directions, even in an area of a few square yards. The inference is drawn that the Grenville gneisses were already strongly metamorphosed when the anorthosites entered."[3] It is thus clear, in spite of the usual assumption to the contrary, that the foliation of the Grenville could not have been the result of lateral pressure brought to bear after, or even during, the intrusion of even the oldest of the great igneous masses.

General absence of granulation.—Another fact favoring a process of essentially static metamorphism as opposed to that of dynamic metamorphism is that the Grenville gneisses are, as a rule, comparatively little granulated. Some rather local granulation is to be expected because of magmatic movements, especially where Grenville masses have been crowded against the upwelling magmas. The great intrusive syenite-granite series is very notably more

[1] R. A. Daly, *Geol. Surv. Can., Transcont. Excur. C 1, Guidebook 8,* 1913, p. 132.

[2] C. H. Smyth, *15th Ann. Rep. New York State Geologist,* 1895, p. 491.

[3] J. F. Kemp, *Geol. Soc. Am. Bull.,* XXV (1914), 47.

granulated than the Grenville series. How is this fact to be explained if both series have been subjected to strong regional compression after the intrusions?

THE SYENITE-GRANITE SERIES AND ITS FOLIATION

Character of the syenite-granite series.—The main bulk of syenites and granites in the Adirondacks are regarded by the writer as facies of a single great body intrusive into the Grenville, the intrusives being much more extensively exposed than the Grenville. Perfect gradations from basic (dioritic) facies of syenite to true granite are commonly shown, a quartz syenite being the prevailing rock. As regards granularity, structure, and mineral composition, the members of the syenite-granite series are very variable. The granularity ranges from fine to coarse grain, with medium grain decidedly prevalent. A porphyritic texture is sometimes well developed. Granulation is common, especially in the more acidic rocks, the feldspars generally being notably more crushed than the other minerals. In structure the rocks range from very faintly gneissoid to very clearly gneissoid or sometimes almost schistose, the foliation being accentuated by the roughly parallel arrangement of the dark-colored minerals. The minerals, especially quartz and feldspar, often show more or less flattening or elongation parallel to the foliation. In general the more highly foliated rocks appear to be most granulated. In mineral composition the range is from dioritic types rich in plagioclase, orthoclase, pyroxene, and hornblende; to syenite rich in microperthite, orthoclase, and hornblende or augite together with some quartz and plagioclase; to granite rich in microperthite, quartz, orthoclase, and microcline together with some plagioclase, hornblende, and biotite. Various accessory minerals in smaller amounts also occur. The color of the typical fresh syenite is greenish gray which weathers to light brown, while the fresh granite colors vary from greenish gray to light gray and pinkish gray to almost red. In common with the Grenville, the syenite-granite foliation shows a tendency toward a northeast-southwest strike, with parallelism of syenite-granite and adjacent Grenville quite common, though there are many notable exceptions.

Northeast-southwest structure of rocks.—We have shown that the Grenville series has never been closely folded or severely compressed, and that its foliation was not caused essentially by lateral pressure. The syenite-granite masses, being younger than an intrusive into the Grenville, cannot, therefore, have had their foliation developed chiefly by lateral pressure, though the probable existence of a very moderate lateral pressure is admitted.

In spite of many important exceptions, there is some tendency toward a general parallel northeast-southwest to east-west strike of Adirondack rock masses (Grenville and syenite-granite) and foliation. One view, clearly stated by Cushing, is that "since the rock [granite] solidified it has been subjected to compression, together with the Grenville rocks, giving to each a foliation parallel to the other, and elongating the batholiths in a northeast-southwest direction."[1] At another place he refers to this compression as "thoroughgoing" and of much later date than the granite intrusion. Cushing suggests the possibility of the development of "a similar and parallel foliation"[2] during the solidification of the batholiths due to their shouldering pressure exerted upon the adjacent rocks during the intrusion, but he says that if any such foliation developed it was obliterated by subsequent compression.

The writer's view is that the general northeast-southwest structural parallelism was brought about by just enough tangential compression to control the general directions of the upward-moving batholithic magmas. Accordingly, the intrusive bodies were more or less elongated during the process of intrusion, and there must have been a strong tendency for large and small bodies of previously horizontal, or only slightly deformed, Grenville strata to have been caught up and arranged with their long axes and foliation parallel to the magmatic currents, while the foliation of the intrusives would also have developed, as a sort of flow structure under moderate pressure, parallel to the magmatic currents. This pressure was doubtless in part due to the shouldering effect of the intrusives upon the adjacent rocks. In other words, the syenite-granite gneisses are "primary gneisses." Thus we should

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 10.

[2] *Ibid.*, No. 145, 1910, p. 102.

expect a general northeast-southwest strike of both rock masses and foliation of Grenville and intrusives to be of common occurrence.

A statement made by Smyth twenty years ago regarding black gneiss inclusions in the syenite-granite series of St. Lawrence County is significant in this connection: "The parallel arrangement of the neighboring bands [inclusions] doubtless results from currents in the molten magma, which would tend to produce such a result. It is probable that the breaking into blocks resulted, in part, from strains applied after the magma was in a pasty and partially crystallized state. The blocks were more or less widely separated, and the intervening space was filled by the magma which flowed around the blocks without destroying their angular contour, and, at the same time, often produced an obscure flow structure in the gneiss parallel to the sides of the inclusions."[1] The bandlike inclusions here described by Smyth are seldom more than a few rods long, but the writer believes the principles set forth are applicable on a much larger scale throughout the Adirondack region.

Such parallelism of structural features does not, therefore, demonstrate that the rocks have been thoroughly compressed subsequent to the syenite-granite intrusions. The northeast-southwest structural features here referred to are more pronounced in the Thousand Islands region than is usual throughout the Adirondacks, and this may be readily explained by granting somewhat greater lateral pressure during the intrusion in the first-named region. In any case it is necessary to assume only very moderate compression—far less than would have been necessary to elongate the batholiths and develop distinct foliation in them after their complete solidification.

Exceptions to northeast-southwest structure.—There are many exceptions to the general northeast-southwest structural arrangement, and these prove that no severe tangential compression could ever have been exerted throughout the region after or during the intrusions. Among such exceptions are sharp variations in strike of groups of inclusions of well-foliated Grenville gneiss in the intrusives. Examples have already been cited. If the whole region has been subjected to compression thoroughgoing enough to flatten

[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist*, 1895, p. 491.

out batholiths and develop foliation after the consolidation of the magmas, how are these sharp variations in strike of Grenville inclusions to be accounted for? According to the writer's view, such inclusions present no difficulties, because their foliation was produced prior to the intrusions, and some fragments, especially those caught up late in the stiff, nearly consolidated magmas with poorly defined currents, would not have been swung into parallelism in the uprising magmas.

Also there are important exceptions to parallelism of foliation of adjacent syenite or granite and Grenville gneisses in relatively large areas. A few examples will suffice: eastern side of Port Leyden quadrangle where Grenville with north-south strike is surrounded with syenite with strike N. 30° E.; northwest corner of North Creek quadrangle (see geologic map); near northeast corner of Lake Pleasant quadrangle (see geologic map); northwest of Indian Lake Village; one mile west of Long Lake Village; and in the Broadalbin quadrangle where the large areas of Grenville and adjacent syenite-granite show very different strikes. If the foliation has been produced by compression after the intrusions, how are such sharp differences in strike to be accounted for? Granting the writer's conception that the Grenville was foliated prior to the intrusions, and that the syenite-granite foliation was the result of magmatic flowage, it is to be expected that the magmatic currents would occasionally have broken across the Grenville and its foliation.

Very strong evidence against the development of foliation by compression of the great intrusives is the frequent occurrence of sharp variations in the strike of the foliation, often within short distances. Examination of the Long Lake, North Creek, and Lake Pleasant geologic maps, upon which foliation strikes are plotted, shows many strikes in granite or syenite ranging from parallel to right angles to each other, often within distances of a mile or two. Similar foliation variations occur upon the writer's Blue Mountain and Lake Placid geologic maps, not yet published. How can such foliation variations possibly be explained as due to lateral pressure? If due to compression of the whole region, should not the foliation always strike essentially at right angles to the compressive force?

If, however, we regard the foliation as essentially a sort of flow structure, such phenomena are readily accounted for as due to local variations in the magmatic currents.

Curving strike of foliation.—Still another piece of evidence, though less commonly shown, is the existence of certain broad, sweeping curves in the foliation of syenite or granite. The North Creek, Lake Pleasant, and Long Lake geologic maps show such features. When larger areas of the Adirondacks are mapped in detail, it is probable that more and better examples will be brought to light.

An excellent case of curving of foliation on a large scale is in the Panther-Snowy mountain mass above described as extending nearly across the southern portion of the Blue Mountain sheet and the northern portion of the Indian Lake sheet. The great mass of syenite shows an almost perfect radiation of foliation dips from its center toward the west, north, and east. The only reasonable explanation of such an arrangement of dips is that the foliation was produced as a flow structure in the uprising magma, the most rapid currents having been toward the center of the mass. In the writer's opinion, such a large-scale curved arrangement of foliation strikes and dips not only cannot possibly be explained as due to lateral pressure, since the foliation would then everywhere be practically at right angles to the pressure, but also conclusively proves that no severe compression ever affected the syenite.

Nearly thirty years ago, in his study of the Rainy Lake region, Lawson described a somewhat similar curved foliated structure in granite gneiss and said regarding its origin: "The simplest explanation that suggests itself to account for the structure is that of an uprising force acting on a plastic mass (pasty magma), such force acting with greatest intensity in the vertical line which would correspond to the axis of the cone or dome."[1]

A similar type of structure appears to be common in the Haliburton-Bancroft area of Ontario as described by Adams and Barlow, who say: "Within the batholiths themselves the strike of the foliation follows sweeping curves, which are usually closed and centered about a certain spot. . . . . From these central areas

[1] A. C. Lawson, *Ann. Rep. Geol. Surv. Can.* (N.S.), III (1887–88), 116.

of flat-lying gneiss the dip . . . . is generally outward in all directions. The batholiths, therefore, are undoubtedly formed by an uprising of the granite magma, and these foci indicate the axis of greatest upward movement, and those along which the granite magma has been supplied most rapidly."[1]

There are not only important variations from the general northeast-southwest arrangement of the region within the quadrangles themselves, but also much broader variations shown by a comparison of the average foliation strikes of all the quadrangles of the Adirondacks which have been mapped in detail. This is graphically presented by the accompanying sketch map. Such marked differences in foliation directions on large scales throughout the Adirondacks is certainly incompatible with any idea of thoroughgoing compression of the region. Thus in the Lake Pleasant, North Creek, Blue Mountain, and Saratoga quadrangles the foliation, either wholly or largely, strikes at high angles across the general northeast-southwest strike of the region, while in the Lake Placid quadrangle the strikes are exceedingly variable. If due to compression, the foliation strikes would be much more nearly northeast-southwest than they actually are.

Flow structure character of foliation.—Another significant feature of the foliation should be mentioned, namely, that, while all the minerals are arranged with long axes roughly parallel to the direction of foliation, the dark-colored minerals which accentuate the structure most often appear as narrow, irregular, wavy streaks which are seldom continuous for more than a few inches or a foot. In the writer's experience this type of foliation is by far the most common in the syenite-granite series, and it is believed to be the result of magmatic flowage. Lawson has noted an exactly similar phenomenon in certain granite gneisses of the Rainy Lake region of Ontario and says: "The lines of streaking are very often not straight but are wavy or contorted, sometimes intricately so, and are evidently due to flow movements in the magma prior to its final consolidation."[2] As already suggested, flow structures are locally

[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 14.

[2] A. C. Lawson, *Geol. Surv. Can., Mem. 40*, 1913, p. 93.

very distinctly developed, especially around some of the inclusions in syenite or granite.

Differences in degree of foliation.—Another important consideration is the frequent pronounced variation in degree of foliation in the rocks of the syenite-granite series. They are mostly distinctly gneissoid, rarely so much so as to be almost schistose, while in other cases they are so faintly gneissoid as to be practically massive. A striking feature is the frequent rapid change within a few rods or yards, from rocks which are very clearly gneissoid to others in which the foliation is scarcely discernible. Sometimes, within a foot or two, a very gneissoid zone lies between others which are only moderately foliated. In many cases there is no evidence whatever of shearing to account for these variations. It seems impossible to conceive that such abrupt foliation changes could ever have been produced by severe compression of the rocks after solidification. Such compression would certainly have brought about a much more uniform degree of foliation.

According to the writer's view, these variations are best explained as due to forced differential flowage in the pasty magmas, probably after partial consolidation. Regarding the origin of igneous rock foliation, Pirsson says: "Sometimes this texture has been imposed upon the igneous rocks after they had solidified, by intense pressure and shearing, and sometimes while they were still soft, pasty, and crystallizing, by forced differential flowage, due to various causes."[1] Those portions of the magma which were forced in probably a more fluid condition between other, probably more pasty or solidified, portions would have had a more perfectly developed foliated structure.

According to Leith: "Many more schists than gneisses have been proved to be the result of mashing of igneous rocks. . . . . In fact, so commonly do the igneous rocks appear when mashed to take on schistose as contrasted with gneissic structure as to raise the question whether gneisses are not exceptional results, most gneisses to be explained as igneous rocks with original flow structures."[2] The evidence from the Adirondacks is in harmony with

[1] L. V. Pirsson, *Rocks and Rock Minerals* (1908), p. 356.

[2] C. K. Leith, *Structural Geology* (1913), p. 103.

this statement by Leith, since anything like true schists are very rare if not wholly absent from the syenite-granite series.

Significance of granulation.—Granulation of the rocks of the syenite-granite series is of common occurrence. Most of the mineral constituents are more or less granulated, though it is quite the rule that the quartz shows the effects of crushing less than the others. In the greatest bulk of the rock the cataclastic texture shows itself by flattened or irregular lens-shaped quartz individuals, and more or less lens-shaped broken feldspars, imbedded in a mass of small broken feldspar grains together with some crushed quartz and leaves of mica. In many cases more or less thoroughly elongated and crushed hornblende or augite also occur.

This granulation has usually been regarded as proof that the rocks have been subjected to severe lateral compression and crushing after their consolidation. Thus Smyth, keeping in mind the frequent lack of crushing of the quartz, has said: "As the quartz could hardly flow while the feldspar fractured, the conclusion is obvious, and seems to be well grounded, that, in the case of the quartz, there has been crystallization after the production of cataclastic structure in the rock."[1] But does this prove the quartz to be largely recrystallized or of secondary origin? Could not movements in the magma during a late stage of consolidation, and before much quartz (the last to form) had crystallized out, have caused granulation of the earlier-formed crystals, while the quartz would have been more or less unaffected? In explaining the origin of foliation in the granite-gneiss of the Thousand Islands region, Cushing says: "The rock has been much crushed and somewhat recrystallized under compressive stress, since it originally congealed."[2] Now, while some granulation and recrystallization may have taken place after the magma consolidation, it is by no means a necessary inference that the granite has been much crushed and principally foliated after it had congealed. Strong evidence against severe compression of the Adirondack region has been presented in this paper, while the best evidence points to the origin of the foliation as essentially a flow structure developed under moderate

[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist,* 1895, pp. 488–89.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 102.

pressure. This being the case, it is only necessary to consider that there were movements in the slowly cooling and stiffening magma whereby the minerals already crystallized out were more or less broken and drawn out into a sort of fluidal arrangement parallel to the foliation, while the minerals last to form were much less granulated. A significant point in this connection is that, in rocks which are definitely known to have been subjected to severe compression, quartz is quite generally more granulated than feldspar. Both Leith[1] and Loughlin[2] have emphasized this point. Now, in the Adirondack intrusives, as we have shown, the feldspar is very commonly distinctly more granulated than the quartz, and the evidence is, therefore, opposed to deformation of the Adirondack rocks by severe regional compression.

The facts that degree of foliation and granulation often vary markedly within a few feet or yards, and that the most perfectly foliated portions are often also the most highly granulated, are to be expected, because flowage in certain portions of the magma during the late stage of consolidation would produce in those portions not only good primary foliation but also notable crushing of the already formed minerals by the movements in the stiff, pasty magma. It seems impossible to explain satisfactorily such marked differences in degree of both foliation and granulation in the syenite-granite series except as the result of movements in the congealing magma. In few cases, if any, is there evidence for shearing, so that if compression of the region be assumed as the cause of the foliation and granulation, it is impossible to explain why adjacent zones often present such differences in degree of foliation and granulation.

Again, the general lack of notable granulation in the oldest rocks of the region—the Grenville—is not compatible with the idea of production of cataclastic structure in the intrusives by lateral pressure, else why were the still older rocks also not proportionately affected?

Other workers have presented strong evidence for the production of a granulated or protoclastic texture in igneous rocks by some

[1] C. K. Leith, *U.S. Geol. Surv., Bull. 239*, 1905, pp. 33–34.

[2] G. F. Loughlin, *ibid., Bull. 492*, 1912, p. 128.

such process as that outlined above. Barlow, describing the granite of central Ontario, says: "The movements . . . . continued as the rock cooled and while it was filled with abundant products of crystallization, the movements being brought to a close only by the complete solidification of the rock. Evidence of protoclastic structure can, therefore, be seen throughout all the areas colored as granite or granite-gneiss on the map."[1]

Teall says, regarding the granite of the county of Kircudbright: "The quartz and alkali feldspar, which . . . . were the last constituents to solidify, are those which have yielded most to the deforming stresses. They show signs of crushing. . . . . It is probable that the pressure acted before the rock mass had actually cooled."[2]

McMahon, discussing the gneissic granite of the Himalayas, says: "It is no argument against the idea of the development of foliation before final consolidation of the granite to point to evidence of strain and mechanical action in the rock; for the existence of strain and mechanical action during the critical period in the history of the granite is an essential part of the theory itself."[3] He admits that the granite has been subjected to lateral pressure but says that this does not prove the foliation to have been produced by such pressure.

Weinschenk,[4] explaining certain schistose Alpine granites, suggests that, in a somewhat advanced stage of magma consolidation, a crystalline skeleton is formed whose interstices are filled with liquid magma. Movements cause crushing of the skeleton, breaking the feldspars and bending the mica plates. Quartz, the last mineral to crystallize, is flattened out but not much broken.

According to Trueman: "It seems not illogical to assume that the movements which were, apparently, present late in the period of consolidation should have sometimes been continued after portions or the whole of the rock had completely solidified. If such

[1] A. E. Barlow, *Geol. Surv. Can.*, *Mem.* 57, 1915, p. 48.

[2] J. J. H. Teall, *Mem. Geol. Surv. Great Britain*, *Expl. Sheet 5*, 1896, p. 43.

[3] C. A. McMahon, *Geol. Mag.*, N.S., Decade 4, IV (1897), 347.

[4] E. Weinschenk, *Congrès géol. inter.*, *Compte rendu*, Session VIII, 1 (1900), 341.

were the case there would result considerable recrystallization and granulation so that typical crystalloblastic or cataclastic textures might be superimposed upon that resulting from primary consolidation."[1]

The possibility of some granulation and recrystallization in the Adirondack intrusives after complete consolidation is admitted by the writer, but, in view of the evidence above presented, such processes must have had relatively little to do with the development of the textural and structural features of the rocks.

Cause of mineral elongation.—Still another matter to consider briefly is the cause of the flattening or elongation of minerals in the primary gneiss. Flattening or elongation of minerals, especially quartz and feldspar, are common in the Adirondack intrusives, varying from rocks in which the phenomenon is scarcely noticeable to others in which it is extremely developed. It is the writer's experience that many such variations exist within short distances. Quartz exhibits such flattening better and more frequently than the feldspars. The writer believes that the mineral flattening or elongation was caused essentially by crystallization in the magma under pressure. Trueman[2] has recently presented considerable evidence to show that elongation (and presumably flattening) of mineral constituents by crystallization under differential pressure must often have been a very important factor in the production of foliation of primary gneisses.

In the Adirondack syenite-granite series, quartz shows the effects of flattening most because it was the last mineral to crystallize out and hence was not subject to so many of the movements in the magmas. Loughlin presents a similar argument regarding the Sterling granite-gneiss of Connecticut as follows: "After crystallization had become so far advanced that the rock became a mass of feldspar crystals (plus a small amount of quartz) with interstices filled with still fluid quartz, the feldspars would suffer strain, rotation, and slicing, and become a more or less granular lens-shaped aggregate elongated in the direction of least pressure. . . . . As the interstitial quartz began to crystallize, it would be

[1] J. D. Trueman, *Jour. Geol.*, XX (1912), 244.

[2] *Ibid.*, XX (1912), 235–42.

obliged to take on the form of the elongated or flattened interstices."[1]

It is not at all necessary to assume a very active lateral compression of the region to account for this pressure. As suggested by Cushing,[2] considerable compression of the magmas must have resulted from the batholithic intrusions, which, in order to make room for themselves, exerted a shouldering pressure upon the adjacent rocks. It is believed that such a shouldering pressure within the magmas was sufficient, not only to cause more or less flattening and elongation of minerals during consolidation and crystallization, but also to determine to a considerable extent the directions of the magmatic currents and hence the resulting strike of the foliation. Under the very conditions of intrusion, differential pressures must have been common, thus best explaining the frequent variations in degree of flattening of mineral constituents. This view does not of course preclude the possibility of moderate lateral pressure exerted throughout the whole region during, or even after, the magma consolidation.

Foliation of batholithic borders.—Before leaving this discussion another feature of the foliation of the intrusive masses should be mentioned, namely, that they often exhibit a greater degree of foliation and granulation around their borders than in their interiors. This phenomenon seems to be best shown in the anorthosite and the gabbro, and will be discussed below. Suffice it to say here that production of foliation and granulation in the congealing magmas affords a more plausible explanation for the peripheral distribution of such features than their production by compression of the whole region.

Summary.—During the process of intrusion, which was long continued, the great syenite-granite magmatic masses were under only enough lateral pressure to control the general strike of the uprising magmas with consequent tendency toward parallel arrangement of syenite-granite and invaded Grenville masses; the foliation is essentially a flow structure produced under moderate pressure during the intrusion; the sharp variations of strike on large and

[1] G. F. Loughlin, *U.S. Geol. Surv., Bull. 492*, 1912, p. 129.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 101.

small scales, and rapid variations in degree of foliation, are essentially the result of varying magmatic currents under differential pressure, principally during a late stage of magma consolidation; the almost universal, but varied, granulation of these rocks was produced mostly by movements in the partially solidified magma, and possibly in part by moderate pressure applied after complete consolidation; and the mineral flattening or elongation was caused by crystallization under differential pressure in the cooling magma.

FOLIATION OF THE ANORTHOSITE

It is not the present purpose to discuss thoroughly the origin of the structural and textural features of the Adirondack anorthosite. Only a few of the more important phenomena will be briefly considered. In general, the explanations above given regarding the foliation and granulation of the syenite-granite series apply also to the anorthosite.

Character of the anorthosite.—With the exception of a few small outlying masses, the anorthosite occupies a practically unbroken area of 1,200 square miles in the central-eastern Adirondack region. It quite certainly represents a single great intrusive body which is older than the syenite-granite series. In its typical development the rock consists almost wholly of basic bluish-gray plagioclase and is very coarse-grained, the feldspars often measuring from one to several inches in length. There are several important differentiation variations of the great mass. One of these is coarse-grained, but carries a considerable percentage of dark minerals; another is finer-grained and more gabbroic looking, owing to dark minerals, chiefly augite and ilmenite; while still another facies consists almost wholly of white basic plagioclase, or such white feldspar and more or less dark minerals. The great bulk of the rock is highly feldspathic and practically devoid of foliated structure, probably partly because of lack of minerals favorable for its production or accentuation, while the more gabbroic (especially finer-grained) types are almost invariably well foliated, frequently excessively so.

All of the varieties show more or less granulation, sometimes to a high degree, this being particularly true of the less coarse-grained gabbroic types. As regards amount of granulation of feldspar, it is probably not very different in anorthosite and syenite-granite. The gabbroic, well-foliated, and granulated facies are developed on a grand scale around the borders of the great anorthosite area, but similar types are often encountered irregularly distributed throughout the area. Large feldspar individuals, usually unaltered rounded or lens-like cores of crystals, quite typically stand out prominently in a finer-grained, generally well-granulated, groundmass. In spite of much granulation, it seems certain that the typical original rock (before thorough consolidation) was characterized by a coarse porphyritic texture.

Cause of the foliation and granulation.—The foliation and granulation of the anorthosite has been explained as due to the same severe compression of the region which is supposed to have caused similar phenomena in the syenite-granite series. According to this view, the more general lack of anorthosite foliation is considered to be due to lesser effect of the regional pressure toward the interior of the great intrusive body than around its borders. Also it is thought that coarseness of original grain and general lack of minerals, especially dark minerals, other than feldspar have militated against such complete granulation and foliation of the rock as characterizes the syenite-granite series.

Regarding severe compression after the magma consolidation as the prime cause of the foliation and granulation is, however, open to many of the same objections already discussed in connection with the syenite-granite series. It is the writer's belief that an insurmountable objection to the severe-compression idea lies in the fact that there are so many sudden variations in degree of foliation and granulation, and in strike of foliation, throughout the great anorthosite area. Thus, well within the area, the writer has repeatedly seen very gneissoid gabbroic facies—both coarse and medium-grained—in close proximity to gabbroic facies of similar grain with little or no foliation. All types of anorthosite also often exhibit varying degrees of granulation in close proximity. If they were caused by regional compression, why are so many portions highly foliated or granulated when others close by are unaffected? Also, if regional compression were the cause of the foliation, how are the frequent very notable variations in strike, often within relatively small areas, to be accounted for?

According to the general principles outlined in connection with the foregoing discussion of the syenite-granite series, it is the writer's conception that the foliation and granulation of the anorthosite were developed essentially by flowage or other movements in the magma under moderate pressure, mostly just prior to its complete consolidation. As Cushing has said regarding the Long Lake quadrangle anorthosite: "In some portions of the rock the feldspar crystals are more numerous, are smaller and are all arranged with their long axes parallel. This is a 'flow structure' due to movements in the mass during solidification."[1] The better foliated or better granulated belts throughout the great mass represent merely places where the magmatic currents or other movements were more pronounced. The coarser-grained portions would of course have undergone less complete granulation, but coarseness of grain and absence of dark minerals would not necessarily have tended to prevent the development of foliation. Thus, in the Broadalbin, North Creek, and Lake Pleasant quadrangles the writer has observed coarse granite-porphyry, almost free from dark minerals, with highly gneissoid structure due to thorough flattening out of both quartz and feldspar, while in other cases the porphyry shows little or no foliation. It would seem, therefore, that the general absence of foliation throughout so much of the anorthosite is best explained as the result of the much more uniform intrusion of this single great body which is less involved with Grenville masses, or, in other words, to much less forced differential flowage. Because of its great size, the pressure due to shouldering effect on adjacent rocks would be relatively slighter toward the interior of the mass.

Not only is the foliation well developed around the margin of the great intrusive, but it also appears to be especially well exhibited in many parts of the area in the gabbroic facies where they are close to masses or inclusions of Grenville. Just as flow structure is often best shown close to the wall-rock of, or an inclusion in, a small intrusive body, probably because of friction against the wall-rock

[1] H. P. Cushing, *New York State Mus. Bull.*, No. 115, 1907, p. 472.

or inclusion and consequent development of differential pressure and flowage, so, on a large scale, in the anorthosite body it is reasonable to think that foliation due to magmatic flowage would have been best developed around the margin of, or close to, masses of country rock within the great anorthosite body. In many other places, however, primary gneissoid structures may have been produced by differential flowage far from any country rock.

The cataclastic texture of the anorthosite is believed to have resulted from the crushing of minerals already crystallized out of the stiff, solidifying magma by movements in the magma. The shouldering pressure exerted by the great intrusive mass in order to make room for itself must have been sufficient to have affected the whole mass until final consolidation.

Kemp says, regarding the anorthosite of the Elizabethtown quadrangle: "The entire area has been subjected to such severe pressure and granulation that the outer borders of the crystals are always crushed to a finely granular and whitish mass. Within this rim the bluish nuclei of the plagioclases remain. When shearing and dragging have been added the nuclei yield augen-gneisses."[1] It is, however, not at all necessary to assume severe regional pressure to account for these phenomena. Forced differential flowage in the stiff, nearly congealed magma (under pressure due chiefly to its own shouldering action) could have produced most, if not all, of the granulation and dragging effects, the "augen" being cores of what were large, probably porphyritic, feldspars in the nearly solidified magma. Moderate pressure during or even after consolidation may possibly have operated to accentuate the phenomena.

Adams says, concerning the Morin anorthosite north of Montreal: "The circumstance that the streaks or irregular bands (foliation), when present in the otherwise massive rock, assume no definite direction, but twist about as if owing to movements of the rock while in a pasty condition, indicate that they have been produced by movements before the rock solidified. . . . . The granulation of the coarsely crystalline massive anorthosite, usually with concomitant development of more or less foliated or schistose structure in the way described, is undoubtedly due to movements

[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 28.

in the rock, resulting from pressure which acted subsequent to or possibly during the last stages of its consolidation."[1]

FOLIATION OF THE GABBRO

The gabbro here considered is the latest Adirondack intrusive which exhibits foliation and granulation. Diabase is the only intrusive still younger. A few years ago the writer[2] discussed the origin of certain primary variations of Adirondack gabbro. At that time, in accordance with the usual idea, the foliation was thought to be largely a secondary structure and so was omitted from the discussion.

Character of the gabbro.—Most of the gabbro is in the form of small stocks or bosses, the outcropping areas typically ranging from elliptical to almost circular, and the dimensions from a few rods to one or two miles. They are especially well-shown on the North Creek, Long Lake, Elizabethtown, and forthcoming Blue Mountain geologic maps. Most of them are of pluglike or pipelike form, with practically vertical, sharp contacts against the country rock. The stocks exhibit many variations in composition and texture from the normal, homogeneous, dark, basic gabbro with diabasic texture, to lighter-colored rocks of dioritic and even syenitic make-up. They also range from fine-grained to very coarse-grained with feldspars up to an inch or more in length. The typical gabbro contains principally basic plagioclase, pyroxene, hornblende, biotite, garnet, and ilmenite, while orthoclase and quartz often occur in the more acidic facies.

A very important feature, from the standpoint of our present discussion, is the almost universal development of highly foliated amphibolitic borders which often completely surround the stocks, while the interior portions of the typical stocks are usually non-foliated. In many cases, however, stocks seem to be wholly changed to amphibolite, or only very small cores remain. In still other cases coarse-grained gabbro shows gneissoid structure thoroughly developed throughout. As a rule the gabbro exhibits as good, if not better, foliation than the older intrusives. Often

[1] F. D. Adams, *Geol. Surv. Can., Guide Book No. 3*, 1913, p. 17.

[2] W. J. Miller, *Jour. Geol.*, XXI (1913), 160–80.

the degree of foliation varies much even well within single stocks.

Another very persistent feature is granulation which appears to be of two types, that of so-called "corrosion rims" around certain minerals, and a more generally distributed granulation. Granulated "corrosion rims" occur even in non-foliated gabbro with diabasic texture.

Cause of foliation and granulation.—The foliation and granulation of the gabbro, like that of the older intrusives, are quite generally regarded as secondary features brought about by the influence of regional pressure, the non-foliated, uncrushed cores of stocks being considered as portions protected from pressure influence. Granting the existence of regional compression severe enough to give rise to these phenomena, it is evident that the same pressure must have affected the older intrusives in a similar manner, but this we have proved to be not the case. It is very difficult to imagine a process of development of foliation, which boxes the compass around the borders of the gabbro stocks, by regional compression. Such foliation of course often strikes directly across the foliation of the older adjacent rocks, an excellent case in point being at the south end of the large stock just north of Loon Lake of the North Creek sheet. How can such phenomena be explained as due to regional pressure when it is well known that cleavage or foliation produced by this means must everywhere strike at least approximately at right angles to the direction of application of pressure? Also how are such frequent notable variations in foliation and granulation, not only in near-by stocks but also within stocks, to be explained?

According to the thesis of this paper, the foliation and granulation are largely, if not wholly, primary features. There are, admittedly, some puzzling things about the foliation and granulation of the gabbro, but certainly they are to be much more reasonably interpreted as caused by movements in the magma before complete consolidation.

Weinschenk, in explaining schistose peripheral zones around certain Alpine granitic cores, has suggested: "The consolidation of the rock commenced with the separation of the dark minerals—

biotite and hornblende. Mica formed first in the liquid mass. At this time the orogenic pressure acted upon the peripheral zone of the magma by orienting this mineral normal to the pressure. In the heart of the viscous mass this faculty of orientation was replaced by an interior tension not directed in any particular way."[1] Orogenic pressure did not exist in the Adirondack region, but if for it we substitute the pressures within the stock magmas themselves, this idea of Weinschenk affords a plausible explanation of the foliated borders. Considerable pressures must have obtained within the stock magmas which were intruded under very deep-seated conditions. Such pressure against the country rock, combined with the usual development of differential flowage in the magmatic borders, as already explained in this paper, would readily account for the peripheral foliated zones which were produced, no doubt, during a late stage of magma consolidation. But the conditions for magmatic pressure and flowage must often have varied a great deal, so that it is to be expected that, in some cases, even coarse-grained gabbro would exhibit primary foliation, while, in other cases, amphibolite would make up the whole mass, or, in still other cases, finer-grained, very gneissoid, and granulated belts or bands would occur in the midst of coarser, less foliated types. It should be noted in this connection that unmistakable flow structures do often occur around inclusions in the gabbro.

Applying these ideas, the puzzling features of various gabbro stocks find a ready interpretation. A good example is the stock near Blackbridge in the Lake Pleasant quadrangle.[2] For most part this is a very basic, gabbroic-looking rock, sometimes pretty massive and very coarse-grained, and at other times not so coarse, but streaked or almost banded, owing to layers of amphibolite. All phases of the rock are much granulated and distinctly gneissoid, the coarser-grained portions being least so. A diabasic texture frequently occurs. Differential flowage and other movements under pressure in the congealing magma best explain these phenomena. The more foliated, finer-grained belts in the midst of the

[1] E. Weinschenk, *Congrès géol. inter., Compte rendu*, Session VIII, 1 (1900), 340. Freely translated from the French.

[2] W. J. Miller, *New York State Mus. Bull.*, No. 182, 1916, p. 29–30.

coarser, less foliated rock may be readily interpreted as the result of a forcing of slightly more liquid portions of the congealing magma through more solidified portions.

Highly developed "corrosion rims" are beautifully and extensively developed in the Adirondack gabbros.[1] Their occurrence even in non-foliated gabbro with diabasic texture argues strongly for their production before final consolidation of the magma, this possibility having been recognized by other investigators. How could regional compression have caused so much of this sort of granulation without otherwise affecting the rock? Also, if granulation of this sort has resulted from movements prior to solidification of the magma, why could not the more general cataclastic textures of the syenite-granite, anorthosite, and gabbro have been similarly produced? As in the older intrusives, so in the gabbro, the finer-grained more foliated portions are quite generally the most granulated, this doubtless resulting from more pronounced flowage movements in certain portions of the magma late in the process of consolidation.

[1] W. J. Miller, *Jour. Geol.*, XXI (1913), 168–70.

THE COMPOSITION OF THE AVERAGE IGNEOUS ROCK[1]

ADOLPH KNOPF
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The composition of the "average igneous rock" has been computed by Clarke, Harker, and Washington. Clarke's most recent estimate was published in 1915.[2] The earlier computations were made by averaging the results of large numbers of analyses, and the later by averaging each constituent according to the number of determinations made, and reducing the sum to 100 per cent. The objection to these methods, as is well known, is that they take no direct account of the quantitative distribution of the rocks; each analysis or determination receives the same weight, regardless of the size of the geologic body that it is held to represent. The force of this objection has been recognized by Clarke,[3] who concludes that "the whole land surface of the earth must be taken into account before the true average can be finally ascertained."

A first approximation to this true average can be reached by calculations based on data recently assembled by Daly in *Igneous Rocks and Their Origin*. In Table IV is given the total areas covered by each of the rock species named and mapped in the Cordilleran and Appalachian folios of the United States Geological Survey. The area occupied by any rock species divided by the total area of igneous rocks (16,728 square miles) gives a weight-factor, and this factor multiplied by the average composi-

[1] Published with the permission of the Director of the U. S. Geological Survey.

[2] *Analyses of Rocks and Minerals from the Laboratory of the United States Geological Survey*, U.S. Geological Survey Bulletin, No. 591, pp. 18–22, 1915.

[3] *The Data of Geochemistry* (3d ed.), U.S. Geological Survey Bulletin, No. 616, p. 26, 1916.

tion of the species, which has been computed by Daly in Table II, gives the percentage contribution of that species to the composition of the average igneous rock. In this calculation species covering less than 2 square miles were omitted, as their inclusion would not affect the second decimal place of the result. The composition thus calculated is that of the average exposed igneous rock; whether it represents the composition of the average igneous rock of the 10-mile crust depends on the verity of certain petrogenic considerations.

The following proportional factors were used in the computations:

Granite, including allied porphyries	0.23212
Granodiorite	.12195
Rhyolite	.12834
Andesite	.23864
Basalt	.20773
Quartz monzonite and allied porphyry	.00108
Diorite	.01802
Gabbro	.02225
Anorthosite	.00311
Syenite and syenite porphyry	.00389
Monzonite	.00161
Nepheline syenite	.00024
Shonkinite	.00054
Theralite	.00036
Peridotite	.00436
Pyroxenite	.00011
Diabase	.01602
Dacite	.00536
Trachyte	.00036
Latite	.00030
Phonolite	.00048
Nepheline melilite basalt	.00018
Limburgite	.00012
Total	1.00000

The result of the new calculation of the composition of the average igneous rock is given in column I of the accompanying table; for comparison, the most recent estimate by Clarke is given in column II.

Notwithstanding the widely different methods employed in the calculations the new estimate agrees to a remarkable extent with

COMPOSITION OF THE "AVERAGE IGNEOUS ROCK"

	I	II
SiO_2	61.64	60.47
TiO_2	0.73	0.80
Al_2O_3	15.71	15.07
Fe_2O_3	2.91	2.68
FeO	3.25	3.50
MnO	0.16	0.10
MgO	2.97	3.85
CaO	5.06	4.88
Na_2O	3.40	3.41
K_2O	2.65	3.03
H_2O—	1.26	0.48
H_2O		1.44
P_2O_5	0.26	0.29
	100.00	100.00

Clarke's average. The most notable departures are the increase in silica and the relatively strong decreases in magnesia and potassa.

Reviews

The General Magnetic Survey of the Earth. By L. A. Bauer. Bull. Am. Geog. Soc., XLVI, July, 1914, pp. 481–99. Figs. 6.

About the earth sphere are lines of magnetic force very similar to those of any magnetic field, their poles not quite coincident with those of the earth axis. That the magnetic needle varies from true north was discovered at least as early as the fifteenth century, when Columbus sailed west from Europe. Subsequent observations have shown in addition that there is a constant change in the earth's magnetism, making repeated magnetic surveys necessary. In magnetic observations, the horizontal declination, vertical magnetic dip, and intensity of the attraction are measured. Since 1904 the Carnegie Institution of Washington has conducted extensive magnetic surveys of the earth in which a total mileage of approximately one million miles has been traveled. Ocean surveys have been conducted in a specially constructed non-magnetic vessel.

R. C. M.

The Mud Lumps at the Mouths of the Mississippi. By Eugene W. Shaw. U.S. Geol. Surv., Prof. Paper 85, Part B, 1913. Pp. 17, pls. 3, figs. 6.

The territory within a mile or two of each of the mouths of the Mississippi is characterized by large swellings or upheavals of tough bluish-gray clay, to which the name "mud lumps" has been applied. Many of the mud lumps rise just off-shore and form islands having a surface extent of an acre or more and a height of 5 to 10 feet, but some do not reach the water surface. Almost all occur near the bars at the mouths of the rivers. In contrast with the general structure of the delta, which is composed of thin, alternating sandy and clayey beds, the mud lumps are of thick, compact clay. On and around the clay core lies a series of faulted and folded strata of sand and silt which have been carried up from the sea bottom and deformed in the upheaval. It seems most likely that these lumps owe their origin to a squeezing of the soft layers, and an accumulation of clay from such layers in places where the pressure is less strong. This postulates a gentle seaward flow of layers of semifluid clay, the flow meeting resistance particularly at the ends of the Passes, where there is an accumulation of more resistant material and a greater lack of equilibrium between the heavy land on one side and the water on the other. The report is somewhat preliminary in nature.

R. C. M.

The Upper Cretaceous and Eocene Floras of South Carolina and Georgia. By E. W. Berry. U.S. Geol. Surv., Prof. Paper 84, 1914. Pp. 200, pls. 29, figs. 12.

The Upper Cretaceous of South Carolina is represented by the Black Creek formation, which is divisible into two members, the Middendorf arkose, with certain related clays, and a sandy, marine member. A number of localities in the Middendorf have yielded plant remains, among which are found magnolias, figs, laurels, oaks, walnuts, cinnamon, the eucalyptus, etc. The collection numbers 75 species. The climate, indicated by the types present, is subtropic, or at least mild temperate, for with little variation the flora extends to the western coast of Greenland.

The Upper Cretaceous of Georgia, the flora of which is described in the second part of the paper, is confined to a triangular area lying west of the Ocmulgee River and comprises the eastward extension of the Eutaw and Ripley formations. The former contains an abundant fossil flora in its lower division, but the latter, except in the upper part, contains little plant life. The physical conditions suggested are in accord with the evidence from South Carolina and point to a mild, humid climate, without frosts.

A small but very interesting Middle Eocene flora from Georgia is described in the third division of the paper. The Middle Eocene of Georgia is for the greater part deeply buried beneath younger sediments, but in the area lying between the Ocmulgee and Savannah rivers there are outcrops which have yielded a fossil flora of 17 species. Most of these have not been described previously and the author compares them with European Eocene and modern related types. The conclusion is reached that the Middle Eocene of this region enjoyed a much more tropical climate than is represented by any other known Eocene flora. The Georgia flora was probably immigrant from the south and reached northward at least as far as latitude 33° N.

R. C. M.

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THE GENESIS OF LAKE AGASSIZ:[1] A CONFIRMATION

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CONTENTS

INTRODUCTION

In a paper published in the *Journal of Geology* in 1896, J. B. Tyrrell stated that the results of his field work in the region lying to the west and southwest of Hudson Bay showed that—

the Keewatin glacier seems to have retired northward well into Manitoba and possibly even beyond the northern limit of that province before it was joined by the eastern glacier. When they united the water was ponded between the

[1] Published by permission of the Director of the Geological Survey of Canada.

fronts of the two glaciers to the north and northeast and the high ground to the south and west. Thus Lake Agassiz had its beginning. Its waters rapidly rose until they overflowed southward into the valley of the Mississippi and then gradually declined as River Warren deepened its channel.[1]

By his more recent work in the region lying to the south of Hudson Bay, Tyrrell has shown that the last invasion of glacial ice in that region was by an ice sheet which advanced in a southwesterly direction and overlapped a portion of the area previously occupied by an ice sheet which he named the Patrician Glacier. This last advance of the ice extended in a southwesterly direction at least as far as the headwaters of the Severn River and in a westerly direction approximately as far as the Hayes River, where it was met by a readvance of the Keewatin glacier.[2]

Field work done by the writer during portions of the seasons of 1913 and 1914 in the vicinity of the Rainy River and Lake of the Woods, Ontario, has brought forth evidence which confirms Tyrrell's view that Lake Agassiz had at first a rising stage, due to the blocking of the northward drainage, and later subsided, and that, during the entire existence of the lake, the ice border was far to the north and northeast. This conception of the life-history of Lake Agassiz differs radically from that of Warren Upham, by whose work Lake Agassiz is best known, and whose interpretation has been most widely accepted. The object of the present paper is to present the evidence which confirms Tyrrell's view as to the genesis of Lake Agassiz and to point out that the acceptance of this view has an important bearing upon the question of the character and cause of the epeirogenic movements which deformed the shore lines of Lake Agassiz.

UPHAM'S CONCEPTION OF THE LIFE-HISTORY OF LAKE AGASSIZ

Glacial Lake Agassiz is best known from the work of Warren Upham, the results of which were published in 1895 by the United States Geological Survey as *Monograph 25*. Upham's field work in connection with the investigation of the basin of Lake Agassiz was done some thirty years ago and was largely confined to the

[1] J. B. Tyrrell, "The Genesis of Lake Agassiz," *Jour. Geol.*, IV (1896), 813.

[2] J. B. Tyrrell, "The Patrician Glacier South of Hudson Bay," *Congrès Géologique International, Canada, 1913, Compte-Rendu* (Ottawa, Canada, 1914), pp. 523–34.

western or prairie portion of the basin. At that time little was known of the extension of the lake in the northern portion of the state of Minnesota or in the adjoining portions of Canada, for much of this region was densely wooded, largely unsettled, and difficult of access. At that time, also, the general conception was that during Pleistocene time the Laurentide glacier occupied the greater portion of Central and Northwestern Canada. It was not until some time later that the subdivision into Keewatin and Labradorean ice fields was recognized.

Upham believed, as the result of his investigations, that the northward drainage of Red River valley and adjacent areas was ponded between the retreating front of the Laurentide glacier on the north and northeast and the divide on the south, that the lake had at first a small beginning in the southern part of the basin and gradually grew in size as the ice withdrew toward the northeast, and that a great series of moraines was deposited in the waters of the lake at stages of halt or slight readvance during the general retreat of the ice sheet. He found that the lake, during its higher stages, discharged southward to the Mississippi along the course of the present Lake Traverse and Minnesota River valleys. During the operation of the southern outlet several strong shore lines of the lake were developed. As the ice retired and uplift took place, lower outlets were opened toward the northeast and other and lower beaches were developed in the northern part of the basin. He also showed that beaches which are single in the southern portion of the basin split into series in the northern portion of the basin and rise differentially toward the north-northeast, the highest being most upwarped and the lowest least, thus proving that differential elevation of the land went on during the existence of the lake.[1]

DIFFICULTIES IN ACCEPTING UPHAM'S INTERPRETATION

Some of the difficulties involved in accepting Upham's interpretation of the life-history of Lake Agassiz were pointed out by T. C. Chamberlin. It was found by Upham that the uppermost or Herman beach was continuous for a long distance northward

[1] Warren Upham, "The Glacial Lake Agassiz," *U.S. Geol. Survey, Monograph 25*, 1895.

and that it overrode three prominent moraines which marked halts or readvances of the ice front. Upham supposed that the Herman beach represented the whole time of the formation of the several moraines and of the retreat of the ice front for at least 250 miles, in spite of the fact that he found the beach to be not very massive and not very notably stronger in the southern than in the northern portion. Recognizing this difficulty, Chamberlin suggested that "the whole history of Lake Agassiz may not have fallen within the period of stationary or rising crustal movement but that the early part of it may have taken place during the latter portion of the period within which the crust was being depressed."[1] In this way it may be supposed that shore lines were formed at early stages of the lake but were later submerged. The uppermost Herman beach would have been formed at the time of maximum submergence. It would be all of one age and would represent a comparatively short time.

Another difficulty arises from the character of the deposits laid down in the basin of the lake. Upham held that the greater part of these deposits were derived from the ice sheet and its inclosed drift—a necessary inference from his interpretation of the history of the lake. But he found that "bowlders are absent or exceedingly rare in the beaches, deltas, and finer lacustrine sediments."[2] If it is true that a series of moraines was deposited in the lake, and if the sediments of the lake basin were largely derived from the ice sheet, it seems highly probable that berg deposits would form an important part and that bowlders would be included in the sediments.

A serious difficulty also arises if Upham's interpretation of the mode of origin of the sediments which occur in Red River valley is accepted. Upham held that these sediments are recent fluvial deposits laid down in local depressions and on flood plains of streams after the disappearance of Lake Agassiz. The deposits, he states, "have commonly greater thickness and extent than the underlying silt of glacial Lake Agassiz."[3] In the southern portion of the basin they are in places underlain at considerable depths by "sheets of turf,"[4] etc., apparently indicating the presence of an old soil. The

[1] "The Glacial Lake Agassiz," *U.S. Geol. Survey, Monograph 25*, p. 245.

[2] *Ibid.*, pp. 183 and 201. [3] *Ibid.*, p. 202. [4] *Ibid.*, p. 253.

great thickness and extent of these deposits and the occurrence of "sheets of turf" in their lower portions seem difficult of explanation on the assumption that they are "recent fluvial deposits."

All these difficulties disappear, however, if it is considered, as the evidence seems to show, that Lake Agassiz had at first small beginnings in Red River valley and gradually rose until it overflowed to the south, owing to a blocking of the northward drainage by an advance of the ice, and that the ice advanced only into the northern portion of the basin, so that the whole southern part of the lake was practically free from ice during the entire existence of the lake.

RECORDS OF LAKE AGASSIZ IN RAINY RIVER–LAKE OF THE WOODS DISTRICT

Geographical relations of the district.—The eastern portion of Rainy River–Lake of the Woods district lies about midway between Lake Superior and the Red River of the province of Manitoba. The Rainy River connects Rainy Lake and Lake of the Woods and for a distance of 82 miles forms the international boundary between the state of Minnesota and the adjoining portion of the province of Ontario. The Rainy River, the main stream of the region, flows westward to Lake of the Woods, which drains northwestward to Lake Winnipeg and thence to Hudson Bay, so that the whole area lies within the Hudson Bay drainage system. The altitude of Rainy Lake is 1,107 feet and of Lake of the Woods 1,060 feet above the sea, and the general altitude of the plain bordering the Red River on the west is about 200 feet lower. The southern portion of Lake of the Woods is shallow and is generally bordered by drift deposits. The divide southwest of the lake, separating the lake basin from that of the Red River on the west, is low and for some distance is less than 30 feet above Lake of the Woods. On the northwest, near Northwest Angle, the divide is also only a few feet above the level of the lake, so that the plains of Manitoba and northern Minnesota are practically continuous on the southwest and northeast into the southern portion of the Lake of the Woods basin. In southeastern Manitoba, and west of the southern portion of Lake of the Woods, the continuity of the plain's surface is broken by a relatively high area which rises to a maximum height of about 200 feet above the general level of the plains. The area lying between Rainy Lake and Lake of the Woods is so deeply drift-covered that comparatively few solid-rock exposures occur. The surface has generally very slight relief, and slopes gently toward the west, so that the area really forms a portion of the eastward extension of the wooded portion of the prairie plains of Manitoba and northern Minnesota, from which it is separated by the shallow basin of the southern portion of Lake of the Woods. In the northern portion of Lake of the Woods and north of a line drawn from the central part of the lake southeastward to Rainy Lake, the country is generally rocky and has comparatively little drift covering.

Till sheets.—There are at least two distinct till sheets in the district. The upper and younger is distinguished from the lower and older till sheet by the calcareous nature of its materials, and by the presence in it of bowlders of limestone and other rocks which are known to outcrop in Manitoba, but not in the district itself nor in the region lying to the northeast. Striae observed on the bedrock beneath the till sheet trend southeastward or eastward. These striae were not seen to be crossed by later striae, and no till was seen to overlie this till sheet. It seems evident, therefore, that the calcareous till was deposited by a lobe of the Keewatin glacier and that the area in which the calcareous till occurs was not overridden by an advance of ice from the northeast at a later time.

The lower and older till sheet was deposited by an ice sheet advancing from the northeast. This is shown by the southwestward trend of striae on the bedrock underlying this till sheet and by the fact that the till contains no limestone similar to that which occurs in the upper sheet. Associated with the lower till sheet are considerable deposits of fluvio-glacial sands and gravels which also contain no limestone. No evidence was seen which would suggest that there was any considerable lapse of time between the deposition of the two till sheets, and it is presumed that they were nearly contemporaneous in age and were deposited during the Wisconsin stage of glaciation.

Laminated stony clays.—A series of laminated clays, containing in places striated stones and bowlders, occurs in the district. The clays overlie and in the eastern portion of the district also underlie the calcareous till, with which they are closely associated. In some sections there is a sort of transition upward from the unstratified till into the laminated clays; that is, in the lower portion of the clays distinct laminae of clay are separated by unstratified stony material resembling the underlying till. The stony layers at the base rarely exceed a few inches or at most a foot in thickness and rapidly die out, so that "the transition beds" are, as a rule, only 4 or 5 feet thick. The laminated clays in the district range in altitude from 1,060 up to at least 1,200 feet, but they are generally only a few feet in thickness. These clays were deposited in a glacial marginal lake which is here referred to as Early Lake Agassiz. This lake was associated with an advance of the Keewatin glacier which deposited the calcareous till in the region. The clays were in part deposited during the time of advance of the ice sheet, for in places till overlies the clays. This relation is well seen in the sections exposed in the gravel pit one and one-half miles west of Fort Frances, where 8 feet of calcareous till overlie laminated clays, which are again underlain by non-calcareous, fluvio-glacial sands and gravels. The laminated clays were also in part deposited during the time of retreat of the ice. Early Lake Agassiz was, however, largely if not wholly drained before the later Lake Agassiz came into existence, for the desposits of Lake Agassiz rest unconformably on the calcareous till and on the closely related laminated clays.

Deposits of Lake Agassiz.—Numerous raised beaches of Lake Agassiz occur in the district, at altitudes ranging from 1,100 to 1,200 feet. The strongest and best-developed beach extends northward for some distance from the vicinity of the town of Rainy River. The altitude of this beach near the town of Rainy River is 1,117 feet. Ten miles northeast of this locality its altitude is about 1,125, and twenty-four miles northeast its altitude is about 1,140. Higher beaches occur at various altitudes up to at least 1,200 feet. A comparatively small part of the drift-covered area lying between Rainy Lake and Lake of the Woods rises more than 1,200 feet, but in the northern portion of Minnesota immediately south of Rainy River district drift-covered areas rise considerably higher. In this area a number of beaches rising well above 1,200 feet have been found by Mr. Leverett, who states that bars of gravel and sand formed by the waters of Lake Agassiz occur on the highest points of Beltrami Island.[1]

The lacustrine deposits of Lake Agassiz in the district occupy areas of considerable extent and are in places at least 30 feet thick. They are generally even-bedded but not strongly laminated. In places they are characterized by an irregular alternation of sandy and clayey layers and occasionally thin gravelly layers. The beds are in places more sandy toward their base than in their upper portion, and are frequently ripple-marked but not cross-bedded. The material is more oxidized than that of the older laminated stony clays, and there can be little doubt that the material was derived from erosion of land surfaces by wave and stream action. The sandy ripple-marked beds underlying clay, and the occurrence of gravelly layers interbedded with sandy and clayey layers are explained by the fact that the sediments were deposited in a rising body of water. The lacustrine beds are also characterized by the presence, in their lower portions at least, of fossil fresh-water shells. Fossil fresh-water shells also occur in some of the beach ridges at various altitudes up to 1,149 feet, or 88 feet above Lake of the Woods.

Unconformity at the base of Lake Agassiz sediments.—The evidence found in Rainy River district, which confirms Tyrrell's contention that Lake Agassiz had at first a rising stage, is based largely on the fact that the sediments deposited in Lake Agassiz rest unconformably upon the underlying deposits; that is, a period of erosion intervened after the deposition of the calcareous till and associated laminated stony clay, and before the later lacustrine sediments were laid down.

This is well shown in numerous sections exposed along the Rainy River and around the shores of the southern portion of Lake of the Woods. Fig. 1 illustrates the character of one of these sections which has been exposed by wave erosion on the present shore of Lake of the Woods at its southern side. At the base a

[1] Frank Leverett, "Surface Formations and Agricultural Conditions of Northwest Minnesota," *Minn. Geol. Soc., Bull. No. 12*, 1915, p. 37.

small thickness of calcareous till is exposed, passing up into laminated, stony clay which is overlain unconformably by Lake Agassiz lacustrine clays containing fresh-water shells. The contact is a wave-cut plain. The lacustrine deposits above the wave-cut plain are clayey in character and evenly and thinly bedded, so that it is evident that the water must have risen to a considerable height to permit of such deposition. In places around the southeastern portion of Lake of the Woods these lacustrine deposits are at least

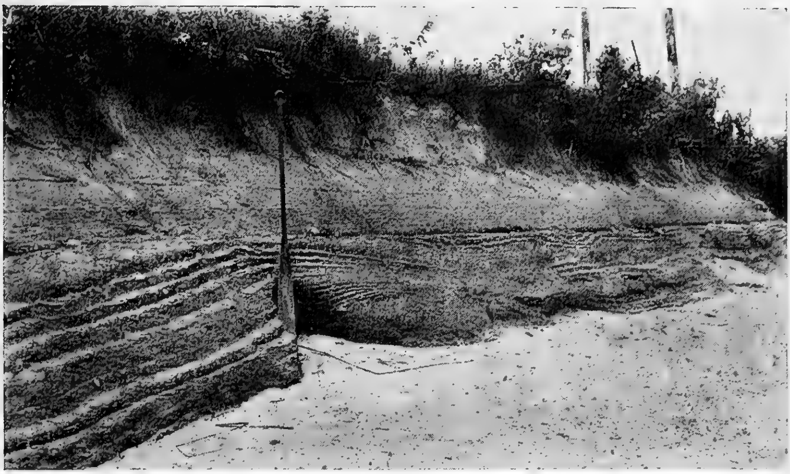

FIG. 1.—Section exposed on south shore of Lake of the Woods, showing at the bottom calcareous till passing upward into laminated, stony clays unconformably overlain by Lake Agassiz lacustrine clays. The contact is a wave-cut plain.

30 feet thick and rise to an altitude higher than the divide separating the Lake of the Woods basin from that of the Red River on the west. Furthermore, the first strong raised beach above the level of Lake of the Woods, at the level of which the water must have stood, if not at some higher level, when the lacustrine deposits were laid down, is in the southern portion of the district from 45 to 55 feet above the level of Lake of the Woods; and this beach passes over the divide to the southwest of the lake.[1] Hence it follows that these lacustrine deposits were not laid down in a local lake

[1] *Minn. Geol. Survey, Bull. No. 12,* 1915 (map).

but in a body of water which covered not only the Rainy River and Lake of the Woods districts but also occupied Red River valley, and that this was the last great glacial-marginal lake in the region, viz., Lake Agassiz.

Numerous sections also show that weathering and erosion took place during the interval of erosion before the deposition of Lake Agassiz sediments. This is well shown in sections along the Rainy River from one to three miles below the town of Rainy River. In places, small stream valleys were eroded and later partially or wholly filled with lacustrine deposits. This relation is well seen in the small creek valley which enters the Rainy River three miles below Fort Frances. In one place, on Buffalo Point on the southwest side of Lake of the Woods, thin peaty bands occur in the lower portion of Lake Agassiz deposits.

The sections exposed on the south shore of Lake of the Woods (Fig. 1) afford a demonstration that the water must have risen to a sufficient height to permit of the deposition of the fine lacustrine clays overlying the old wave-cut beach, and it is clear that these waters formed part of Lake Agassiz during a rising stage. There is evidence in the district that the waters rose through a vertical interval of at least 60 feet; for the lake clays are unconformable on the underlying sediments throughout this vertical interval. The highest shore line found in Rainy River district has an altitude of 1,200 feet. During the highest stages of the lake, practically the entire district was submerged and the highest shore line, if there had been land high enough to have received it, would have a present altitude of approximately 1,350 feet, as estimated from Upham's determination of the highest beaches in other parts of the basin. It is not certain that the water rose to the level of the highest shore lines recognized in other portions of the basin; but it seems probable that it rose to the uppermost strong beach (Herman), because this beach, as already stated, is continuous for a long distance northward and is apparently all of one age. It is possible that the Milnor beach which Upham found to be traceable for only a short distance in the southern part of the basin marks a shore line of Early Lake Agassiz, but the extent of this lake or of any of its shore lines is not definitely known. This lake was largely drained before Lake Agassiz came into existence and its sediments are buried beneath those of Lake Agassiz.

It is at least certain that the waters of Lake Agassiz stood at one time at about the present level of Lake of the Woods, and that they later rose considerably higher. It seems probable also that the lake which preceded Lake Agassiz was almost completely drained, and that Red River valley was a land surface before the latest advance of the ice brought Lake Agassiz into existence; for the character of the deposits in Red River valley, which Upham[1] regarded as post-Lake Agassiz fluvial deposits, suggests rather that they are lacustrine deposits and that they are unconformable on the underlying sediments.

Regarding these deposits Upham stated:

> Thus the occurrence of shells, rushes and sedges in these alluvial beds at McCauleyville, Minnesota, 32 and 45 feet below the surface or about 7 and 20 feet below the level of Red River, of sheets of turf, many fragments of decaying wood and a log a foot in diameter at Glyndon, Minnesota, 13 to 35 feet below the surface, and numerous other observations of vegetation elsewhere along the Red River valley in these beds, demonstrate that Lake Agassiz had been drained away, and that the valley was a land surface subject to overflow by the river at its stages of flood when these remains were deposited.[2]

He also stated: "The deposits have commonly greater thickness and extent than the underlying silt of glacial Lake Agassiz."

It is evident that a land surface existed in Red River valley before these sediments were laid down; but it seems probable that the sediments are largely lacustrine in origin and not fluvial. G. M. Dawson, in describing the section across Red River valley near the international boundary stated that the valley is floored with a fine silty deposit, a portion of the upper layers of which may have been formed by the overflow of the river itself. He described the typical deposit as of great thickness and consisting of fine yellowish, marly, and arenaceous clay, holding considerable calcareous matter, and effervescing freely with an acid.[3] The great extent and thickness and the high calcareous content of the clays

[1] Warren Upham, *U.S. Geol. Survey, Monograph 25* (1895), p. 253.

[2] *Ibid.*, p. 202.

[3] G. M. Dawson, *Report on the Geology and Resources of the Region in the Vicinity of the Forty-ninth Parallel*, 1875, pp. 248–49.

would seem to show that they are lacustrine in origin and not fluvial. It seems probable that they are Lake Agassiz deposits and that they are unconformable upon the underlying sediments.

It is concluded, therefore, with Tyrrell, that after the retreat of the Keewatin glacier well toward the north there was comparatively free drainage to the north and that a later advance of the ice from the northeast was met by a slight readvance of the Keewatin glacier, which resulted in the ponding of the northward drainage and the inception of Lake Agassiz. It is not certain just how far the latest advance of the ice extended. It did not reach Rainy River district, for the calcareous till derived from Manitoba is not overlain by till derived from the northeast, and the southeastward- and eastward-bearing striae are not crossed by later striae. At Stony Mountain, near Winnipeg, southeastward-bearing striae cross striae trending nearly south, but are not themselves crossed by later striae. Tyrrell found that along the east side of Lake Winnipeg southwestward-bearing striae cross earlier striae bearing nearly southward.[1] Tyrrell[2] also held that the "Winnipeg Moraine" represented by islands in Lake Winnipeg and developed in places along the western shore of the lake marked the termination of the Labradorean glacier. It seems evident that during the life of the last great glacial marginal lake of the region, viz., Lake Agassiz, the ice margin in Manitoba was at no time farther south than the southern portion of Lake Winnipeg, and that the whole southern portion of the lake was practically free from ice. Lake Agassiz was associated with a readvance of the ice sheet, chiefly of the Labradorean glacier at a very late time during the Wisconsin stage of glaciation, and its disappearance followed the final withdrawal of ice sheets from the region.

BEARING OF THE LIFE-HISTORY OF LAKE AGASSIZ ON THE QUESTION OF THE CHARACTER AND CAUSE OF THE DIFFERENTIAL UPLIFT

If it is true, as seems probable, that during the existence of Lake Agassiz the ice border was far north of the southern end of the lake, this fact has an important bearing on the character and

[1] J. B. Tyrrell, *Amer. Geol.*, VIII, 21.

[2] *Bull. Geol. Soc. Amer.*, XXIII (1911), 733.

cause of the differential uplift which is shown to have taken place by the deformation of the shore lines of the lake.

It is known that the whole of the southern portion of the Lake Agassiz basin was affected by uplift but that the region south of the southern outlet of the lake was unaffected, for the abandoned shore line of Lake Dakota in this region is apparently nearly horizontal.[1] That is, there is a sort of "hinge-line" here. The location of this "hinge-line" was not due to "quick recovery of the crust by uplift" following removal of the ice from the immediate neighborhood, for the ice border was at least 250 miles north of the location of the "hinge-line."

The question also arises whether, as Chamberlin suggested, the land was being depressed during the time of advance of the latest ice sheet. It would be possible to determine this if the present altitude with respect to sea-level of the beaches which were made during the rising stage of the lake could be determined. It was found in Rainy River district that the strongest beach of Lake Agassiz apparently marks a long stand of the waters during the rising stage and again during the subsiding stage; for the beach deposits show evidence of having been partly eroded and spread out by the rising waters and beach ridges having a slightly different trend were later built on the older deposits. This would seem to show that the land was already depressed during the rising stage of the lake, but the evidence is not very conclusive. In the case of the "fossil" shore line seen in sections along the south shore of Lake of the Woods (see Fig. 1), it was found that the beach maintains the same altitude in a direction corresponding to the trend of the isobases of the beaches formed during the subsiding stage of Lake Agassiz. It is not known whether it rises toward the northeast, for unfortunately no record of its occurrence could be found in the northern part of Lake of the Woods.

The evidence suggests, but does not prove, that if, as seems probable, the uplift of the land was due to isostatic readjustment following the removal of the burden of the ice sheets, there was no close sympathetic relation; but that uplift lagged[2] considerably

[1] *U.S. Geol. Survey, Monograph 25*, p. 267.

[2] J. Le Conte, *Bull. Geol. Soc. Amer.*, II (1891), 329–30; W. B. Wright, *The Quaternary Ice Age*, 1914.

behind the removal of the great mass of the Wisconsin ice sheets and was only completed after the final retreat following the latest advance of the ice.

SUMMARY

Evidence bearing on the life-history of Lake Agassiz, found in the Rainy River–Lake of the Woods district, Ontario, confirms Tyrrell's conclusion that Lake Agassiz had at first a rising stage. The evidence is based largely on the fact that an unconformity exists at the base of the Lake Agassiz lacustrine sediments. The lake was associated with the latest advance of ice sheets, chiefly of the Labradorean glacier, during the Wisconsin stage of glaciation. An earlier glacial marginal lake, which is herein referred to as Early Lake Agassiz, was associated with a lobe of the Keewatin glacier; but this lake was largely if not wholly drained before Lake Agassiz came into existence. The latest advance of the ice into the Lake Agassiz basin did not extend farther south than the southern portion of Lake Winnipeg, so that the ice border of Lake Agassiz was at least 250 miles north of the southern end of the lake during the entire existence of the lake.

The acceptance of this interpretation of the genesis of Lake Agassiz has an important bearing on the question of the character and cause of the differential uplift which is shown to have affected the region by the deformation of the shore lines. The evidence suggests, but does not prove, that if the uplift was due to isostatic readjustment following the removal of the burden of the ice sheets, there was no close sympathetic relation, but that, as Le Conte and Wright have supposed, uplift lagged considerably behind and was only completed after the final retreat following the latest advance of the ice sheets of the Wisconsin stage of glaciation.

THE LOWER EMBAR OF WYOMING AND ITS FAUNA

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About ten years ago Mr. N. H. Brown sent me a few *Helodus* teeth from the Embar limestone near Lander, Wyoming, and in the summer of 1911 I had the good fortune to discover a rather abundant fish fauna in the same region and on Bull Lake Creek. In the former region the fossils occur about 25 feet from the bottom of the formation and their vertical range is little more than 3 feet, while in the latter they are found at from 35 to 38 feet from the bottom.

Blackwelder[1] and Woodruff[2] have reported two distinct faunas from the Embar, the upper of which Girty[3] refers to the Permian, but the fauna reported here is older and entirely distinct from the other two. Collections from bottom to top of the Embar in several localities show only one species common to the fish horizon and the upper horizons.

DESCRIPTION OF THE EMBAR LIMESTONE

The Embar formation lies conformably, for the most part, below the Chugwater formation on the eastern slope of the Wind River Mountains and without apparent unconformity above the Tensleep sandstone. In the Big Popo Agie region, near Lander, it is about 400 feet thick, is largely limestone, and bears three and perhaps more phosphate beds. The lowest bed is 23 feet from the bottom, ranges from 1 foot to 5 or 6 feet in thickness, and bears fish remains and *Orbiculoidea utahensis* in abundance. This bed has been traced some 15 miles southeastward along the strike and about 5 miles nothwestward. I have examined the same bed on

[1] Eliot Blackwelder, "New or Little Known Paleozoic Faunas from Wyoming and Idaho," *Am. Jour. Sci.*, XXXVI (1913), 177–79.

[2] E. G. Woodruff, "The Lander Oil Field," *U.S. Geol. Surv., Bull. 452* (1913), pp. 12–14.

[3] *Ibid.*, p. 13.

the North Fork of Little Wind River, 27 miles to the northwest, and on Bull Lake Creek, 35 miles to the northwest. On Bull Lake Creek it is 38 feet from the bottom and 3 feet 6 inches in thickness. This is probably the same bed that Blackwelder describes as occurring in Dinwoody Canyon 29 feet 8 inches from the bottom, 2 feet 2.5 inches thick, and containing *Lingulodiscina utahensis*. Wherever the bed was examined it contained fish remains, and *Orbiculoidea utahensis* in abundance.

In Big Popo Agie Canyon a 4-inch phosphate bed, as it was measured, but probably much thicker, occurs 58 feet from the bottom, and 6 miles southeast along the strike a bed 2 feet thick occurs 54 feet from the bottom, and is followed 10 inches higher by 14 inches of phosphatic shale. About 150 feet higher a 5-foot bed of gray phosphatic limestone is present in Big Popo Agie Canyon, and 6 miles southeast along the strike a 5-foot bed occurs at the same horizon. This is the bed that Blackwelder describes as occurring 12 miles west of Lander—"Brownish-gray oölitic and nodular phosphate rock full of *Productus subhorridus* and other fossils (42.4 per cent tricalcium phosphate)"[1]—4 feet 7 inches thick. This bed is readily distinguished from the lowest bed by its fauna. It contains *Producti*, spirifers, and *Spiriferina pulchra* in abundance, while the lower bed contains none of these.

The Embar limestone is well exposed in Little Popo Agie Canyon and the following description was worked out in 1913:

32.	Greenish sandy shales and limestones: covered with talus and with a bed outcropping here and there	75′ to 100′	
31.	Light-gray, highly siliceous limestone with the silica in druses as quartz and not as chert; this is the limestone that forms long dip slopes on the east side of the Wind River Mountains	29′	3″
30.	Light-gray, cherty limestone	10′	2″
29.	Dark phosphate		4″
28.	Gray, cherty limestone	5′	7″
27.	Dark-gray phosphate speckled with white		7″
26.	Green shale		8″
25.	Phosphate, black to dark-gray		3″
24.	Dark-gray, siliceous limestone	3′	..

[1] Eliot Blackwelder, "Reconnaisance of the Phosphate Deposits in Western Wyoming," *U.S. Geol. Surv., Bull. 470*, p. 477.

23.	Phosphate like No. 25		1″
22.	Limestone like No. 24		10″
21.	Phosphate like No. 25		3″
20.	Gray, cherty limestone	3′	2″
19.	Shale, drak-gray to bluish-gray, calcareous, somewhat nodular	23′	..
18.	Dark phosphate with thin layers of gray phosphate	2′	6″
	In another place the details of this bed (No. 18) were as follows:		
	Phosphate . . . 8″		
	Yellow limestone . . . 4″		
	Phosphate . . . 2″		
	Yellow limestone . . . 8″		
	Phosphate . . . 4″		
	Yellow limestone . . . 4″		
17.	Light gray, compact limestone, glauconitic in places	4′	..
16.	Greenish, sandy shale, covered but near the surface (the talus was removed in places with picks in order to examine the rocks)	12′	..
15.	Light-gray, compact, even-textured limestone	20′	..
14.	Like No. 16	29′	..
13.	Light-gray, coarse-grained, compact, thin-bedded limestone	3′	6″
12.	Covered, but the rock in place within a few inches of the surface; seems to be of greenish and yellowish shale	73′	..
11.	Light-purple, very compact limestone	1′	..
10.	Light-gray, compact limestone	14′	..
9.	Light-bluish-gray, friable limestone containing many nodules of calcite	2′	9″
8.	Light-gray rock composed largely of chert nodules	1′	..
7.	Light-gray, compact limestone; fragments of fossils abundant, and in some places these have been dissolved out, leaving the rock porous; *Orbiculoidea utahensis* abundant	1′	6″
6.	Light-gray, cherty limestone crowded with small geodes with calcite interiors	5′	..
5.	Dark-gray to black phosphate packed with *Orbiculoidea utahensis;* this is the horizon of the fish teeth, but they are rare along the Little Popo Agie	3′	6″
4.	Light-gray, compact limestone containing many bryozoans and crinoid stems	1′	..
2.	Light-gray limestone, in some places almost all chert; usually stands in vertical cliffs	11′	..
1.	Cherty, in some places nodular, thin-bedded, closely-jointed, light to dark-gray limestone; mostly covered	14′	..
	Total	375′	11″

The Tensleep contact is assumed to be at the top of a few feet of thin-bedded sandstone.

The phosphate exposures are in vertical cliffs and could not be better. Nos. 20 to 29 probably represent the upper phosphate bed in the Big Popo Agie Canyon region. The rocks above the lowest phosphate horizon contain few fossils and cannot be correlated by means of them.

The rock in which the fish remains occur is a sort of coquina, made up, for the most part, of pedicle valves of *Orbiculoidea utahensis* (I have seen only one brachial valve). Remains of many small pelecypods and gastropods are common. Just below the phosphate there is a silicified coquina made up almost entirely of pelecypod shells so closely packed that it is almost impossible to get out a good one.

The fish fauna contain six species that also occur in the Upper Coal Measures of the Mississippi Valley and one species that is known only from the Middle Carboniferous (Moscowian) of Samara, Russia. Stuckenberg[1] figures it as "genus et sp. indeter.," but gives no description, and the writer had described it as a new genus before seeing his paper. The genus is so widely different from any other that its presence in the two regions is significant for correlation purposes. One species, *Cladodus occidentalis*, occurs in the Embar, the Upper Coal Measures of the Mississippi Valley, and the Moscowian.

The invertebrates in the fauna are mainly gastropods and pelecypods and are poorly preserved. Most of the identifications are uncertain, but nearly all the specimens may be referred to species that occur in the Coal Measures of the Mississippi Valley.

DESCRIPTIONS OF SPECIES OF EMBAR FISHES

Helodus subpolitus n. sp. (Pl. I, Figs. 6–16)

The teeth of this species resemble those of *Helodus politus* so closely that they are not distinguishable in every case, but the differences are constant enough to warrant recognition.

The teeth are of various forms and sizes, generally oblong and with rounded or quadrangular ends, and slightly arched in both direc-

[1] A. Stuckenberg, "Die Fauna der obercarbonischen Suites des Wolgadurchbruches bei Samara," *Memoires du Comité Géologique*, Nouvelle Série, Livraison 23, 1905.

tions. The crown is smooth but shows a tendency to become convoluted in old age; the surface is finely and evenly punctate. Convex lateral margins terminate in a rounded edge with incipient crenulations in old forms. The concave edge is vertical and has evenly spaced crenulations on the lower half. The smaller teeth are more strongly arched in both directions than the larger.

This species differs from *Helodus politus* in having the crenulations on the sides of the teeth evenly spaced, while they are generally unevenly spaced in the latter form; they are regular in size in this form, but irregular in *H. politus;* of almost uniform width from top to bottom, but thicker at the bottom in *H. politus;* they are longer than in *H. politus.* The crenulations are generally on a retreating edge, while those of *H. politus* are on a protruding edge. *H. politus* teeth have a tendency to form a marked projection, almost a boss, in the middle of the tooth, while this is only rarely present in *H. subpolitus. H. subpolitus* becomes convoluted in old age; this is not true of *H. politus.*

These teeth are the most abundant in the Embar formation but their vertical range was not found to be more than 4 feet. More than 300 specimens are in the paleontological collection of the University of Missouri.

Helodus rugosus N. and W. (Pl. II, Fig. 20)

1870. *Helodus rugosus* N. and W., *Geol. Surv. Ill.*, IV, 359, Pl. II, Fig. 10.
1889. *Helodus rugosus* Woodward, *Catalogue of Fossil Fishes in the British Museum*, Part I, p. 227.
1903. *Helodus rugosus* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 182–83, Pl. 2, Fig. 14.

One Embar specimen agrees with the original description of this form, though the peculiar surface marking is indistinct.

Crassidonta stuckenbergi gen. and sp. new (Pl. I, Figs. 17–27)

The main part of the tooth is a short, symmetrical, rounded ridge with its long axis in the line of the long axis of the tooth, and flanked on either side by narrow, thickened, winglike extensions. The ridge makes up two-thirds of the height of the tooth and one-half of the width. Its sides are steep and the top is gently rounded transversely and arched longitudinally. Near one end the longitudinal arching is sharply increased. The crowns of the smaller teeth are smooth, but in older forms incipient, transverse wrinkling appears, and is more prominent on the wings. The ends of the central ridge project beyond the base. The base is a rhomboid with obtuse angles of slightly more than 100 degrees. The wings project downward and give to the bottom of the teeth a trough-like appearance, with the trough slightly deeper in the middle. In the largest specimen the greatest thickness is about 15 mm., the greatest length 34 mm., and the greatest width 28 mm. The average size is considerably smaller. The crown surface is closely and evenly punctate with subcircular punctations.

Co-types of it are 31 specimens from the Popo Agie and Bull Lake regions. It is No. 703 of the paleontological collection of the University of Missouri. About 25 other fragments of teeth are in the collection. Owing to the thickness of the teeth they are usually well preserved.

The foregoing description was written before the writer had seen Professor Stuckenberg's paper, "Die Fauna der obercarbonischen Suites des Wolgadurchbruches bei Samara,"[1] in which he figures the same species but lists it as "genus et sp. indeter.," and does not describe it. Stuckenberg's figures are reproduced in Pl. I, Figs. 22–24.

Campodus corrugatus Newberry and Worthen (Pl. III, Figs. 1–6)

1870. *Orodus corrugatus* N. and W., *Pal. Ill.*, IV, 358, Pl. III, Figs. 18 and 18a.
1875. *Agassizodus corrugatus* St. J. and W., *ibid.*, VI, 323–24, Pl. VIII, Fig. 24.
1879. *Chiastodus obvallatus* Trautschold, *Nouv. Mem. Soc. Imp. Natur. Moscou.*, XIV, 156–57, Pl. XVIII, Figs. 19a–d.
1889. *Campodus corrugatus* Woodward, *Cat. of Fossil Fishes*, Part I, p. 239.
1902. *Campodus corrugatus* Eastman, *American Naturalist*, XXXVI, 853–54, Fig. 2.

Trautschold's figures of *Chiastodus obvallatus* from the Moscowian of Russia are reproduced in Plate III for comparison with a specimen from above coal No. 5 at Galatea, Illinois, and the differences seem too small to recognize as specific. The Russian specimen has deeper lateral lobations than the one figured, but a specimen in the Walker Museum of the University of Chicago has lobations of about equal depth. The surface ridges appear more

[1] *Mémoires du Comité Géologique*, Nouvelle Série, Livraison 23, 1905.

pronounced in two of the drawings of the Russian specimen, but the third drawing of the same tooth places less emphasis on this character.

Campodus corrugatus has been reported from both the Upper and the Lower Pennsylvanian, but the identifications are uncertain. Those identified from the Lower Pennsylvanian are all from the lateral series of teeth and those from the Upper are from the median series.

This species is not known to be present in the Embar, but is listed here to show the relationship of Mississippi Valley strata, of the same age as the Embar, with the Moscowian of Russia.

Campodus sp. undet. (Pl. II, Figs. 21 and 21a)

A small tooth from the Embar may belong to *Campodus variabilis* N. and W. It differs from the figured forms of the lateral series in being narrower and having more numerous and more regular ridges crossing the top, but *C. variabilis* is highly variable in this respect.

It is of interest to note that *Campodus variabilis* seems to occur in the Moscowian at Gshel, Russia. Trautschold described as *Arpagodus rectangulus*[1] a form that cannot be distinguished from teeth of the lateral series as figured by St. John and Worthen.[2]

Cochliodont gen. and sp. not determined (Pl. IV, Fig. 8)

Two fragments that seem to represent the outer ends of teeth of a large cochliodont cannot be referred to any genus. They may belong to a described genus, but are too fragmentary for reference. The tooth thins and narrows toward the outer end, but does not twist, as is the case with most cochliodonts.

Janassa unguiformis St. J. and W. (Pl. II, Figs. 1–4)

1870. *Peltodus unguiformis* N. and W., *Geol. Surv. Ill.*, IV, 362–63, Pl. II, Figs. 7 and 7a.

1889. *Janassa unguiformis* Woodward, *Catalogue of Fossil Fishes in the British Museum*, Part I, p. 39.

One specimen from the Embar appears to belong to this species, and a specimen from the Upper Pennsylvanian of Missouri is also

[1] Trautschold, *Nouv. Mem. Soc. Imp. Natur. Moscou.*, Vol. XIV, Pl. XVII, Figs. 12a–d.

[2] St. John and Worthen, *Pal. Ill.*, Vol. VI, Pl. VIII, Figs. 1–22.

referred to it. They are much larger than the type, but appear to agree with it in every other respect. The present location of the type was not ascertained.

Janassa unguicula Eastman (Pl. II, Figs. 7–18)

1903. *Janassa unguicula* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 173–74, Pl. II, Fig. 13.

1903. *Janassa unguicula* Woodruff, *Nebr. Geol. Surv.*, Vol. II, Part II, p. 288, Pl. XVIII, Fig. 8.

Classed together under this species are 25 teeth that would probably be referred to two genera and four species if they were isolated. Fig. 7 of Pl. II stands at one end of this series and Figs. 8 and 9 at the other end, and the series arranged to show small variations would be Figs. 7, 17, 16, 14, 12, 10, 9, and 15.

All of the teeth have part of the root missing but the one shown in Figs. 13 and 14 is nearly complete. The teeth range in width from 11 mm. to 19 mm., and one imperfect tooth seems to have been 25 mm.; the length is indeterminate; the thickness at the thickest part is 2 mm. to 6 mm. In every specimen the cutting edge is more or less worn and rather dull. The edge ranges from almost straight to bilobed, with three sharp cusps, the lateral ones much larger than the other. Numerous dentine tubules run lengthwise a short distance below the surface of the tooth and turn outward almost at right angles near the surface. Near the cutting edge the surface of many of the teeth is worn or eroded until the longitudinal tubules are open, as shown in Figs. 7, 10, 14, and 17, and on the rest of the surface the vertical tubules open, giving a finely punctate appearance. Teeth that are unworn are not punctate at the surface.

Three teeth have small longitudinal ridges on the posterior face, as shown in Fig. 8, but as some that agree with these in other respects lack the ridges their presence is not considered of much value in classification.

The anterior surface of the parts preserved is strongly and regularly convex and the posterior face regularly but much less strongly concave. The mark of the overlapping tooth appears on almost every specimen and is shown in nearly all of the figures. Fig. 10 shows overlap to near the cutting edge, while Fig. 17 has much less overlap. The shape of the overlapping tooth is rarely the same as that of the tooth which it overlaps, and it is significant that none of the overlapping teeth are lobed. Fig. 10 lay next to a much narrower tooth, while all of the rest were overlapped by teeth of almost their own size.

This series indicates that some genera and several species of this type of teeth will probably prove to be invalid when more specimens are known. Eastman[1] says that the chief characteristic distinguishing this genus (*Fissodus*) from *Janassa* is that the trenchant margin is cleft or divided into two or three broad acuminate points; but that characteristic seems not to be of specific value in this case.

The type of *Janassa unguicula* would be like the tooth shown in Fig. 14, if the slight lobation of the latter were not present, and it is like that shown in Fig. 15, but the latter is a worn tooth, while the type is not worn. The type is not as thick and strong as the Embar teeth.

A specimen from Nebraska that Eastman refers to, *Fissodus inaequalis* St. J. and W., has the cutting end almost exactly duplicated in four specimens from the Embar, one of which is shown in Fig. 7 of Pl. II. This specimen is not preserved to the region where the posteriorly curved folds occur on the Nebraska form, and they were probably not present in the Embar tooth, as they do not appear on other teeth that have that part preserved.

The Carlinville, Illinois, specimen (Fig. 18 of Pl. II) is much thinner than those from the Embar but otherwise agrees with them.

Janassa angularis n. sp. (Pl. II, Figs. 5 and 6)

The type specimen of this species is incomplete but presents some marked peculiarities. From the cutting edge, which is 17 mm. wide, the tooth narrows gradually toward the other end, but only 14 mm. of the length is preserved and the condition at the missing end is not known. The cutting end is sharply curved and much worn. It seems to have been lobed originally, but wear has reduced the projecting points to the level of the bottom of the lobe. On the convex surface, 7 mm. from the edge, a shallow groove

[1] *Bull. Mus. Comp. Zoöl.*, XXXIX, 174.

less than 4 mm. wide and bounded on either side by a sharp crested ridge runs toward the narrow end. The lateral edges are sharp. Six to ten narrow grooves run parallel with the margins on each side of the tooth, beginning 11 mm. from the outer end, extending outward for 7 mm., and bifurcating and becoming obsolete in passing outward. Next to the lateral margins close-set grooves that pass backward and outward intersect the longitudinal grooves at an angle of about 45°. The concave surface of the tooth is marked with close-set longitudinal grooves formed by the etching of the surface, and opening the longitudinal pores.

Deltodus mercurii Newberry (Pl. V, Figs. 1–11; Pl. II, Figs. 27 and 28; Pl. VI, Figs. 1–6)

1876. *Deltodus mercurii* Newberry, J. N. Macomb, *Rept. Exp. Exped. from Santa Fe, N.M., to the Junction of the Grand and Green Rivers of the Great Colorado of the West*, p. 137, Pl. 3, Figs. 1, 1a.

1883. *Deltodus powellii* St. J. and W., *Geol. Surv. Ill.*, Vol. VII, 154–56, Pl. IX, Figs. 1a–f.

1883. *Deltodus mercurii* St. J. and W., *Geol. Surv. Ill.*, Vol. VII, Pl. X, Figs. 2a–d.

1883. *Deltodus propinquus* St. J. and W., *Geol. Surv. Ill.*, VII, 156–58, Pl. X, Figs. 4a–e (not Figs. 3a–e).

1889. *Deltodus mercurii, Deltodus powellii,* and *Deltodus propinquus* A. S. Woodward, *Catalogue of the Fossil Fishes in the British Museum*, Part I, pp. 200–201.

Newberry described *Deltodus mercurii* from one imperfect specimen and St. John and Worthen described *Deltodus propinquus* from three specimens. The following descriptions are based on a large series, though only a few teeth are nearly perfect. Some specimens from the Embar agree with the figures of *D. powellii*, others in the same series agree with the mandibular teeth described as *D. propinquus*, and others with *D. mercurii*. St. John and Worthen suggested[1] that a large series might show these forms to be conspecific.

The maxillary teeth are large, of medium width compared to the length; the posterior margin is strongly arched, with an angle between the outer and inner ends of the crown of about 147°; the anterior margin is almost straight. The inner end of the tooth is

[1] *Op. cit.*, p. 158.

thick, thinning rapidly outward from the summit of the arch on the posterior edge, and not quite so abruptly about the middle of the anterior edge. The anterior edge is turned downward at the outer end, giving to the end a twisted appearance, without causing it to be greatly recurved. A broad depression runs from the outer end to the inner at about the middle of the tooth. At the outer end this depression is very shallow and has no well-defined bounding ridge in front. The entire coronal surface is marked by rather strong, subequally spaced, transverse undulations, three to six of which are unusually deep in front of the top of the arch. In most specimens wear has reduced the surface until the deep undulations are the only ones remaining, and in some specimens the undulations seem never to have been very pronounced.

No tooth from the Embar agrees perfectly with the figures and descriptions of the type of *D. propinquus*, but the similarity is striking. Unfortunately the type of maxillary tooth of this species could not be found and the identifications had to be made entirely from figures and descriptions. *D. mercurii* and *D. powellii* were described from mandibular teeth only.

The mandibular teeth are broad and short, thick at the broad end and thinning rapidly toward the narrow end; they are strongly arched longitudinally along the anterior edge but gently curved to nearly straight along the posterior edge; the narrow end is curved to form a semicircle, but this is preserved in only one specimen. The teeth are divided into anterior and posterior parts by a furrow that runs from the outer to the inner end at about one-third of the width from the posterior edge. The furrow is broad and shallow at the outer end and narrows to a deep groove near the inner end. The part in front of the furrow is much elevated, and in the middle is crossed by two to four transverse grooves that often become deep pits on the front edge of the furrow and do not cross the hinder ridge. The outer end has no hinder ridge, but back of the middle a ridge becomes prominent and a sharp narrow part of it borders the furrow. The most perfect teeth show the origin of this posterior ridge. Originally it seems to have been a thin, flat, winglike expansion, which later doubled back on itself for 1 cm. and crumpled up at the place where the fold occurred. In some specimens the upper part lies on the lower without having become cemented to it, while in others the evidence of folding is lacking. Behind this ridge there is, in some cases, a short, shallow, longitudinal depression. The entire coronal surface is marked by subequally spaced transverse undulations that are often indistinct.

The foregoing description refers to the large teeth. The smaller teeth lack the conspicuous posterior ridge and the strong transverse undulations, and the longitudinal furrow is less pronounced.

Fig. 10 of Pl. V shows the undulations very well, but no good specimen shows them distinctly enough over the entire surface to permit of their being brought out in a photograph, though they are readily traceable on the teeth themselves. The presence of the strong undulations suggests the formation of the large teeth by the union of several smaller teeth, but the older teeth have much the stronger undulations, unless they are reduced by wear, and the small teeth are nearly smooth.

Comparison with the type of the maxillary tooth, which is preserved in the Illinois State Museum, discloses some differences. The Wyoming teeth are larger and thicker compared to other dimensions. The Illinois specimen has subequal longitudinal ridges which are lacking in the Wyoming form. The surface of the Illinois form is marked by a sort of reticulate, threadlike network which is not present in the Wyoming specimens; but there is only one specimen of the Illinois form and there are many of the Wyoming. Specimens no larger than the type are in the collection, but they are proportionately thicker. Some specimens show irregular and discontinuous longitudinal ridges. The network on the Illinois specimen is preserved where the tooth is not worn, and all of the Wyoming specimens are worn.

I am inclined to think that the Wyoming maxillary teeth are not specifically identical with the Illinois form, and I also think that St. John and Worthen's types of mandibular and maxillary teeth from Illinois are not conspecific. The Wyoming and Illinois mandibular teeth seem to belong to the same species.

Comparison with the type of *D. mercurii* discloses very close agreement. The transverse grooves are inconspicuous on account of wear and the small size of the specimens, but the location of the grooves is easily made out.

Associated with the other specimens are forms of the following description that belong with the lower teeth. The teeth are long, slender, and narrow gradually toward the strongly arched inner end. The inner end forms a 35° arc of a circle 11 cm. in diameter; the outer end forms a 90° arc of a circle 35 mm. in diameter. The tooth is thick along the hinder margin to near the outer end, and thin along the front margin to near the outer end, where it sometimes becomes knifelike. A high, rounded ridge with a narrow top forms the greater part of the tooth. From the top of the ridge the surface slopes steeply to the back margin and almost as steeply toward the front, where the slope becomes gentle and the edge is slightly upturned. The surface is marked by undulations of the same type as on the maxillary teeth, but these are often indistinct. The surface punctation is fine. Only a few of the teeth show strong wear, and this is at the top of the arch and toward the front end.

These teeth were compared with the fragment described by St. John and Worthen and agree with it in every way, except that they are more massive.

The most striking peculiarity of *Deltodus mercurii* is the strong, subequally spaced, transverse undulations, but in many specimens these are inconspicuous or absent.

Trautschold[1] figures and describes as *Poecilodus grandis* part of a tooth that probably belongs to *Deltodus mercurii*.

The restoration.—The *Deltodus mercurii* teeth from the Embar all come from the same horizon, and there appears to be no other species of Deltodus associated with them. They thus afford a chance for determining their arrangement in the jaws. The teeth figured in Pl. V, Figs. 3 and 5, were found in the matrix within 6 inches of each other, and they fit perfectly as upper and lower dental plates. As shown in Pl. V, Figs. 2 and 4, the mandibular teeth are much more strongly curved than the maxillary, and the narrow teeth described above fit against them as shown in Pl. III, Figs. 1 and 3. By working a mandibular tooth against modeling clay a depression of the same kind as shown in the teeth figured is formed in the clay.

The maxillary tooth is not adapted to fit against any other teeth, and no teeth that seem to belong in the same jaw were

[1] *Nouv. Mem. Soc. Imp. Natur. Moscou.*, XIV, 149–50, Pl. XVII, Figs. 13a and b.

found. There are holodont teeth in abundance in the phosphate bed that bears *D. mercurii*, but there seems to be no way of associating them with the *Deltodus* teeth.

In 1905 the writer differentiated *Sandalodus* from *Deltodus* on the basis of the theory that the former had only one tooth to each ramus of the jaw and the latter three.[1] The present investigation indicates the correctness of the conclusion that *Sandalodus* had only one tooth in each ramus, but this was a maxillary tooth, and the *Deltodus* teeth are mandibular of the same species. One of the evidences given by Branson that *Deltodus* had three teeth to each ramus was the truncated or grooved anterior edge of the median teeth, adapted for articulation with other teeth. The restoration here given shows the median teeth articulating with each other and dispenses with the probability that there was a third tooth in each ramus. It is probable that the dentition of forms described from the Mississippian of the interior may be reconstructed, and the writer intends to attempt such reconstruction.

The restoration presented in Pl. VI, Figs. 1–3, is the result of the study of a large series of teeth and is believed to be approximately correct.

The right maxillary tooth is modeled and the left is perfect. The right outer mandibular has the outer end restored and the left inner mandibular is restored at the outer end. The extent of restoration is easily determined in the photograph. Fig. 1, showing the upper and lower dentition apposed, probably represents the back end of the jaws, and the teeth were probably deeply inserted.

Cladodus occidentalis Leidy (Pl. II, Figs. 23 and 24)

1859. *Cladodus occidentalis* Leidy, *Proc. Acad. Nat. Sci. Phila.*, p. 3.
1866. *Cladodus mortifer* Newberry and Worthen, *Geol. Surv. Ill.*, II, 22, Pl. I, Fig. 5.
1870. *Cladodus mortifer* St. John, *Proc. Am. Phil. Soc.*, XI, 431.
1872. *Cladodus mortifer* St. John, *Final Rept. U.S. Geol. Surv. Nebr.*, p. 239, Pl. III, Fig. 6; Pl. VI, Fig. 13.
1873. *Cladodus occidentalis* Leidy, *Rept. U.S. Geol. Surv. Territ.*, I, 311, Pl. XVII, Figs. 4–6.
1897. *Cladodus mortifer* Newberry, *Trans. N.Y. Acad. Sci.*, XVI, 285, Pl. XXII, Fig. 2.
1903. *Cladodus occidentalis* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 168, Pl. II, Figs. 3, 8, and 9.

[1] E. B. Branson, *Jour. Geol.*, XIII, 26.

Four imperfect specimens and several fragments of this species were collected. They agree with St. John's excellent description of 1872 except in two minor details. The striae on the main cone project nearly to the summit instead of only half-way. St. John does not figure any specimens with the summit of the cone preserved, and this part of the description probably came from Newberry and Worthen's description of *Cladodus mortifer*. The lateral denticles do not have sharp cutting edges except as these are formed by one more prominent ridge on each side.

This species has been reported from the Upper Coal Measures near Springfield, Illinois, southwestern Iowa, Manhattan, Kansas, Nebraska City and Table Rock, Nebraska, and from the Coal Measures of Indiana and the Permo-Carboniferous of Roca, Nebraska.

Trautschold[1] identified a form from the Moscowian as *Cladodus lamnoides* Newberry and Worthen, but his figures and descriptions indicate *C. occidentalis*, and, as other species are common to the Moscowian and the Upper Pennsylvanian of the Mississippi Valley, this is probably the correct reference.

ICHTHYODORULITES

Ctenacanthus browni n. sp. (Pl. IV, Fig. 7, and Text-Fig. 6)

The holotype is an imperfect spine. The part preserved is 13 cm. long, 2 cm. wide at the outer end, and 27 mm. wide at the inner. None of the inserted portion is retained. The curvature is very slight. The pulp cavity at the outer end is 7 mm. by 2 mm., and at the inner end 11 mm. by 4 mm. The surface is ornamented by 20 to 23 longitudinal, smooth, closely spaced costae that are slightly wider than the intercostal spaces and are imperfectly divided into three sets. In the anterior set there are 4 costae and 4 intercostal spaces in 5 mm., in the second there are 6 costae and 6 intercostal spaces in 5 mm., and in the third 7 or 8 in 5 mm. The costae in the first set are high and narrow, in the second set narrower and about half as high, and in the third of about the same width as in the second, but very low and becoming obsolete at the back. The posterior face of the spine is slightly excavated, contains closely

[1] "Die Kalkbruche von Mjatschkowa: Eine Monographie des obern Bergkalks," *Nouv. Mem. Soc. Imp. Natur. Moscou*, XIII, 10–12, Table I, Figs. 3a–e.

spaced, linear markings, and has lateral margins, with denticles obscure or lacking. The anterior face is marked by a high, thin, almost knifelike ridge.

This species is named for N. H. Brown, who collected the first fishes from the Embar and who has rendered many valuable services to geologists working in the Lander region.

Ctenacanthus obscuracostatus n. sp. (Pl. IV, Fig. 2, and Text-Figs 2 and 3)

This imperfect spine differs from that last described in that the ribs are much finer and lower, in that they change gradually from coarser behind to finer in front, and in that the spine narrows to a knifelike edge in front. It agrees with the other spine in the absence or obscurity of ornamentation.

The length of the part preserved is 165 mm., the width 27 mm. at the outer end and 41 mm. at the inner. It was inclined backward at a sharp angle. A large part of the inserted end is missing, but in the part preserved the pulp cavity is open at the back for more than 6 cm. The cavity is shown at the outer and inner ends of the spine in Figs. 2 and 3.

Ctenacanthus amblyxiphias Cope (Pl. II, Fig. 25, and Text-Fig. 5)

1891. *Ctenacanthus amblyxiphias* Cope, *Proc. U.S. Nat. Mus.*, XIV, 449, Pl. XXVII, Fig. 3.

1903. *Ctenacanthus amblyxiphias* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, Pl. 2, Figs. 22 and 23.

1903. *Ctenacanthus amblyxiphias* Woodruff, *Geol. Surv. Nebr.*, II, Part II, 288, Pl. XVIII, Fig. 5.

1911. *Ctenacanthus amblyxiphias* Hussakof, "Revision of the Amphibia and Fishes of the Permian of North America," *Carnegie Institution Publication No. 146*, pp. 161–62, Pl. 30, Figs. 6 and 6a.

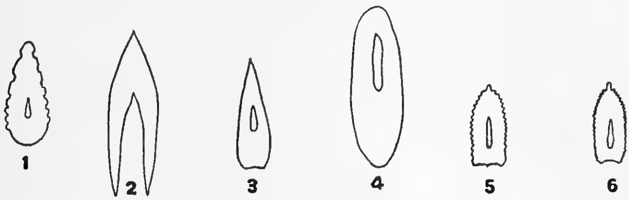
This fragment is referred provisionally to Cope's species though it does not agree with his description in these respects: that the ribs do not become smaller posteriorly so as to be of half the diameter of the anterior ribs and that there are no tubercles on the posterior margins. Most of the ornamentation has weathered off, but that preserved agrees with Eastman's figures and not with Cope's.

Eastman makes definite reference to the locality and formation from which the specimens that he figures were collected, but Cope and Hussakof give their specimens as from the Permian of Texas.

As considerable doubt has recently been expressed concerning the age of much of the so-called Permian of Texas, it is not safe to give the range of this species as extending into the Permian without more specific data.

Eunemacanthus keytei n. sp. (Pl. IV, Fig. 1, and Text-Fig. 1)

The preserved part of this spine is only 35 mm. in length but includes parts of both exserted and inserted portions. The pulp cavity is small and completely inclosed. The front of the spine is formed of one rounded enameled ridge. Next to the inserted



FIGS. 1–6.—(1) Cross-section of spine of *Eunemacanthus keytei* Branson; (2) cross-section of spine of *Ctenacanthus obscuracostatus* Branson, at base of preserved part; (3) cross-section of spine of *Ctenacanthus obscuracostatus* Branson, at outer end of preserved part; (4) cross-section of spine of *Batacanthus gigas* Branson, at outer end of preserved part; (5) cross-section of spine of *Ctenacanthus amblyxiphias* Cope; (6) cross-section of spine of *Ctenacanthus browni* Branson.

part, one side has 9 broad, flat-topped ribs, and the other 8 such ribs. The space between the ribs is narrower than the ribs, flat-bottomed, and marked with longitudinal striae formed by the out-cropping of longitudinal pores. The ribs increase downward by bifurcation and probably by implanation. The back of the spine is convex and is marked by about 25 striae formed in the same way as those between the ribs. The spine tapers rapidly and the exserted part seems to have been about 10 cm. long.

This form differs from *E. costatus* N. and W.[1] in tapering more rapidly and in the convexity of the back.

The species is named for I. Allen Keyte, of Colorado Springs, Colorado, whose untiring zeal in collecting added many specimens to the cabinets of the University of Missouri.

[1] *Geol. Surv. Ill.*, VII, Pl. XXIII, Fig. 2.

Batacanthus gigas n. sp. (Pl. IV, Figs. 3–6, and Text-Fig. 4)

The holotype is a spine with outer and inner ends missing. The part preserved is 26 cm. long, 41 mm. wide at the outer end, and about 65 mm. wide at the inner. If the rate of tapering did not change in the missing parts, about 18 cm. are gone from the outer end and about 8 cm. from the inner. The spine is much compressed, narrowly oval in outline, without flattening on the back edge and with only an indication of an angle on the front. It is so poorly preserved that the ornamentation over most of the surface cannot be made out. Sharp-topped, ribbed denticles lie in close-set rows parallel to the front edge, and the presence of a few elongated, low denticles, set diagonally near the front edge, suggests a type of ornamentation like that in *Xystracanthus mirabilis* St. John and Worthen.[1]

The preservation does not permit of the determination of the angle of insertion of the inner end. The pulp cavity is not large at the inserted end and is open at the back for about 12 cm. After becoming closed it takes its course near the back of the spine.

This species may be recognized by its large size, oval shape, and ornamentation.

Spine denticles of an Elasmobranch (Pl. II, Fig. 26)

Isolated specimens of little, cone-shaped denticles shown in this figure are abundant wherever the lowest phosphate bed was examined and several specimens with a number of associated denticles are in the collection, but they have not been found attached to spines. In some specimens three layers of denticles occur and the individuals of the overlying layers alternate with those of the underlying. The denticles are smooth, semicircular to hexagonal in outline, irregular in size, have thin walls, and are strongly concave from below.

VALUE OF PALEOZOIC FISHES IN CORRELATING STRATA

Fish remains have been used very little in exact correlation of formations, but they should be of high value for such purposes. As fishes swim freely and as few have their habitat determined by

[1] *Geol. Surv. Ill.*, VI, Pl. XX, Fig. 1.

depth of water, most species are widely distributed. As most of them are not bottom dwellers, their remains are about as likely to be found in one kind of rock as in another. The time range of most species is small. Of 112 species of cochliodont sharks listed by Hay in his *Bibliography and Catalogue of Fossil Vertebrates*, only three have a vertical range of more than one formation and the identifications in the three cases are not always reliable. The wide distribution, independence of bottom conditions, and small vertical range make them of particular value in correlating strata. But unfortunately most fossil fishes are labeled, as the older collections of invertebrates were, as from a given locality and formation, without more specific data.

The writer has been at work for several years in trying to assemble the data on fossil fishes for use in correlation.

INVERTEBRATES FROM THE LOWER EMBAR

Orbiculoidea utahensis Meek (Pl. III, Figs. 22–25)

1877. *Discina* sp. undet. Meek, *U.S. Geol. Expl. 40th Par., Rept.*, IV, 99, Pl. 10, Fig. 3.
1877. *Discina utahensis* Meek, *ibid.*, IV, 99.
1910. *Lingulidiscina utahensis* Girty, *U.S. Geol. Surv., Bull. 436*, pp. 24–25. Pl. I, Fig. 11.
1911. *Lingulidiscina utahensis* Woodruff, *U.S. Geol. Surv., Bull. 452*, p. 13.
1911. *Lingulidiscina utahensis* Blackwelder, *U.S. Geol. Surv., Bull. 470*, p. 477.
1913. *Lingulidiscina utahensis* Blackwelder, *Am. Jour. Sci.*, 4th Ser., XXXVI, 178.

Much of the lowest phosphate bed is a sort of coquina made up, for the most part, of pedicle valves of this species. The average diameter of the shells is a little more than 2 cm. I have followed Girty in identifying this species as *O. utahensis*, but comparison with specimens from the Coal Measures of Missouri, identified as *Orbiculoidea convexa* Shumard, shows no differences of specific value. The brachial valve figured in Pl. III proves that the species is not a *Lingulidiscina*.

Plagioglypta canna White (Pl. III, Fig. 13)

This species is common and seems to be the only one that ranges from the lowest phosphate bed through the higher beds.

Nucula perumbonata White (Pl. III, Figs. 18–19)

1879. *Nucula perumbonata* White, *Bull. U.S. Geol. and Geog. Surv. Terr.*, V, 217.

1880. *Nucula perumbonata* White, *Cont. to Inv. Pal.*, No. 6, p. 136, Pl. 34, Figs. 7a–b.

The type came from Wild Band Pockets, in northern Arizona, 15 miles southward from Pipe Springs, in the Carboniferous, near the top.

The Embar specimens are abundant, but only two good ones were collected, and they came from the coquina just below the phosphate. The surface markings are not well preserved, but seem to be exactly like those of the type. The Embar specimens come from the Big Popo Agie region, S.W. $\frac{1}{4}$ S. 16, T. 32 N., R. 100 W.

Nucula pulchella Beede and Rodgers (Pl. III, Figs. 7–8)

1899. *Nucula pulchella* Beede and Rodgers, *Kan. Univ. Quart.*, VIII, 132, Pl. XXXIV, Figs. 5a–c.

1900. *Nucula pulchella* Beede and Rodgers, *Univ. Geol. Surv. Kan.*, VI, 151, Pl. XXI, Figs. 5a–c.

1909. *Nucula pulchella* Beede and Rodgers, *Univ. Geol. Surv. Kan.*, IX, 368, 380, Pl. XLII.

This species is represented as interior molds, which agree in shape and size with *N. pulchella*, but the reference is uncertain. They are found in the lower phosphate bed in Big Popo Agie Canyon, Little Popo Agie Canyon, and Bull Lake Creek Canyon, Wyoming, and in the Kickapoo limestone about the middle of the Missouri group of Kansas.

Nucula sp. (Pl. III, Figs. 20–21)

This is one of the most abundant forms occurring in the lower phosphate bed, but the specimens are all interior molds. They agree in shape and size with the forms which Meek found at Nebraska City and which he identified provisionally with *Nucula beyrichi*.[1] They also agree in shape and size with Girty's[2] *Nucula* sp. a. from the Guadalupian.

[1] Meek, *Paleontology of Eastern Nebraska*, p. 203, Pl. 10, Figs. 18 and 19a–b.

[2] Girty, *Prof. Paper 58*, p. 421, Pl. XXIV, Fig. 22.

Leda bellistriata Stevens (Pl. III, Figs. 9–12)

1898. *Nuculana bellistriata* Weller, *U.S. Geol. Surv., Bull. 153*, pp. 380–81. Synonomy to 1898.
1900. *Nuculana bellistriata* Beede, *Univ. Geol. Surv. Kan.*, VI, 148, Pl. 20, Figs. 14 and 14b.
1903. *Leda bellistriata* Girty, *U.S. Geol. Surv., Prof. Paper 63*, pp. 442–43.
1909. *Leda bellistriata* Grabau and Shimer, *North America Index Fossils*, "Invertebrates," I, 401.
1909. *Nuculana bellistriata* Beede and Rogers, *Univ. Geol. Surv. Kan.*, IX, 368, 380, Pl. XLII.

Specimens referred to this species are preserved as internal molds and the identification is uncertain. The shape and size suggest the variety *attentuata*. The length of the largest specimen is 12 mm., the length in front of the umbones 8 mm., the width 7 mm. It is found in the lower phosphate bed from Bull Lake Creek to south of the Little Popo Agie River, ranges from the bottom of the Coal Measures to the top of stage G in Kansas, and has been reported from both the Upper and Lower Coal Measures from various states in the Mississippi Valley and eastward.

Pleurophorus sp. undet. (Pl. III, Figs. 14 and 15)

This species is represented by interior molds. It is very small; the length of an average specimen is 7 mm. and the width 4 mm. It resembles *P. subcostatus* Meek and Worthen, except in size. It is common in the lowest phosphate bed from Bull Lake Creek to the Little Popo Agie River.

Euphemus carbonarius Cox

1898. *Bellerophon carbonarius* Weller, *U.S. Geol. Surv., Bull. 153*, pp. 139–40. Synonomy to 1897.
1909. *Euphemus carbonarius* Beede and Rogers, *Univ. Geol. Surv. Kan.*, IX, 369, 382.
1909. *Euphemus carbonarius* Grabau and Shimer, *North America Index Fossils*, "Invertebrates," I, 621.

This species is common in the coquina just below the phosphate, but the preservation has left the surface markings obscure and the identifications are not positive.

In the Big Popo Agie Canyon, specimens were collected for two or three miles south of the canyon. It ranges through the Upper and Lower Coal Measures in the Mississippi Valley, and occurs in the Marshall of Michigan.

Bellerophon bellus Keyes (Pl. III, Figs. 16 and 17)

1895. *Bellerophon bellus* Keyes, *Mo. Geol. Surv.*, V (1894), 148, Pl. 50, Fig. 7. Found in the Upper Coal Measures, Kansas City, Missouri.

1899. *Patellostium nodocostatum* Girty (not Gurley), *19th Ann. Rept.*, *U.S. Geol. Surv.*, Part 3, p. 590. Found in the Upper Coal Measures, Atoka quadrangle.

1903. *Patellostium bellum* Girty, *U.S. Geol. Surv.*, *Prof. Paper 16*, pp. 474–75. Found in the Hermosa and Rico formation, San Juan region, Colorado.

1906. *Bellerophon bellus* Woodruff, *Geol. Surv. Nebr.*, Vol. II, Part 2, p. 282, Pl. 15, Fig. 2. Extreme upper part of the Coal Measures of Nebraska.

Only one specimen of this species was found, and it agrees in every detail with Keyes's description, though the transverse ridges are not as regular as shown in his figures. The following is the original description:

Shell subglobose, expanding rapidly at the aperture, which is somewhat reniform, with the lip reflected at the sides. Surface marked by a rather prominent, longitudinal carina along the median portion of the shell; strong transverse ridges parallel to the lines of growth pass from one umbilical region to the other; these are crossed by less prominent longitudinal lines, the two sets forming a beautiful cancellated area.

The Embar specimen was collected in the Big Popo Agie Canyon, S.W. ¼ S. 16, T. 32 N., R. 100 W.

CONCLUSIONS

1. The abundance of cochliodont sharks, which have never been reported from strata younger than the Pennsylvanian, indicate an age older than the Permian.

2. The presence of invertebrates that are nearly all referable to species occurring in the Upper Coal Measures of the interior and of sharks that are also common to the Upper Coal Measures indicate the homotaxy of the Lower Embar of Wyoming and the Upper Coal Measures of the Mississippi Valley.

3. The presence of a peculiar genus of shark in the Moscowian of Samara, Russia, and in the Embar makes probable the correlation of these widely separated formations. This conclusion is strengthened by the presence of *Chomatodus corrugatus* in the Rus-

sian Moscowian and in the Upper Pennsylvanian of the Mississippi Valley, and *Cladodus occidentalis* in the Moscowian, the Embar, and the Mississippi Valley Upper Pennsylvanian.

Unfortunately the data for the fish remains from the Mississippi Valley are not complete enough to furnish a basis for exact correlation. The fossils are labeled, in most cases, as from the Coal Measures, Upper Coal Measures, or Lower Coal Measures, and the designations "Upper" and "Lower" are not trustworthy in all cases.

The data for the Russian specimens is not all that is to be desired. *Crassidonta stuckenbergi*, with positive identification, is from Samara, from beds correlated with the Moscowian by Stuckenberg. *Campodus corrugatus* "appears to come from the *Fusulina limestone* of Miatschkowa," the implication being that the specimen is not labeled. The identification of *Cladodus occidentalis*[1] is somewhat uncertain without comparison with American specimens.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the writer's obligations to Professor Stuart Weller for the loan of specimens and the privilege of studying the fish remains in the Walker Museum of the University of Chicago; to Dr. A. R. Crook for the loan of specimens from the Illinois State Museum; to Dr. E. H. Barbour for the loan of specimens from the University of Nebraska museum; to Dr. T. E. Savage for the loan of material from the University of Illinois; to Dr. Louis Hussakof for the loan of specimens from the American Museum; and to Mr. D. K. Greger for assistance in preparing and photographing the specimens.

EXPLANATIONS OF PLATES

PLATE I

FIGS. 1–5.—*Helodus politus* Newberry; co-types for comparison with the figures of Helodus subpolitus (collection of the University of Chicago).

FIGS. 6–16.—*Helodus subpolitus* n. sp.: Figs. 6–13, top views showing variations; Figs. 14–16, side views showing crenulations (No. 704).[2]

[1] Girty, *Prof. Papers 58*, p. 157.

[2] All specimens not otherwise designated are in the collection of the University of Missouri, and the number given is the University of Missouri museum number.

FIGS. 17–21, 25–27.—*Crassidonta stuckenbergi* n. gen. and sp.: Figs. 17, 18, 21, and 26, top views of four teeth; Fig. 19, side view; Fig. 20, end view; Figs. 25 and 27, bottom views (No. 703).

FIGS. 22–24.—Stuckenberg's figures of a specimen of *Crassidonta stuckenbergi* from the Moscowian, for comparison with the specimens from the Embar.

PLATE II

FIGS. 1–4.—*Janassa unguiformis* St. John and Worthen: Fig. 1, outer coronal face of tooth with part of inserted end missing; Fig. 2, lateral view of the same specimen; found in the Embar, Big Popo Agie Canyon, Wyoming (No. 706); Fig. 3, outer coronal face of almost perfect tooth; Fig. 4, lateral aspect of the same specimen, Upper Pennsylvanian of Missouri (No. 421). (All figures show about natural size.)

FIGS. 5 and 6.—*Janassa angularis* Branson: Fig. 5, outer coronal view of specimen with inserted end missing; Fig. 6, lateral aspect of the same specimen; found in the Embar, Bull Lake Creek, Wyoming (No. 713). (Figures show about natural size.)

FIGS. 7–19.—*Janassa unguicula* Eastman: Figs. 7, 9, 10, 12, 14, 17, outer coronal views of several teeth showing variations (inserted end of all specimens missing); Fig. 8, inner coronal view of the same tooth as Fig. 9; Fig. 11, lateral view of the same tooth as Fig. 12; Fig. 13, lateral view of the same tooth as Fig. 14; 9/10 natural size, found in the Embar, Bull Lake Creek and Big Popo Agie Canyon, Wyoming (Nos. 708 and 720); Figs. 18 and 19, lateral and outer coronal views of a tooth from Carlinville, Illinois, Upper Pennsylvanian, 16/13 natural size (No. 7056 of the Illinois State Museum).

FIG. 20.—*Helodus rugosus* Newberry and Worthen: side view of the only specimen collected from the Embar; twice natural size; the peculiar surface markings may be made out in the photograph.

FIGS. 21 and 21a.—*Campodus* sp ?: top and end views of the only specimen collected from the Embar.

FIG. 22.—*Deltodus mercurii:* end view of an Embar specimen of mandibular tooth for comparison with Fig. 16, of the type; ×7/8.

FIGS. 23 and 24.—*Cladodus occidentalis* Leidy: bottom and inner views of an imperfect tooth; summit of cones restored after other specimens; ×7/8; found in the Embar, Big Popo Agie Canyon, Wyoming (No. 705).

FIG. 25.—*Ctenacanthus amblyxiphias* Cope; side view of imperfect spine from Bull Lake Creek, Wyoming, 38 feet from the bottom of the Embar; ×10/9 (No. 718).

FIG. 26.—Denticles probably coming from the spine of an Elasmobranch; ×10/9; found in the Big Popo Agie Canyon, Wyoming, Embar (No. 707).

FIGS. 27 and 28.—*Deltodus mercurii* Newberry; side and top views of an almost perfect right median mandibular tooth; ×8/9; found in the Embar, Bull Lake Creek, Wyoming (No. 716).

PLATE III

FIGS. 1–3.—*Campodus corrugatus* N. and W.: specimen figured by Trautschold as the holotype of *Chiastodus obvallatus;* ×1; found in the Moscowian of Mjatschkowa, Russia.

FIGS. 4–6.—*Campodus corrugatus* N. and W.: found in the Upper Coal Measures above coal No. 5, Galatea, Illinois; ×3/4.

FIGS. 7–8.—*Nucula pulchella* Beede and Rodgers; found in the Embar, Big Popo Agie Canyon, Wyoming; lateral views of two specimens; ×4/3 (No. 751).

FIGS. 9–12.—*Leda bellistriata* Stevens: found in the Embar, Big Popo Agie Canyon, Wyoming; Figs. 9–11, lateral views of casts; Fig. 12, hinge line of a cast; ×4/3 (No. 722).

FIG. 13.—*Plagioglypta canna* White: found in the Embar, Big Popo Agie Canyon, Wyoming; view of imperfect specimen; ×4/3 (No. 726).

FIGS. 14–15.—*Pleurophorus* sp?: found in the Embar, Big Popo Agie Canyon, Wyoming; lateral views of two nearly perfect casts; ×4/3 (No. 727).

FIGS. 16–17.—*Bellerophon bellus* Keyes: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 16, dorsal aspect; Fig. 17, lateral aspect; ×4/3 (No. 723).

FIGS. 18–19.—*Nucula perumbonata* White: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 18, dorsal aspect; Fig. 19, lateral aspect; ×4/3 (No. 725).

FIGS. 20–21.—*Nucula* sp?: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 20, lateral aspect of a cast; Fig. 21, dorsal aspect of a cast; ×4/3 (No. 724).

FIGS. 22–25.—*Orbiculoidea utahensis* Meek: found in the Embar, Big Popo Agie Canyon and Little Popo Agie Canyon, Wyoming; Fig. 22, lateral view of brachial valve, ×3/2; Fig. 23, outer surface of pedicle valve, ×7/5; Fig. 24, inner surface of pedicle valve, ×3/2; Fig. 25, brachial valve; ×4/3 (No. 750).

PLATE IV

FIG. 1.—*Eunemacanthus keytei* Branson: lateral view of holotype, ×9/10; found in the Embar, Big Pópo Agie Canyon, Wyoming (No. 711).

FIG. 2.—*Ctenacanthus obscuracostatus*: Branson lateral view of holotype, ×7/8; found in Big Popo Agie Canyon, Wyoming (No. 710).

FIGS. 3–6.—*Batacanthus gigas* Branson: Fig. 3, lateral view of imperfect spine, ×1/2; Figs. 4 and 5, top views of spine denticles, ×3; Fig. 6, surface ornamentation; ×2 (No. 715).

FIG. 7.—*Ctenacanthus browni* Branson: lateral view of type, ×4/5; found in Big Popo Agie Canyon, Wyoming (No. 709).

FIG. 8.—Unidentified cochliodont: top view of outer end of tooth, ×3/4; found in Big Popo Agie Canyon, Wyoming (No. 714).

PLATE V

All figures are of *Deltodus mercurii* Newberry.

FIG. 1.—Top view of median mandibular tooth with outer end missing (No. 712).

FIG. 2.—Lateral view of complete left outer mandibular tooth; ×4/5 (No. 712).

FIG. 3.—Top view of same tooth; ×9/10.

FIG. 4.—Lateral view of complete left maxillary tooth; ×4/5 (No. 712).

FIG. 5.—Top view of same tooth.

FIG. 6.—Top view of right mandibular tooth with outer end missing (No. 712).

FIG. 7.—Lateral view of mandibular tooth with outer end missing; ×5/6 (No. 716).

FIG. 8.—Top view of right outer mandibular tooth with outer end missing; ×2/3 (No. 716).

FIG. 9.—Top view of left outer mandibular tooth with outer end missing (No. 712).

FIG. 10.—Top view of right maxillary tooth restored after Fig. 5 for comparison with Fig. 4a of the type; ×3/4; markings like those on the outer end of the specimen cover the entire surface of unworn teeth (No. 716).

FIG. 11.—Side view of the tooth shown in Figs. 4 and 5.

The specimens figured as 7 and 8 are from the Bull Lake Creek region, Wyoming, and the others from the Big Popo Agie region, Wyoming.

PLATE VI

All figures are of *Deltodus mercurii* Newberry.

FIG. 1—Restoration of upper and lower dentition viewed from the rear; ×9/15.

FIG. 2.—Restoration of upper dentition; right tooth restored; ×9/15.

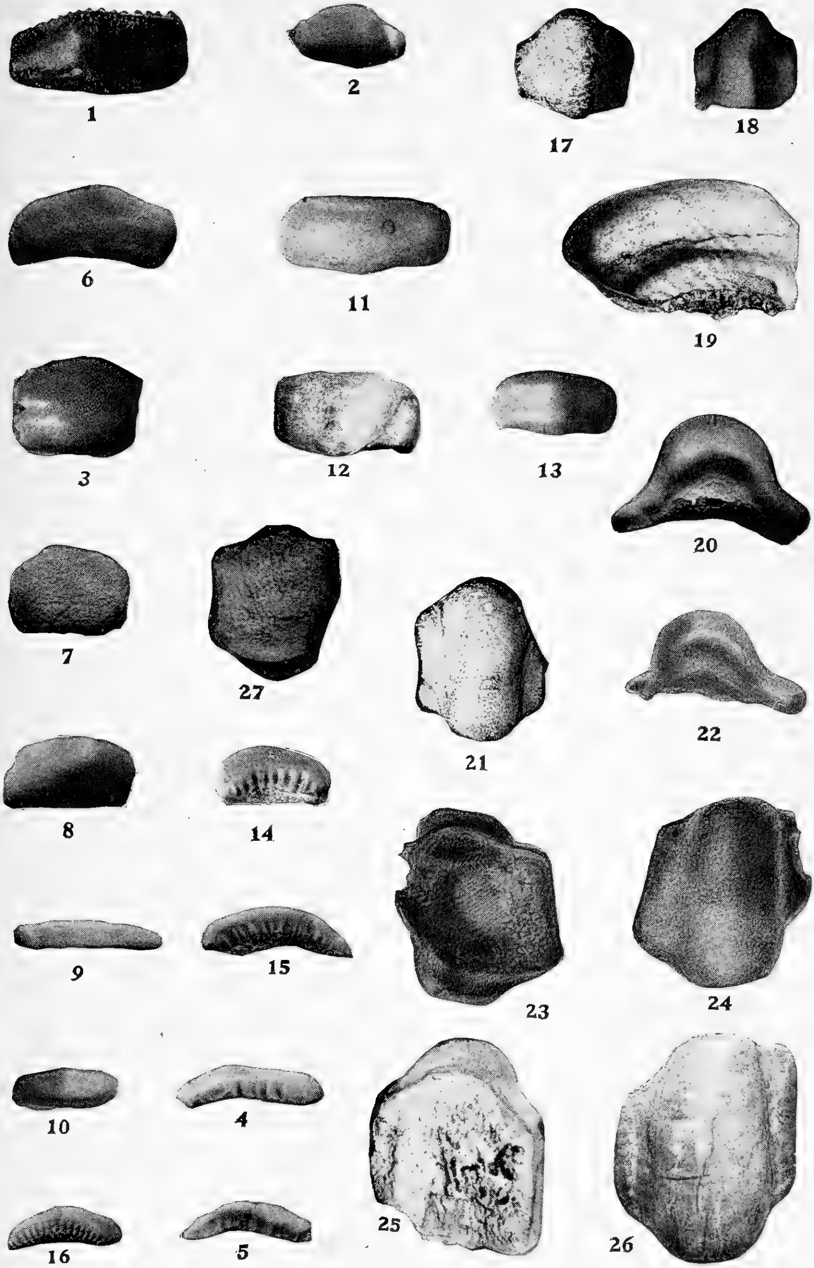
FIG. 3.—Restoration of lower dentition; stippled area of inner tooth of left side and outer of right restored; ×5/8.

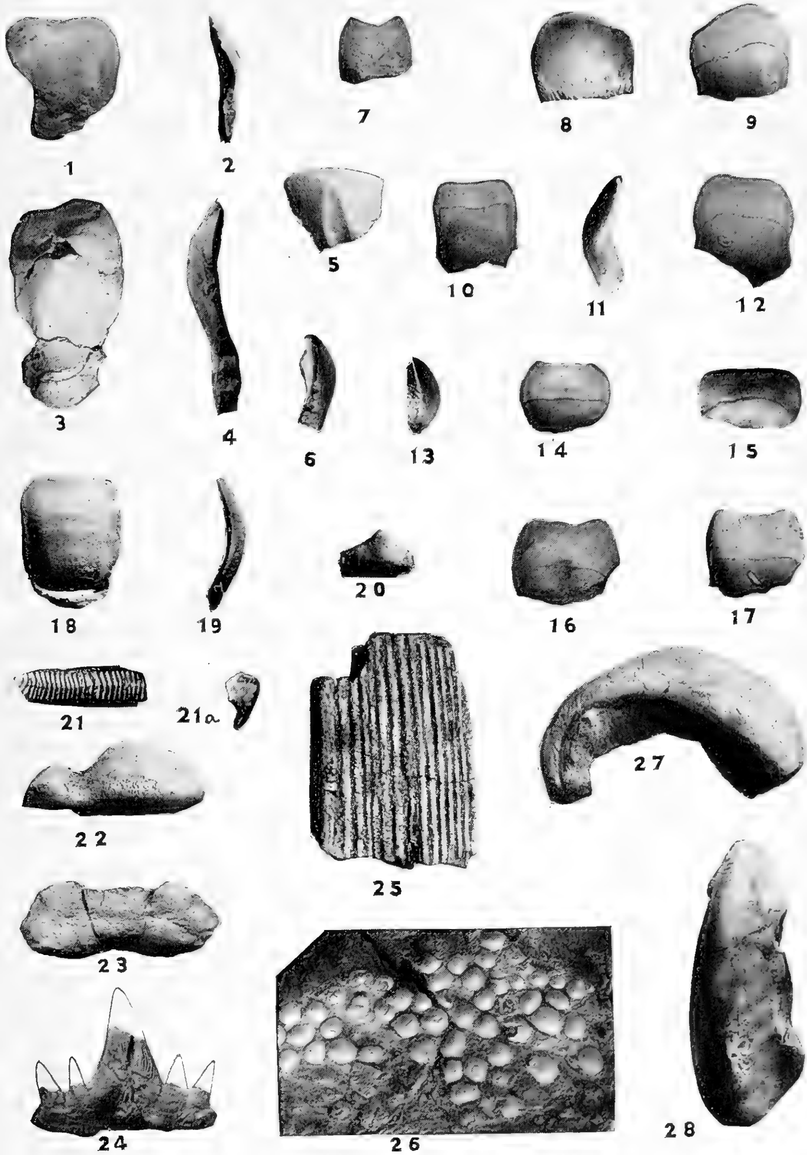
FIG. 4.—Mandibular tooth from the Embar for comparison with the type; ×13/16; restored in outline.

FIG. 5.—Side view of same tooth; ×1.

FIG. 6.—Top view of type of *Deltodus mercurii:* mandibular tooth; ×13/16; restored in outline; found in the Coal Measures, Santa Fe, New Mexico (No. 462 of the collection of the American Museum of Natural History).

Plate I

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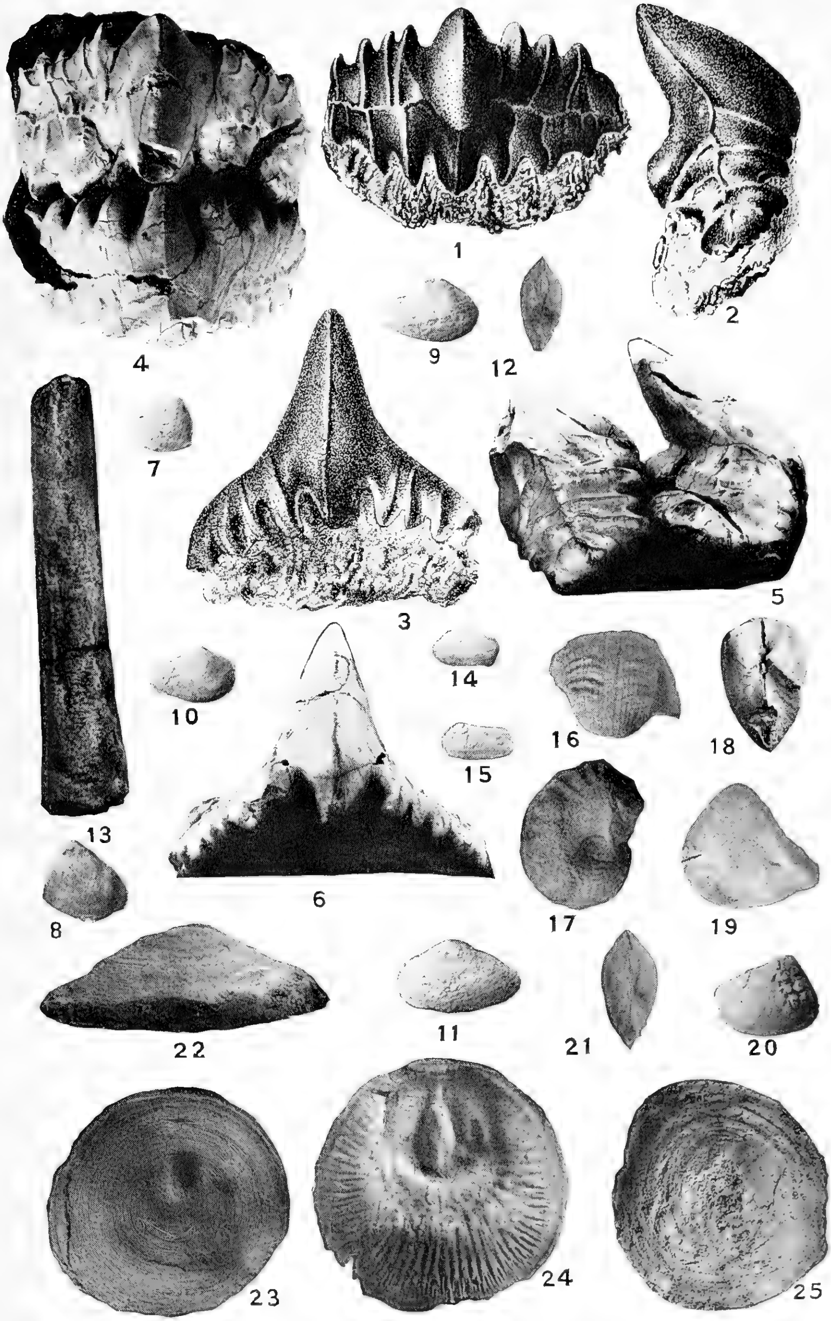
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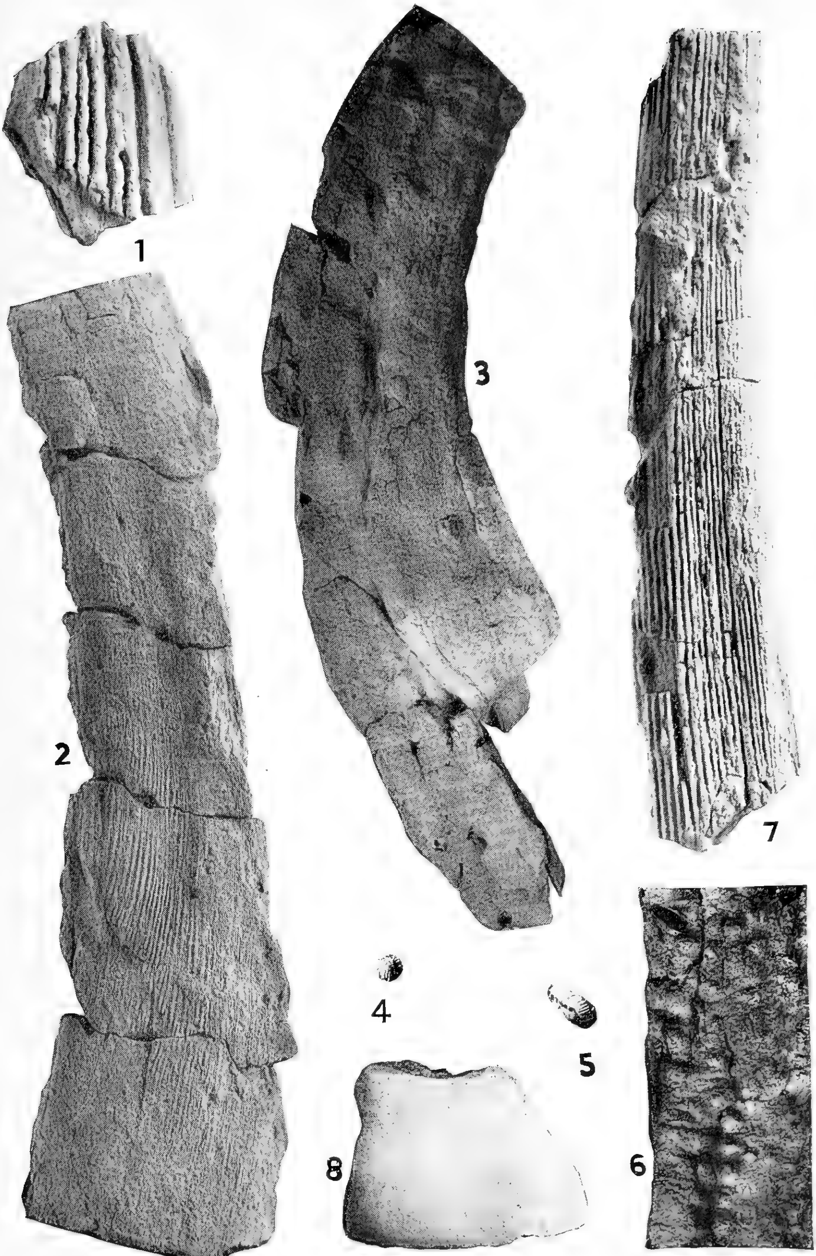
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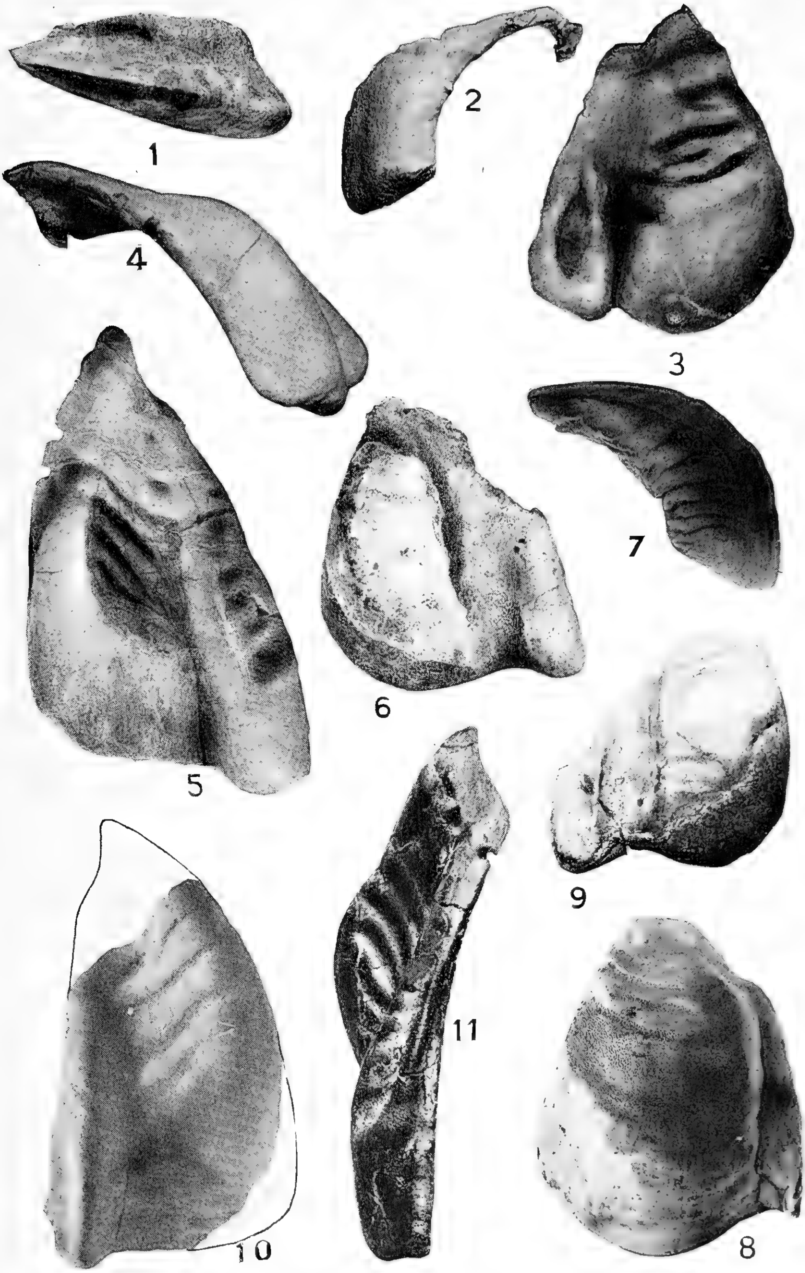
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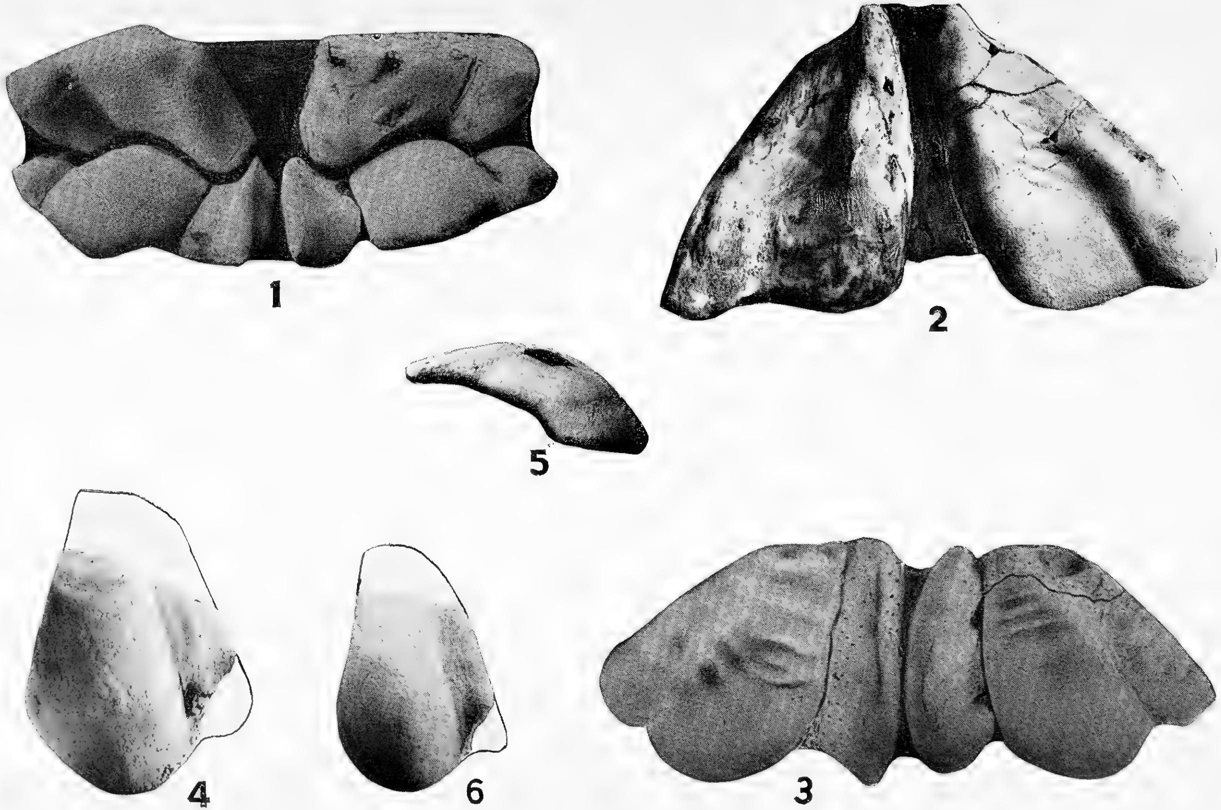
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EVOLUTION OF THE BASAL PLATES IN MONOCYCLIC CRINOIDEA CAMERATA

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PART III

EVOLUTION OF THE BASE IN MONOCYCLIC CAMERATA

I. EVOLUTION OF THE PENTAGONAL BASES

Having assumed that the anal plate plays no part in the evolution of the pentamerous base in the monocyclic Camerata, the succession of changes modifying this base may now be considered.

Starting with the simple pentagonal base *a—b—c—d—e—* (Fig. 9, No. 1), the first change noted is the reduction in number of basals from five to four. It is evident that this change is due to the anchylosis of but one pair of plates, either the anterior pair or occasionally in *Melocrinus* the sinistro-laterals. Accompanying this change there is usually a symmetrical reduction of the compound plate and an asymmetrical reduction of the adjacent basals. The formula for the base so developed is *a—b—cd—e—* (Fig. 9, No. 2) for the anterior anchylosis and *a—bc—d—e—* for anchylosis of the sinstro-laterals (Fig. 5, No. 2*a*). The next step is the reduction to three unequal basals by the anchylosis of two pairs of basals. In this combination the simple basal may be any one of the five primary plates, although the left- or right-anterior plate is usually the simple one. Anchylosis is here accompanied either by asymmetrical reduction of the compound plates on the side apposed to the simple basal or by deep-seated and symmetrical reduction. In either case the enlargement of the simple basal is usually symmetrical. Any of the three-basal forms might arise from any of the possible combinations of four basals, provided that the anchylosed pair in the four-basal form appears as one of the compound units in the three-basal form. Thus the four-basal form *a—b—cd—e—* might have given rise to a type in which either of the postero-lateral basals is free, as in *ea—b—cd—*, or *ab—cd—e—* The probabilities are, however, that the three-basal forms originated directly from the five-basal forms, without an intermediate four-basal stage. This succession is shown diagrammatically by changing formula *a—b—c—d—e—* to *ab—c—de—* for the *Platycrinus* type of base and to *ea—bc—d—* for the *Hapalocrinus* type of base (Fig. 9, Nos. 1, 3, and 4). Two-basal forms are not known in this

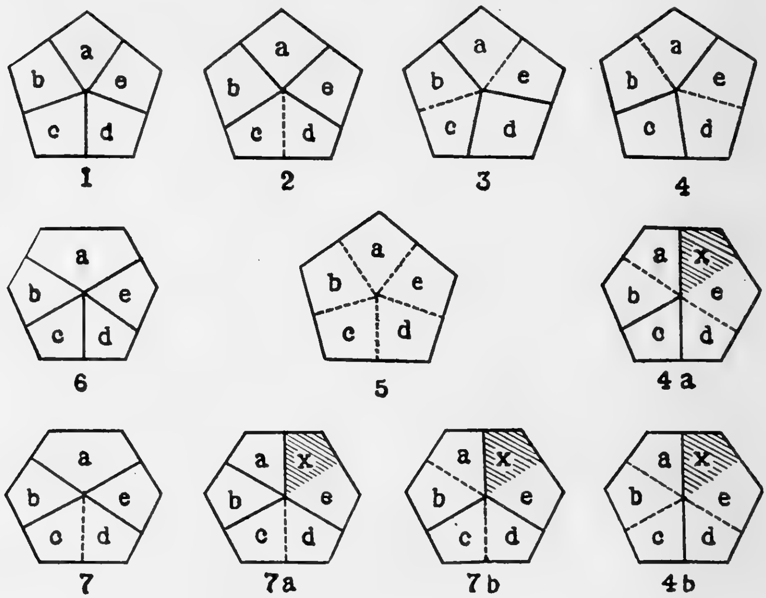

FIG. 9.—Diagrams illustrating the evolution of the base in the Camerata on the theory of atrophy and compensating hypertrophy: 1–5, combinations of the primitive five-basals; 1, 6, 7–7*b*, succession in the Batocrinidae; 1, 7*b*, succession in formation of the tripartite base in the Hexacrinidae; 1, 4–4*b*, succession in the formation of the bipartite base in the Hexacrinidae.

succession, so the next stage is that of complete anchylosis (Fig. 9, No. 5). This change consists in the complete union of the basal plates, and may occur in either the five-, four-, or three-basal forms. The formula for complete anchylosis is *abcde.*

2. THEORIES FOR THE EVOLUTION OF THE BASE IN HEXAGONAL CAMERATA

a) *Enlargement of the posterior basal.*—Having in mind the time and place of development of the anal plate, let us examine the changes its introduction between the posterior radials would probably cause in the posterior basal in the cup of the primitive embryo. Since the zone of potential weakness caused by the enlarging hindgut is evidently in the right-posterior radius of the calyx, there can be but three possibilities for the enlargement of the posterior basal, which are: (i) normal symmetrical enlargement; (ii) enlargement through the anchylosis of a sixth basal factor appearing between the posterior and right-posterior basals; and (iii) enlargement through acceleration of growth in the right- or left-posterior sides.

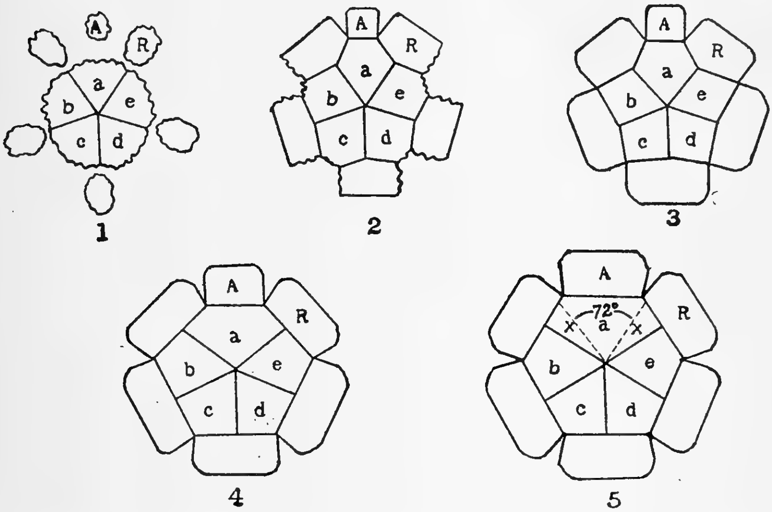

FIG. 10.—Diagrams illustrating modifications in shape and position of the basals and radials by the introduction of the anal plate; wavy lines indicate plate margins not in contact, smooth lines indicate plate margins in contact: 1–4, stages based upon the development of *Antedon;* 5, *Tanaocrinus* stage.

i. When the anal plate came into contact with the posterior basal (Fig. 10, No. 2), mutual trunkation of their apposed margins would take place, perhaps to a slight degree by absorption, but mainly from atrophy and broadening by lateral growth. As the radials and anal came into contact (Fig. 10, No. 3), growth pressure would cause a gradual spreading of the radial cycle at the posterior side, the lateral radials swinging outward and slightly forward (Fig. 10, No. 4), with a hinging motion along the lateral suture margins, until the anal plate reached its full proportionate size in development (Fig. 10, No. 5). The lateral basals, with their distal angles still in continuous growth-contact with the proximal ends of the radials, would separate slightly and gradually at their bases, as their longitudinal axes swung with the movement of the radials. The posterior basal would also move outward from the axial canal. These movements, however, are not migrational, but are of approximately the same type found in normal growth (see p. 502); for continuous growth along the plate margins, more rapid in the expanding areas than elsewhere, would keep the plate margins in continuous contact as in normal growth.

Since expansion by proximo-lateral growth is obviously not as rapid as by disto-lateral growth, the proximal ends of the basals would probably not be carried out from the center of the cup by growth pressure proportionately as far to the distal ends as they are in normal growth. Thus the proximal ends would apparently be lowered toward the horizontal plane of projection, and the projected angles of the proximal ends, which were 72° in the pentagonal base, would approach 60° in the hexagonal base. With greater expansion in the sarcode and greater plate growth taking place in the posterior region, the proximal angle of the enlarging posterior basal would increase, while those of the lateral basals would decrease through lengthening of their proximo-lateral margins by growth as well as by change in the angle of projection and shifting of their longitudinal axes. This method of basal change is symmetrical, normal, and apparently in keeping with the development in *Antedon* and the early monocyclic and dicyclic Camerata as we now know them.

The first expression of the pent-up energy in the developing intestine seems then to have been used up in a normal expansion of the posterior interray, which in this group proved to be a plane of weakness in the cup. Later, however, when the tendency for spreading was established, this energy was expressed in another direction, and in some of the modern crinoids (*Pentometrocrinus*, etc.) results in an almost complete flattening of the dorsal cup.

ii. The theory of the interpolation of a sixth basal factor to the right of the posterior basal is based upon the appearance of the radianal in that position in *Sagenocrinus*. It requires, first, the duplication of the posterior basal; secondly, the locking in of the sixth basal in the basal cycle; and, thirdly, closure of the posteriorly directed basal suture by anchylosis. On the ground of possibilities there can be no objection to this hypothesis, for we know that this certainly occurred in *Sagenocrinus*, nor can there be serious objection to the locking in of this plate in the basal cycle, for the radianal of *Pisocrinus* is locked in in the radial cycle. The most serious objection to this theory is that in the series of sutural reappearances in species with a hexagonal base a normal right-posterior basal suture has not been found, although the writer has made careful search for such examples.

iii. The theory of asymmetrical enlargement requires either enlargement of the left side of the posterior basal, or of the right side, which is Wachsmuth and Springer's theory for enlargement. In favor of the first development is the fact that in the Flexibilia Springer has found a general enlargement of the left side of the posterior basal.[1] In favor of the second part of this theory is the development to the right of the radianal in *Pisocrinus*, apparently in the face of the influence of the growing intestine which in the Flexibilia tends to carry this plate to the left of the right-posterior radial. The abundance of evidence Springer has brought in his work on Flexibilia far outweighs the slight evidence shown in *Pisocrinus* and inclines one to believe that factor x might have been added to left of basal *a;* but when we consider the evidence of increasing potency for distortion on the part of the intestine, there is a strong possibility that the intestine may have shoved the posterior basal to the left, as Wachsmuth and Springer believe, and may have at the same time inhibited the tendency of expansion on the part of the right-posterior basal, permitting the posterior basal to enlarge on the right side. We are here involved in a question of directive controls which cannot be readily answered, and, since the posterior basal in *Tanaocrinus* is symmetrically trunkated and developed, the writer is forced to the conclusion that asymmetrical development had not at that time appeared in the posterior basal.

The formula for a base developed upon the first theory is $\overline{xax}$—*b*—*c*—*d*—*e*—, or in shortened form $\bar{a}$—*b*—*c*—*d*—*e*— (Fig. 9,

[1] Ref. 31, p. 496.

No. 6); that of the second theory is *xa—b—c—d—e—*, while those of the third theory are $\overline{ax}$*—b—c—d—e—* for lateral enlargement of the left side, and *xa—b—c—d—e—*for lateral enlargement of the right side.

b) Development of the quadripartite base.—In the evolution of the four-basal, hexagonal base there can be no disagreement, as but one pair of basals, the anterior pair, is anchylosed. Anchylosis in this type of base is generally accompanied by symmetrical reduction of the compound plate and an asymmetrical and compensating enlargement of the apposed basals. The formula for the four-basal type, based upon the theory of symmetrical enlargement of the posterior basal, is $\overline{a}$*—b—cd—e—* (Fig. 9, No. 7); that of Wachsmuth and Springer, *xa—b—cd—e—* (Fig. 1, No. 7).

c) Development of the tripartite base.—In the discussion of the evolution of the tripartite base three theories will be considered: (i) the tortional theory of Wachsmuth and Springer; (ii) the bisection theory; and (iii) theory of atrophy and compensating hypertrophy.

i. Tortion theory: Wachsmuth and Springer's theory may be stated as follows: The equally tripartite base of the hexagonal Camerata originated from an unequally tripartite base of the *Platycrinus* type by the addition of an anal plate, which caused (1) a spreading of the posterior interradius; (2) a tortion of the base which brought the right-posterior and anterior basal sutures respectively into contact with the anal plate and the right-anterior radial; and (3) the addition of a lateral-growth factor (*x*), to the right of the left-anterior basal. The evolution of the base upon this theory may be expressed in formula as follows: *ab—c—de—* to *ab—cx—de—* (Fig. 1, Nos. 3, 9, 10).

Since this theory was thought to have been confirmed by an abnormal example of *Teleiocrinus umbrosus* in which the anal plate is missing and the base, supposedly, reduced to the *Platycrinus* type (*ab—c—de—*), it assumes (1) that the subequally tripartite base did not originate from the hexagonal five- or four-basal forms, but from another line, or (2) that it did originate from them and that an intermediate form existed in which the anal plate was temporarily lost and the base was like that of *Platycrinus*. This latter assumption demands the loss of factor *x* and anchylosis of two pairs of plates in the five-basal form, as in changing *xa—b—c—d—e—*to *ab—c—de—*, or the factor *x*, the anchylosis of two pairs of plates, and the reappearance of the anterior suture in the four-basal form, as in changing *xa—b—cd—e—*to *ab—c—de—*. Bather in accepting[1] this theory apparently assumes an intermediate step, for in the generic discussion of *Abacocrinus*[2] he says: "From the imagined intermediate step [not from *Abacocrinus* itself], *Periechocrinus* may have been derived by fusion of 2 BB [*two basals*]."

In the review of the evolutional characteristics in the Batocrinidae and Actinocrinidae, we have seen that the anal plate first appeared in the five-basal form of the *ā—b—c—d—e—* type, and that it was probably introduced without other distortional changes than those assumed in the hypothesis here offered (see p. 667). In the four-basal form anchylosis of one pair of basals, the anterior pair, resulted. So far there have been no relative distortional shiftings of the basals or radials except in the posterior region.

Furthermore, there is not throughout the succession of Batocrinoidea and Actinocrinoidea a single species with the *ab—c—de—* type of base. Only in two similarly abnormal specimens, one of *Teleiocrinus umbrosus*, in the Springer collection, the other of *Steganocrinus pentagonus*, in the Walker Museum collection, is the unequally tripartite base belonging to the *ab—c—de—* group found. It does not seem possible, then, that in a succession so clearly outlined the anal plate should temporarily disappear in the imagined[3] intermediate form between *Abacocrinus* and *Periechocrinus*. The reversion and replacement herein implied are entirely out of harmony with the processes of evolution in crinoid development. Can it then be possible that the anterior suture reappeared in the intermediate form, so that shifting of the basals could take place, as believed by Wachsmuth and Springer? We know of no positive instances of the reversion of a phylogenetic trend by the appearance of such an atavistic feature as a new generic or specific character (see p. 544). Since there is apparently no hope along this line of development, let us start with the original *ā—b—c—d—e—* type of

[1] Ref. 3, p. 427, third notice.

[2] Ref. 6, p. 166. [3] Ref. 6, p. 166.

base, close the left-posterior and right-posterior sutures, and shift the plates in accordance with Wachsmuth and Springer's theory. We are here confronted at once with the fact that neither in *Antedon*, in the five-basal hexagonal forms of monocyclic or dicyclic Crinoidea, nor in the four-basal hexagonal Camerata, has any such shifting taken place. Since the stimulus for widening the posterior interradius has already accomplished its purpose, there is apparently no stimulating cause to accomplish such a shifting, and if there is no such stimulus, there is but one other alternative: the phylogenetic succession as emended by Bather[1] and accepted by Springer[2] is artificial.

Grant for the moment that the succession as outlined is artificial, and starting with the ancestral form as proposed by Wachsmuth and Springer, develop the hexagonal, equally tripartite base from the pentagonal, unequally tripartite base. The anal plate being inserted as proposed, let us follow closely the steps required in the shifting of the basals. The posterior and left-posterior, the right-posterior and right-anterior basals have already anchylosed in pairs, which demands, as we have shown before, closed plate cycles. In order that the right-anterior compound basal *de* may assume a right-posterior position, as Wachsmuth and Springer have affirmed, sufficient expansion must take place between the radials and the basals to permit such shifting, or there must be absorption of the distal angle of this basal, the proximal angles of the radials, or of both coupled with inhibition of plate growth in order to permit their passing. At the same time that widening in the anal area is taking place there must be a compensating widening between the two anterior basals. This change demands a movement of the sarcode on the right side away from the anal plate in the radial cycle and toward it in the basal cycle, which is surely too remarkable a tortion to be deemed possible, especially in forms having the bilaterally symmetrical development shown in the camerate Crinoidea. Furthermore, this theory does not take into consideration the fact that it is the stimulus arising from the push of the rapidly developing intestine against the posterior interradius that has caused the introduction of the anal plate.

[1] Ref. 6, pp. 159–70. [2] Ref. 25, pp. 193–98.

Let us now turn to a study of the specimen of *Teleiocrinus umbrosus* (Pl. I, Nos. 1, 2, 4, 6) by which Wachsmuth and Springer thought their theory to have been confirmed. Upon careful examination of this specimen grave doubts have arisen in the writer's mind concerning the validity of its assigned orientation. *Teleiocrinus umbrosus* has a central anal tube; therefore use of this as a reference point for orientation is denied. If, however, we consider that the interray in which the abnormality (loss of the anal plate) occurred should perhaps show some variation from the supposedly normal interrays, a different answer to the problem is obtained. Four of the interrays in this specimen show the normal *Teleiocrinus umbrosus* type of development: 1, 2, 2, 2. The fifth interray shows the following arrangement: 1, 3, 4, 2, which varies from the normal posterior interray (*A*, 2, 3, 4, 2) or (*A*, 2, 4, 3, 2) by the loss of but two important plates—the anal plate and one plate of the superimposed pair. There is here too close a parallel to be considered entirely accidental, and it does not seem unreasonable that if some plates are missing from an interray, that interray should show signs of abnormality. If, then, it be assumed that the abnormal interray in this specimen of *Teleiocrinus umbrosus* is the true posterior interray, the basal formula is not *ab—c—de—*, as in *Platycrinus*, but *ab—cd—e—*, for the simple basal is bisected by the plane of the right-posterior interray.

Let us, before going farther, examine the specimen of *Steganocrinus pentagonus* (Pl. II, No. 15; Pl. III, Nos. 1, 2) which, like the specimen just described, has lost its anal plate. *Steganocrinus pentagonus*, unlike *Teleiocrinus umbrosus*, has a slightly eccentric anal tube; the vertical convexity of the posterior interray is much flatter than in the other interrays, and the interbrachial plates are ornamented at a lower level by low sharp nodes. If, then, this specimen be oriented according to the position of the anal tube, convexity of interrays, and ornamentation, the basal formula is found to be, not *ab—c—de—*, as in *Platycrinus*, but *b—cd—ea—*, for the simple basal is bisected by the plane of the left-posterior interray. In *Teleiocrinus umbrosus* the posterior basal has anchylosed with the left-posterior basal; in *Steganocrinus pentagonus* it is anchylosed with the right-posterior basal. The reversion herein implied is very close to being a solution for the problem of the appearance of the posteriorly directed basal suture, and we need no longer confuse the issue with origin from *Platycrinus* or other three-basal forms of the *ab—c—de—* type.

It seems then that Wachsmuth and Springer's theory for the development of the hexagonal, tripartite base does not meet the requirements of present needs, and we may turn to a discussion of the remaining theories.

ii. Bisection theory: Briefly stated, the bisection theory assumes that the posteriorly directed basal suture resulted from the bisection of the posterior basal in a quadripartite base, and anchylosis of the portions of the posterior basal to the adjacent basals. This development may be expressed in formula as follows: *ā—b—cd—e—* through *a—b—cd—e—a—* to *ab—c—d—ea—*. The first objection to this theory is that there are no known instances of the bisection of a growing plate in modern Echinodermata. The second objection is that in the examples of recurrence of sutures by delayed anchylosis there are no instances of the reappearance of a normal right-posterior basal suture when the posterior suture is present (see Pls. II, III), although the writer has, as previously stated, made careful search for such examples. This theory and any theory based upon the assumption of plate splitting as a phylogenetic characteristic may apparently be abandoned as a factor in the development of Crinoidea.

iii. Theory of atrophy and compensating hypertrophy: The theory of atrophy and compensating hypertrophy is that the posteriorly directed basal suture and the subequally tripartite base of the hexagonal, monocyclic typical Camerata arose from the atrophy of the right half of the enlarged posterior basal, a compensating enlargement of the right-posterior basal, and the anchylosis of the posterior and left-posterior basals.

This theory is based upon (1) the general presence of atrophy in the right side of the posterior basal in Flexibilia; (2) the non-appearance of the right-posterior basal suture in the specimens showing reappearance of lost sutures through delayed anchylosis, and (3) evidence showing the derivation of *Dichocrinus* from *Platycrinus* stock.

In speaking of the base in the Flexibilia, Springer says:

> The posterior basal upon which it [the anal series] rests is excavated into a sort of shallow socket, like the articulating face of a radial, on the right shoulder of the plate, so that we will usually see a small tongue or angle of that plate rising up to the left of the base of the anal plate higher than to the right; or, if the socket-like excavation is not so plain as this, the upper edge of the basal is distinctly sloped to the right.[1]

Furthermore, in *Abacocrinus* the writer has found a marked reduction of the right side of the posterior basal and a compensating enlargement of the right-posterior basal (Pl. II, No. 7). There is here shown a marked tendency for the stimulus arising from the developing intestine to inhibit the growth of the posterior basal upon the right side and to permit the growth of the adjacent right-posterior basal.

Upon two of the accompanying plates (Pls. I, II) are illustrated the specimens upon which the evidence for sutural reappearance through failure of anchylosis is based. These illustrations show clearly the appearance of the anterior suture in *Melocrinus*, *Actinocrinus*, *Steganocrinus*, and *Hexacrinus*, and this suture is so often represented that it cannot be ascribed to any other cause. The appearance of this suture could only be accounted for upon Wachsmuth and Springer's theory by plate splitting, a supposition which is absolutely without foundation. It will furthermore be noticed that in no instance do the posterior and right-posterior sutures appear in the same specimen. Both sutures are sometimes absent, but in general the posterior suture is present and the right-posterior absent. The reappearance of the anterior suture and the failure of the right-posterior suture to reappear in any specimen in which the posteriorly directed suture is present, and in which other combinations of lost and normal sutures do appear, is the evidence upon which the theory of atrophy and compensating hypertrophy is based, and is here submitted as evidence that plate shifting such as Wachsmuth and Springer assumed probably did not take place, but that the right-posterior basal suture assumed a posterior position upon partial atrophy of the posterior basal and compensating hypertrophy of the left side

[1] Ref. 31, p. 496.

of the right-posterior basal. The formula of the tripartite, hexagonal base, upon the theory of atrophy and compensating hypertrophy, is *ab—cd—ex—*.

The explanation of the reversion implied in the abnormal specimens of *Teleiocrinus umbrosus* and *Steganocrinus pentagonus* may upon this theory be readily explained. Upon loss of the anal plate, stimulus for shifting the posterior basal suture was also lost, but the tendency for anchylosis of the anterior basals established in the early Batocrinoidea was not changed. Anchylosis then took place in as nearly normal a manner as possible, one of the postero-lateral sutures only in each specimen failing to close.

It will be noted that in the preceding discussion no mention has been made of the proportionate amount of growth in the radials, the anal, and the enlarged basals. This is because some misconception has arisen concerning their development, owing to the assumption that the basal outline is a regular hexagon. From careful measurements of the proximal diameter of the radials and anal in over five hundred specimens of Batocrinidae and Actinocrinidae it was found that in general the largest plates in the radial cycle are the antero-lateral radials, while the postero-laterals or the anal are the smallest in the radial cycle. Since the posterior radials are reduced by the interpolation of the anal plate (see p. 549) and the margins of the posterior basal do not extend beyond the center of these radials, it is evident that the posterior basal did not enlarge to a width equal to that of two of the other basals, as Wachsmuth and Springer have assumed, nor is the base a regular hexagon. The reduction of the posterior basal and the compensating enlargement of the right-posterior basal do not then require a formidable amount of plate readjustment, especially when we remember what readjustments have taken place in *Pisocrinus* (see p. 535).

3. EVOLUTION OF THE BASE IN THE HEXACRINIDAE

The evolution of the base in the Hexacrinidae is not as simple a problem as the evolution of the base in the Batocrinidae, for the phylogenetic succession is not as clearly defined. The general affinities of the Hexacrinidae are with the Platycrinidae, but the paths of evolution resulting in the subequally tripartite and bipartite bases are obviously so different that it is better to consider their basal developments separately.

a) *Evolution of the tripartite base.*—As the evolution of the tripartite base in the Hexacrinidae has resulted in essentially the same type of base as in the Batocrinidae, the same theories of descent will be considered; these are Wachsmuth and Springer's theory of torsion, and the theory of atrophy and compensating hypertrophy.

i. Torsion theory: Wachsmuth and Springer's theory for the evolution of the tripartite, hexagonal base of the Hexacrinidae is: Upon interpolation of the anal plate in some form having the *Platycrinus* type of base (*ab—c—de—*), spreading of the radial cycle at the posterior side was accompanied by a spreading of the basal cycle at the anterior side, thus causing the compound, dextrolateral basal to shift so that the right-posterior suture came into contact with the anal plate, and the anterior suture into contact with the right-anterior radial, while at the same time compensating growth of the left-anterior basal filled the vacant space. This metamorphosis may be shown diagrammatically by changing formula *ab—c—de—* to *ab—cx—de—* (Fig. 1, Nos. 3, 9, 10). The method of development is the same as was postulated by Wachsmuth and Springer for the development of the base in the Batocrinidae and the same objections are in force, but as the relationship of the three-basal Hexacrinidae is apparently with the Platycrinidae, these objections will be reconsidered.

The strongest objection to the torsion theory is that the stimulus for widening the posterior interradius is due directly to the oblique pressure of the growing hind-gut upon the right-posterior radius and posterior interradius, and cannot therefore produce a spreading between the anterior basals. The second objection is that in the two cases of sutural reappearance, by delayed anchylosis, in *Hexacrinus* (Pl. III, Nos. 5, 6) the right-posterior suture does not appear, although in the specimen (Pl. III, No. 5), showing the reappearance of the left-posterior sutures it would naturally be expected. Wachsmuth and Springer's theory does not then seem entirely adequate in explaining the formation of this base, and we may consider the second theory.

ii. Theory of atrophy and compensating hypertrophy: This theory has been fully considered in the preceding discussion of the formation of the tripartite base in the Batocrinidae and need not be restated. It requires the interpolation of an anal plate in the radial cycle, partial atrophy of the right half of the posterior basal, a compensating enlargement of the right-posterior basal to bring the right-posterior basal suture into contact with the anal plate, and perhaps the closure of one or more of the primary sutures. However, when this theory is applied to the supposed phylogenetic succession resulting in the Hexacrinidae, a peculiar difficulty is encountered. The *Platycrinus* type of base (*ab—c—de—*) in changing to the subequally tripartite base (*ab—cx—de*) demands upon this theory the reappearance of the right-anterior basal suture. Sutural reappearance as a phylogenetic character is, however, not considered a probability, and the second theory also seems inadequate to meet the demands of this problem. There is, however, another phase of the problem which must not be overlooked, and that is the possibility that *Hexacrinus* and *Arthrocantha* did not originate from one of the Platycrinidae with an *ab—c—de—* type of base. This suggestion is not to be considered as a means of confusing the issue and saving the writer's hypothesis; it is inserted to call attention to the fact that there is practically nothing known about the ancestors of the Platycrinidae nor the predecessors of the Silurian genera belonging to that family. The evidence derived from sutural reappearance by delayed anchylosis in the Batocrinidae and Hexacrinidae is such that there seems to be but one possible conclusion to be drawn, which is that *Hexacrinus* and *Arthrocantha* probably originated, not from a three-basal form of the *ab—c—de—* type, but from a simple five-basal type. The changes required in the suggested line of descent consist of: interpolation of the anal plate by portional migration; closure of the anterior and left-posterior basal sutures; partial atrophy of the posterior basal; and compensating hypertrophy of the right-posterior basal to shift the right-posterior suture to a posterior position (Fig. 9, Nos. 1, 7*a*, *b*).

b) *Evolution of the bipartite base.*—Wachsmuth and Springer's theory[1] for the origin of the bipartite, hexagonal base is stated as

[1] Ref. 39, p. 56.

follows: "The bipartite base is probably derived from the tripartite, which preceded it in time, and *x*, which in the latter constituted a part of *c*, is united with *de*, and *ab* with *c* [Fig. 1, Nos. 11, 12]." Thus upon the shifting of plate *de* the tendency for the enlargement of plate *c* was inhibited, and a compensating growth of plate *de* filled the space formerly filled by the enlargement of plate *c*. This metamorphosis is shown by changing formula *ab—cx—de—* to *abc—xde—*.

To this theory, however, there are the same objections that were encountered in that of the formation of the tripartite base in both the Batocrinidae and the Hexacrinidae. Torsion such as is assumed for the shifting of the compound plate *de* is apparently impossible, as the stimulus for enlarging the posterior interradius is due to the pressure from the growing hind-gut and cannot affect the anterior basal sutures. Furthermore, the examples of suture reappearance in the bipartite base show the potential presence and position of all but the right-posterior suture (Pl. III, Nos. 8, 9, 10). Wachsmuth and Springer's theory again does not seem adequate to explain the changes which have taken place and we may consider the theory of atrophy and compensating hypertrophy.

When the theory of atrophy and compensating hypertrophy, which has been thoroughly discussed, is applied to the phylogenetic succession as formulated by Wachsmuth and Springer, it also meets with the same trouble that was encountered in considering the evolution of the tripartite base. In this case the anterior basal suture must reappear as a phylogenetic character. Phylogenetic reappearance of a suture lost through anchylosis is, however, considered impossible, and the phylogenetic succession as postulated by Wachsmuth and Springer must be examined.

There are, it is true, many similar characteristics in the Hexacrinidae having tripartite and bipartite bases, but when the tegminal structures of the *Hexacrinus* and *Dichocrinus* are compared there is a marked difference. *Hexacrinus* has a ridged tegmen composed of medium-sized plates, and the ambulacrals are usually partially incorporated. *Dichocrinus*, however, has in its earliest expression in the Kinderhook a flexible tegmen composed of minute interambulacrals and unincorporated ambulacrals. *Dichocrinus* therefore apparently could not have originated from the

Devonian expression of *Hexacrinus*, as the reversion from a camerate type of tegmen to the flexible type, and a redevelopment of the camerate type as shown in later forms of *Dichocrinus* and more strongly in its descendants, *Talarocrinus*, etc., are scarcely probable. When, however, *Dichocrinus* (Pl. III, Nos. 12, 15) is compared with a Kinderhook species of *Platycrinus*, namely *P. symmetricus*, (Pl. III, Nos. 13, 14), such a remarkably close parallel in calyx structure is noted that with the insertion of an anal plate and proper modification of the base *P. symmetricus* could scarcely be distinguished in calyx structure from *Dichocrinus inornatus*. However, some species of *Dichocrinus* have uniserial arms, and all have a circular stem. *Dichocrinus* could not then have originated from the immediate ancestor of *P. symmetricus*, but from a somewhat earlier stage where the stem was circular, the arms uniserial, and the base of the *ab—c—de—* type. Hence a new theory for the origin of the bipartite, hexagonal base is suggested:

Dichocrinus and its descendants probably originated from some genus of the Platycrinidae which had a circular stem, flexible tegmen, branching uniserial pinnulate arms, and a base of the *ab—c—de—* type. The hexagonal, tripartite base originated by interpolation of the anal plate in the radial cycle by portional migration, closure of the left-anterior suture, partial atrophy of the right side of the posterior basal, and a compensatory hypertrophy of the left side of the right-posterior basal which shifted the right-posterior basal suture to a posterior position. This metamorphosis is expressed in changing formula *ab—c—de—* to *abc—dex—* (Fig. 9, Nos. 4, 4*a*, *b*).

4. THE SUCCESSION OF BASAL CHANGES IN THE PLATYCRINIDAE AND THE HEXACRINIDAE

The succession of basal changes in the Platycrinidae and the Hexacrinidae seems, from the evidence herein offered, to have followed a different line from that postulated by Wachsmuth and Springer, and the following succession is suggested.

The earliest Platycrinidae, as shown by the ontogenetic development of *Platycrinus*, had a simple pentagonal base of the *a—b—c—d—e—* type and a circular stem. Before the Niagaran (Silurian) this genus gave rise to the *Platycrinus* type of base (*ab—c—de—*)

in *Coccocrinus*, etc., and to the *Stephanocrinus* type of base (*ea—bc—d—*) in *Hapalocrinus*. Anchylosis of the basals in these forms was accompanied by reduction of the compound plate either by superficial or by deep-seated atrophy, and compensating hypertrophy of the simple basal. From *Coccocrinus* two lines of descent seem to have originated: the one culminating in *Platycrinus*, etc., with the *ab—c—de—* (Fig. 9, No. 4) type of base and an elliptical stem; the other culminating in *Dichocrinus* with its hexagonal, bipartite base (*abc—dex—*) (Fig. 9, No. 4*b*) and a circular stem. Interpolation of the anal plate in Dichocrinus is marked by reduction of the posterior radials, and the base is not a regular hexagon. The origin of the hexagonal genera with the tripartite base *ab—cd—ex—* (Fig. 9, No. 7*b*) is doubtful, but they were probably derived from an early branch of the primitive Platycrinidae, in which the base was a simple pentagon of the *a—b—c—d—e—* type and the stem circular.

SUMMARY OF CONCLUSIONS

In the preceding discussion the writer has attempted to portray the various stages of development through which the basal plates of the monocyclic Camerata have passed, and to explain the processes by which these results were obtained. Many of the theories herein set forth will undoubtedly be modified by the discovery of new evidence, and this study is offered merely as a working hypothesis upon which, perhaps, a stronger classification of the Crinoidea may be erected. As a result of this study the following conclusions have been reached:

1. The ancestor of the monocyclic Camerata was a simple, generalized crinoid with pentamerous symmetry.

2. The base of the pentagonal Camerata is not the result of reversion from an intermediate hexagonal stage, but is in a primitive condition as far as influence of the anal plate is concerned.

3. The anal plate is of secondary origin, and originated by primary interpolation between the latero-distal margins of the posterior radials.

4. The hexagonal base of the monocyclic Camerata resulted from the separation of the posterior radials and trunkation of the

posterior basal by the anal plate, the anal plate having been interpolated by portional migration in the space created by the demand of the hind-gut for enlargement.

5. The widening of the posterior basal upon interpolation of the anal plate was bilaterally symmetrical.

6. The quadripartite, hexagonal base resulted from the anchylosis of the anterior pair of basals in a hexagonal genus with a pentapartite base.

7. The posteriorly directed basal suture in the subequally, tripartite and bipartite, hexagonal bases is the homologue of the right-posterior basal suture in the pentapartite and quadripartite bases, which has shifted its position through atrophy of the right half of the posterior basal and a compensating hypertrophy of the left side of the right-posterior basal.

8. The basal sutures lost through anchylosis are potentially present in the basal cup, and liable to reappear in individual cases of delayed anchylosis, but not as a phylogenetic character.

9. The tripartite, hexagonal base in the Batocrinidae resulted from the appearance of the posteriorly directed basal suture (see 7) in a quadripartite base, accompanied by closure of the anterior and left-posterior basal sutures.

10. The hexagonal, tripartite base of the Hexacrinidae resulted from the interpolation of an anal plate by portional migration, through shifting of the right-posterior basal suture to a posterior position, and closure of the anterior and left-posterior basal sutures, in a simple platycrinid with a pentapartite base.

11. The bipartite, hexagonal base in the Hexacrinidae resulted from interpolation of the anal plate by portional migration, shifting of the right-posterior basal suture to a posterior position, and closure of the right-anterior basal suture, in a platycrinid with a pentagonal, unequally tripartite base.

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DISCOVERY OF THE GREAT LAKE TROUT, *CRISTIVOMER NAMAYCUSH*, IN THE PLEISTOCENE OF WISCONSIN

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Some fish remains consisting of a portion of a skull and a number of associated elements, from an interglacial clay deposit in Dunn County, Wisconsin, were recently sent to me for identification by Dr. S. Weidman, of the State Geological Survey of Wisconsin. They turned out to be remains of the great lake trout, *Cristivomer namaycush*, a species now living in Wisconsin waters. They are therefore of interest as carrying back the history of this species to Pleistocene times. Through the kindness of Dr. Weidman, I am permitted to present the following notes on the specimens.

The remains consist of a portion of a skull of a fish about two feet in length, with most of the jaw elements belonging to it, and a number of thin and more or less fragmentary bones pertaining to the opercular and hyoid series. Associated with these remains was a toothed fragment of the jaw of another species of fish, as yet undetermined.

The genus *Cristivomer* is distinguished from all other trouts and salmons (family Salmonidæ), by the shape of the vomer. This element, in side view, and held with the oral face up, is boat-shaped, with a raised crest armed with strong teeth, extending in the median line of the oral face, from the head of the bone backward (Fig. 1*b*). By this element alone the remains are identifiable as belonging to genus *Cristivomer;* and all doubt whatsoever is removed on comparing the other bones with a disarticulated skull of the living lake trout. The correspondence bone for bone is very close, extending to details, so that the fossil form cannot be separated even as a variety from the existing one.

No detailed discussion of the several elements seems necessary; reference may be made to Fig. 1, in which the better preserved

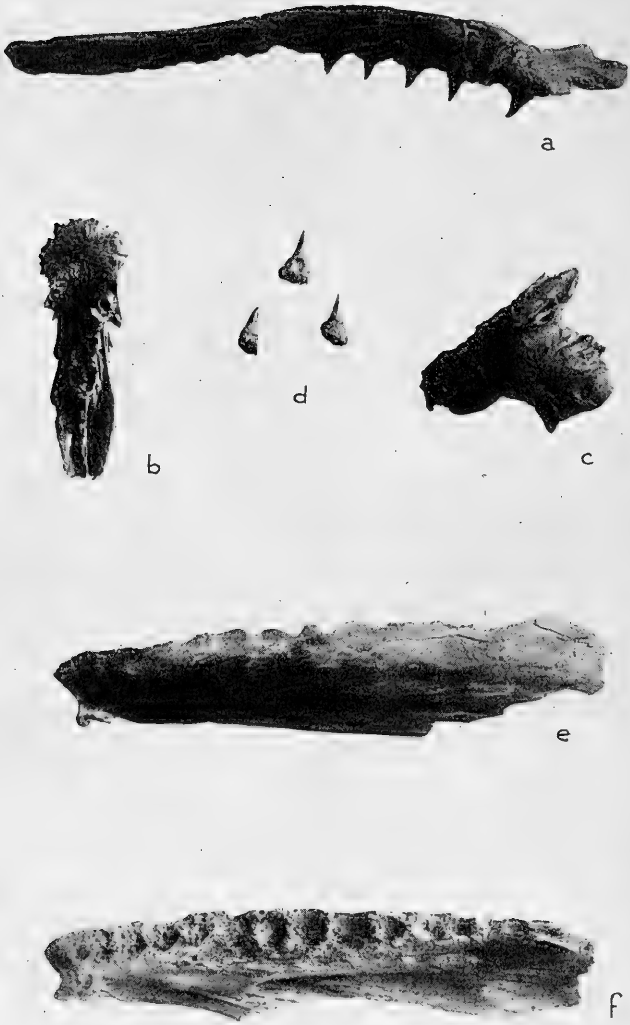

FIG. 1.—*Cristivomer namaycush.* Jaw elements belonging to a single fish, $\times\frac{4}{5}$. Pleistocene; Menomonie, Dunn County, Wisconsin.

a, right maxilla; *b*, vomer, in oral view; *c*, left premaxilla; *d*, teeth from mandible and vomer; *e*, left mandible, outer view; *f*, right mandible, inner view.

of the elements are shown. The parasphenoid is also preserved. It is seen on the under side of the posterior portion of the skull roof, which is the only part of the upper skull surface preserved. This element also agrees closely with that of the existing species.

The discovery of fossil remains of *Cristivomer* is interesting but not unexpected; for the existing species has a wide range in the colder waters of north temperate America, extending into the sub-arctic region. Jordan gives the distribution as follows: "All the larger lakes from New England and New York to Wisconsin, Montana, the Mackenzie River, and in all the lakes tributary to the Yukon in Alaska."[1]

From the extent of this range one would have inferred that the species must have had a long time in which to "spread out" over such an area, and hence that it dated back to at least Pleistocene times. The finding of this specimen proves that this was the case. It shows, moreover, that the genus existed during glacial times in the same region as today, so that its antecedent history—whether it arose in the same region, or wandered into it from somewhere else—dates back to an even earlier time.

The specimen is preserved in the collection of the Wisconsin Geological Survey. The following measurements may be of use for future reference:

VOMER	
Length	44 mm.
Width at neck	12
PREMAXILLA (Left)	
Length, measured along toothed edge	33
Height, at posterior end	27
MAXILLA (Right)	
Total length	105
Length exclusive of anterior process (measured along toothed margin)	95
MANDIBLE	
Both are defective posteriorly; the left as far as preserved measures	95

[1] Jordan, *Guide to the Study of Fishes*, II, 115.

The specimen was collected from a clay bed at Menomonie, Dunn County, Wisconsin. At this locality these beds are from twenty to forty feet in thickness. The following notes regarding them were kindly supplied by Dr. S. Weidman to whom I am also indebted for the geological section here reproduced (Fig. 2).

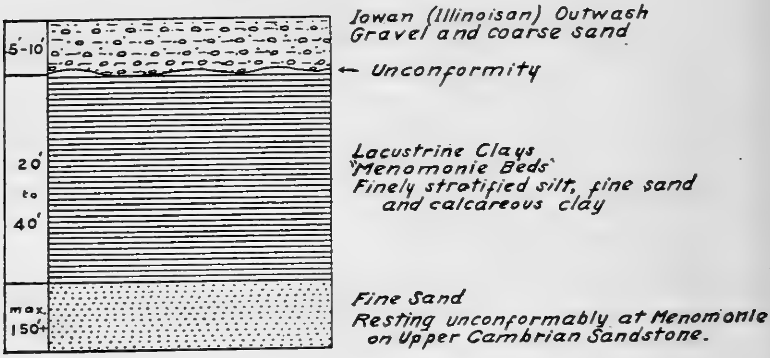

FIG. 2.—Section at Menomonie, showing relations of Pleistocene lacustrine clay beds.

The clay beds are located in the valley of Red Cedar River and have been utilized extensively for many years for the manufacture of brick. The formation consists of finely stratified sand, silt, and clay, usually containing from 5 to 10 per cent of calcium and magnesium carbonate. In other localities the calcareous content is much higher and reaches 20 to 30 per cent. The physical and chemical character of the deposit, as well as the occurrence of the fish remains, indicate the lacustrine origin of the formation. Similar deposits are widespread in Wisconsin and the adjoining states, and have very generally been classed as lacustrine or estuarine. . . . .

The relations of the lacustrine clay ("Menomonie beds") to the overlying Iowan (Illinoisan) glacial gravels indicate that the probable age of the clay is the Interglacial stage between the Kansan and the Iowan (Illinoisan), that is, between the second and third glacial stages of the Pleistocene. No definite relations of the clay beds at Menomonie to the Kansan is exhibited, the border of the Kansan being located 10 or 12 miles to the west, but, based in part on other geologic data, the above inference as to the age seems warranted. The stratigraphic position of the clay beds, in which the species of fish, *Cristivomer namaycush*, is found is therefore near the middle of the Pleistocene series, and as variously estimated in years this particular deposit is probably between 250,000 and 500,000 years old.

Besides the remains of fish, there have been found in the Menomonie clay beds the remains of various mammals such as the elephant, mastodon, reindeer, caribou;[1] the bones of other mammals, the leg bone of a bird, and also fragments of wood identified as spruce.

The fossil remains of the land mammals and of forest trees found in the clays are only in fragmentary pieces, indicating the fact that these were carried some distance by streams, or currents along the lake shore, and dropped into the bed of the old lake.

The remains of the fish, on the other hand, are fairly complete specimens, and seem clearly to indicate that these fish lived in the lake in which the clays were deposited.

[1] *Rangifer*, probably an extinct species, is represented by both male and female antlers, the latter identified by Dr. O. P. Hay.

ASSUMPTIONS INVOLVED IN THE DOCTRINE OF ISOSTATIC COMPENSATION, WITH A NOTE ON HECKER'S DETERMINATION OF GRAVITY AT SEA[1]

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CONTENTS

[1] Criticisms of the conception of isostatic compensation from other viewpoints than those here presented are those of Professor T. C. Chamberlin ("Diastrophism and the Formative Processes," *Jour. Geol.*, XXI [October–November, 1913], 577–87; November–December, 1913, pp. 673–82, and succeeding numbers); and those of Professor Joseph Barrell ("The Strength of the Earth's Crust; Part I," *ibid.*, XXII [January–February, 1914], 28–48, and succeeding numbers), which appeared after its formulation. A sharply critical mathematical discussion of Hayford's trial hypothesis, used in fixing the depth of complete compensation, had already been published (Harmon Lewis, "The Theory of Isostacy," *ibid.*, XIX [1911], 603–26). Hayford's rejoinder appeared in the *Journal of Geology* in 1912 (XX, 562–78).

INTRODUCTION

A rigid versus a plastic earth shell.—The doctrine of isostasy is an expression of disbelief that the outer shell of the lithosphere is sufficiently strong to support the protuberances upon its surface. An added idea is that, since it is a failing structure, it is sensitive to surface transfers of rock material and responds with a subsidence beneath freshly loaded areas and with corresponding elevation within denuded districts. It should never be forgotten that this theory was conceived at a time when belief in a liquid interior of our planet was general, and that its adjustment to the modern view of a rigid earth is a matter of the last decade only. Probably the fact which more than any other has compelled geologists to consider the question of possible high plasticity within the earth's outer shell is the great thickness of shallow-water deposits that have been laid down in geosynclines. Although to some extent the recent recognition of the large importance of continental deposits within ancient sedimentary formations has required a modification of earlier assumptions, there is still a call for some explanation of the apparent balance which has been maintained between subsidence and the quantity of deposited material within the basins of sedimentation. Obviously two contrasted hypotheses may be offered. Upon the one hand, it may be assumed that the adjustments in level are the *cause* of the increased denudation and deposition (doctrine of high rigidity); and, upon the other hand, it may be assumed that these changes in level are the *effect* and not the cause (doctrine of high plasticity—isostasy).

While the name isostasy is of American origin[1] and the crystallization of ideas always connected in time with the providing of a pigeonhole for their assembling has been notably strong in this country, the conception itself is much older and has long occupied the attention of geologists in both Europe and America.[2] It appears to have first found full expression a half-century earlier,[3] and it has ever since played an important rôle in the fields of geodesy and geology. From the failure of astronomic and geodetic locations of position accurately to correspond, and from the "anomalies" of pendulum observations—the so-called "anomalies" of deflection of the vertical and of gravity (Δg.)—it has from the beginning drawn most of its support. Woodward, writing in 1889, says: "In general terms we may say that the difficulty in the way of the use of pendulum observations still hinges on the treatment of local anomalies and on the question of reduction to sea-level."[4]

Pratt's hypothesis.—The remarkable anomalies in the deflection of the plumb line which were discovered in Northern India along the base of the Himalayas led Archdeacon Pratt in 1859[5] to the rather astounding assumption that a mass of less density lies beneath this great protuberance upon the lithosphere. Had the venerable archdeacon conceived the earth to be rigid, as is generally held today, it is not very likely that he would have arrived at this

[1] C. E. Dutton, "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, II (1889), 51–64.

[2] For an excellent summary of the evolution of thought along this line, see F. L. Ransome, "The Great Valley of California: A Criticism of the Theory of Isostasy," *Bull. Dept. Geol. Univ. Cal.*, I, No. 14 (1896), 371–428.

[3] Sir John F. W. Herschel, "Letter to C. Lyell, Esq.," *Phil. Mag.*, II (1837), 212–14.

[4] R. S. Woodward, "The Mathematical Theories of the Earth," *Am. Jour. Sci.* (3), XXXVIII (1889), 341.

[5] John Henry Pratt, "On the Deflection of the Plumb-Line in India Caused by the Attraction of the Himalaya Mountains and of the Elevated Regions Beyond: and Its Modification by the Compensating Effect of a Deficiency of Matter Below the Mountain Mass," *Phil. Trans.*, 1859, pp. 745–96.

conclusion. He assumed further that, since the earth's crust is supposed to be in hydrostatic equilibrium, a level surface must be considered as existing somewhere beneath the crust upon which the pressure of the masses lying above is everywhere the same.[1] This convenient idea of compensation of gravity variations in a deficiency of mass beneath the surface in some cases, and an excess in others, has played a large rôle in subsequent geodetic studies and is generally referred to as Pratt's hypothesis.

In America the measurements of gravity made by Putnam along the line of the Transcontinental Survey have been studied with much thoroughness by Gilbert, who has been led to the belief that a considerable measure of compensation exists.[2] He says:

> The measurements of gravity appear far more harmonious when the method of reduction postulates isostasy than when it postulates high rigidity. Nearly all the local peculiarities of gravity admit of simple and rational explanation on the theory that the continent as a whole is approximately isostatic. Most of the deviations from the normal arise from excess of matter and are associated with uplift. . . . . The fact that the six stations from Pike's Peak to Salt Lake City, covering a distance of 375 miles, show an average excess of 1,345 rock feet indicates greater sustaining power than is ordinarily ascribed to the lithosphere by the advocates of isostasy [pp. 73–74].

THE HAYFORD CONCEPTION OF ISOSTATIC COMPENSATION

Scope of Dr. Hayford's investigations.—Attention has been focused anew upon the subject of isostasy by the papers of Dr. John F. Hayford, lately inspector of geodetic work and chief of the Computing Division of the United States Coast and Geodetic Survey, and now dean of the College of Engineering at Northwestern University. His investigations have treated of the figure of the earth and isostasy, and are now deservedly well known on the basis of labors extending over a considerable period of years and published in a series of official monographs and briefer summary articles.[3]

[1] This is essentially Helmert's statement of Pratt's hypothesis (*Sitzungsber. Berliner Akad.*, 1908, p. 1060).

[2] G. K. Gilbert, "Notes on the Gravity Determinations Reported by Mr. G. R. Putnam," *Bull. Phil. Soc. Wash.*, XIII (1895), 61–65.

[3] "The Form of the Geoid as Determined by Measurements in the United States," *Report of the Eighth International Geographic Congress, Washington, 1904* (Government

The writer shares with many others a natural pride in this notable achievement of American research, which has attracted attention by reason both of the large scale of its operations and of its thorough and painstaking execution. With the conclusions concerning the figure of the earth this paper is not especially concerned. It is with reference to Hayford's theoretical deductions within the realm of geophysics and geology upon the basis of Pratt's hypothesis of compensation that the writer would offer suggestions, particularly concerning the fundamental assumptions of which no account is taken in Hayford's papers. In his later article in *Science*—a presidential address—geologists are informed by Dr. Hayford that they have no recourse but to accept his conclusion. We quote:

> Within the past ten years geodetic observations have furnished positive proof that a close approximation to the condition called isostasy exists in the earth and comparatively near the surface [p. 199].
>
> The geodetic observations show that the isostatic compensation under the United States is nearly complete. It is not merely a compensation of the continent as a whole, it is a compensation of the separate, large, topographic features of the continent [p. 200].
>
> The compensation may properly be characterized as departing from completeness only one-tenth on an average [p. 201].

Elsewhere in the article over- or under-compensation is stated not to exceed that of a mass of rock strata 250 feet in thickness, on an average, and that the limiting depth of compensation is 122 km. (76 miles).

Printing Office, 1905), pp. 535–40; "The geodetic Evidence of Isostasy," *Proc. Wash. Acad. Sci.*, VIII (1906), 25–40; "The Earth a Failing Structure," *Bull. Phil. Soc. Wash.*, XV (1907), 57–74; "The Figure of the Earth and Isostasy from Measurements in the United States," *Dept. Com. and Labor, Coast and Geod. Surv.* (Washington, 1909), pp. 1–178, maps; "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," *ibid.* (Washington, 1910), pp. 1–80, maps; (with William Bowie) "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *ibid.*, Special Publication No. 10 (1912), pp. 1–132, maps; William Bowie, "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (2d paper), *ibid.*, Special Publication No. 12 (1912), pp. 1–28, maps; "The Relations of Isostasy to Geodosy, Geophysics, and Geology," Science, XXXIII (1911), 199–208; "Isostasy, Rejoinder to the Article by Harmon Lewis," *Jour. Geol.*, XX (1912), 562–78. An outline of Hayford's studies from a very sympathetic standpoint is G. K. Gilbert's "Interpretation of Anomalies of Gravity," *Prof. Paper No.* 85 *C, U.S. Geol. Surv.*, 1913, pp. 29–37, Pl. 4.

Hayford's categorical statements reach their culmination in the following:

> These are the facts, established by abundant geodetic evidence. These facts may not be removed or altered by showing that difficulties are encountered when one attempts to make them fit existing theories, geological or otherwise. The theories must be tested by the facts and modified if necessary [p. 201].

Methods and assumptions within the field of the exact sciences.—Inasmuch as Dr. Hayford's statement last cited raises a question concerning the comparative reliability of the data obtained from geodetic and from geological observations, it may perhaps be pointed out that geologists have before been warned of the fallacy of their conclusions by workers in the field of the so-called exact sciences. Two fairly recent instances will suffice, though it would be easy to cite others.

With a degree of assurance which was perhaps warranted by his pre-eminence in research, the late Lord Kelvin served notice upon geologists that the longest period that could by any possibility be allowed them as representing time since the beginning of life upon the globe was a hundred million years, with a probability that it could not exceed twenty million years;[1] and this figure was soon reduced by Professor Tait to ten million years.[2] With the question of whether this allowance is adequate we are not at the moment concerned, since the developments in the realm of physics have destroyed the value of Kelvin's argument. At the meeting of the British Association held at Winnipeg in 1909, Sir J. J. Thomson, referring in his presidential address before that body to studies of radium by Rutherford and others, showed how Kelvin's argument was based upon incomplete evidence and must now be abandoned in view of the new light which has been shed upon the problem.[3]

It was Helmholtz, another conspicuous champion of the exact sciences, who stated that the atmospheric envelope of the earth could not extend above an altitude of 27 or 28 km., since the temperature gradient required that the absolute zero of temperature

[1] Sir William Thomson, "The Age of the Earth," annual address to Victoria Institute, *Phil. Mag.*, 1899, p. 66; also, *Popular Lectures and Addresses*, II, 64.

[2] *Recent Advances in Physical Science*, p. 174. See rejoinder by A. Geikie, *Landscape in History and other Essays* (1905), pp. 206–8.

[3] *Rept. Brit. Ass'n Adv. Sci., Winnipeg Meeting, 1909* (1910), pp. 27–28.

should be reached at that level.[1] From actual sounding of the atmosphere we now know that the convective zone within which the temperature gradient is essentially adiabatic ends abruptly at an altitude ranging from 9 to 18 km., and that the envelope extends to at least 70 km.,[2] with nearly isothermal conditions above the convective zone.

From these examples and others which might be cited, we should learn that while the methods of "exact science" may not be lacking in precision, the assumptions which enter into the solutions, whether they are used consciously or not, possess the same measure of fallibility as those employed in other fields of science. It is therefore with assumptions unconsciously made by advocates of isostatic compensation that this paper will deal.

Hayford's negative argument for a failing earth, based upon data now shown to be inapplicable.—In his paper entitled "The Earth a Failing Structure," Hayford has shown us how his conclusions and those of the late Sir George Darwin dealing with the same subject are diametrically opposed to each other, for the reason that the basal assumptions differ so widely. In the same paper six negative reasons are given why the earth must be a failing structure; that is, be incapable of supporting its protuberances by virtue of its rigidity. These reasons may be reduced to one and stated in this form: Even if the earth throughout had the strength of granite, it would upon the basis of known tests be incapable of supporting without failure the loads upon it. Since this statement was made, studies by Bridgman[3] and Adams[4] have shown that under hydrostatic conditions of compression such as must be conceived to exist within the earth the crushing strengths of materials are enormously enhanced over those derived from tests in which no lateral constraint is imposed—the data employed by Hayford. The studies

[1] Cf. A. Wegener, *Thermodynamik der Atmosphäre* (1911), pp. 109, 185.

[2] W. S. Bruce, *Polar Exploration* (London, 1911), pp. 210–11.

[3] P. W. Bridgman, "The Collapse of Thick Cylinders under hydrostatic Pressure," *Physical Review*, XXXIV (January, 1912), 1–24.

[4] F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (February–March, 1912), 97–118. See also L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior, *ibid.*, pp. 119–38.

by Bridgman were made upon hollow metal cylinders, while Adams has interpreted his results to show that the crushing strength of granite is at least seven fold as great as has been supposed. Test blocks of Westerly (Rhode Island) granite at ordinary temperatures first began to flow with pressures of 200,000 pounds to the square inch. In a discussion of these results King says:

> No state of shearing stress in the crust of the earth due to the weights of continents and mountains can cause the collapse of the rock in the neighborhood of a small cavity. . . . . At a temperature of 550° C. supposed to exist eleven miles below the earth's surface cavities will remain open when submitted to considerably greater pressures than are found at this depth.[1]

Though applying to forces whose continuance of application is short (six hours), many lines of evidence confirm the assumption of the great rigidity of the earth's crust—much the most exact as well as the most recent being the determination by Michelson that in this respect it exceeds solid steel.[2]

Recent unpublished experiments by Bridgman have an important bearing upon this point. I am permitted to quote the following from a personal letter:

> I have recently made a few experiments which show that at least for some substances the viscosity increases enormously with increasing pressure. The effect may certainly be as great as two hundred times for an increase of 1,000 atmospheres, and increases at least as rapidly as the square of the pressure.

Hayford's negative argument in favor of isostasy has thus upon the basis of later work been shown to be fallacious. In his official monographs he has supplied what he considers conclusive positive evidence in support of his contention that isostatic compensation is nearly perfect at a depth of 76 miles below sea-level—in other words, that elevations above the surface persist only by virtue of a deficiency of mass, and that basins are situated above a basement of exceptional density. Upon his hypothesis the quantity of matter is the same in all vertical columns of the same cross-section and limited below at the assumed depth below sea-level of 76 miles. This "positive" argument rests, however, upon Pratt's hypothesis, and implies a weak and failing earth shell.

[1] *Op. cit.*, p. 137.

[2] A. A. Michelson, "Preliminary Results of Measurements of the Rigidity of the Earth," *Jour. Geol.*, XXII (1914), 97–130.

His positive argument and the facts upon which it is based.—Hayford's earlier studies have dealt with the well-known differences between the astronomic and the geodetic determinations of latitude, longitude, and azimuth—so-called deflections of the vertical—measured first at 267 stations, and in a supplementary study at 116 stations, making in all 383, which are fairly well distributed over the domain of the United States. These uncorrected residuals have values which when expressed in terms of astronomic minus geodetic determination (A–G) range between $-26''.50$ and $+32''.43$, the average being, however, comparatively small. The later monographs have dealt with pendulum determinations of gravity, made at 89 stations in the first study and 35[1] in the second, a total of 124. Unfortunately, instead of correcting the measurements of gravity so as to take account of both altitude and topography and obtain a comparison of observed and computed values, Hayford has combined with the correction for topography one for "compensation" with reference to the assumed limiting surface at a depth of 76 miles below sea-level. Fact and theory have thus been combined in his tables in such a way as to make it impossible to extricate the figures representing the anomalies of gravity at each station *except upon the Pratt-Hayford hypothesis.* We are thus thrown back upon those earlier studies which deal with deflection of the vertical.

HAYFORD'S FUNDAMENTAL ASSUMPTION CONCERNING THE DISTRIBUTION OF MASS WITHIN THE EARTH'S SURFACE-SHELL

Lack of knowledge concerning distribution of mass beneath the earth's surface.—If we assume, as Hayford has done in conformity with the usual conception, that the differences between geodetic and astronomic locations of station are a measure of the horizontal components of the earth's gravitation at the station, these differences must be assumed to be made up of the horizontal components of the pulls from all elementary volumes of the earth when multiplied by mass and divided by the square of the distance from the station. But next to nothing is known concerning the distribution of density within the lithosphere. As Gilbert has said, "The inner earth is the inalienable playground of the imagination."

[1] By Bowie alone.

Preponderant effect of near masses due to law of inverse squares.—It is a direct consequence of the law of inverse squares that bodies relatively near the station exert a preponderant influence upon the intensity of gravity, and a relatively small mass of high density within a few miles of the station may thus be responsible for the major portion of the anomaly in the direction or intensity of gravity. To employ an illustration from the field about a magnetic needle: the local variation in the pointing of the needle may be explained either, upon the one hand, by the location of the station with reference to the magnetic poles of the earth, or, upon the other, by the propinquity of excessively magnetic masses—such, for example, as a deposit of magnetic iron ore. Within the Mississippi plain we find generally "normal" conditions explainable by the position of stations with reference to magnetic poles; whereas in many areas of the northern peninsula of Michigan the notable magnetic "anomaly" is explainable almost entirely by local conditions.

It has sometimes been claimed that the extension of Clairaut's theorem by Stokes makes the value of $\Delta g.$ independent of local (that is, near-by) variations in density, which may be both large and abrupt. This, however, is not the case. The non-permissibility of such variations for the application of the theorem was recognized by Stokes[1], as it has been by Rudzki.[2] Clairaut in fact developed the theorem to apply to an earth supposed to have a liquid interior.

Hayford's explanation of anomalies found in systematic regularity as contrasted with local irregularity in distribution of mass.—Hayford's studies of the deflection of the vertical and of gravity irregularities within the United States have been carried out upon the assumption that they are explainable by general, as contrasted with local, conditions; and his method of reducing residuals falls in with the explanation of magnetic variation within the Mississippi plain. A solution of the problem of anomalies in the intensity of terrestrial magnetism in northern Michigan which caused these residuals to disappear through a process of general averaging would constitute a proof, not of the certitude of the hypothesis assumed, but rather of its falsity.

[1] *Mathematical and Physical Papers*, II, 164.

[2] *Physik der Erde*, pp. 35–36.

The earth's density as a whole being more than double that of the part known to us from observation, we may assume almost any distribution of matter which arranges the concentric shells in inverse order of density from the center to the surface. It is in fact quite as probable that near the surface contacts between successive shells of different density are abrupt as it is that they are gradual. Hayford has assumed, though he does not appear to regard it as an assumption of importance, that down to a depth of 76 miles (122 km.)[1] no shell of notably higher density than that at the surface is encountered. It is, however, entirely within the realm of probability that material in all respects resembling the stone meteorites or stone-iron meteorites may be found within this depth. If, further, the surface of contact between a lower shell of higher density and a higher shell of lower density is not only abrupt but irregular and characterized by notable local prominences, an explanation can be found for most local anomalies of gravity.

EVIDENCE OF LOCAL IRREGULARITIES IN DISTRIBUTION OF GRAVITY AND MAGNETIC CONSTANTS

Evidence from Russia and from Southern Italy.—It is proposed now to state certain evidences that local conditions may be responsible for large anomalies in the value of gravity. The evidence now upon record has been drawn from a number of widely separated provinces, in all of which extended series of measurements either of gravity or of deflection of the plumb line have been carried out.[2] The great plain of Russia is of special interest in a discussion of isostasy, since any anomalies in gravity which occur do not require

[1] Helmert has distinctly recognized that there are anomalies of gravity not explainable on general conditions, but, using the same assumption of the truth of Pratt's hypothesis, he has determined the depth of the *Ausgleichfläche* to be 118±22 km. He has chosen for this purpose the zones of special disturbance above and on either side of the steep slope bordering the continental shelves (F. R. Helmert, "Die Tiefe der Ausgleichfläche der Prattschen Hypothese für das Gleichgewicht der Erdkruste und den Verlauf der Schwerestörung vom Innern der Kontinente und Ozeane nach den Küsten," *Sitzungsber. d. k. preusz. Akad. d. Siss. z. Berlin*, 1909, pp. 1192–98).

[2] F. de Montessus de Ballore, "Sur les anomalies de la pésanteur dans certains régions instables," *Comptes Rendus de l'Académie Française*, CXXXVI (Paris, 1903), 705–7.

large corrections for topography. It has been found, however, that in the great triangle Kamiensk-Podolsk, Kazan, Astrakhan, which relatively to the surrounding country is very unstable in a seismic sense and is bordered by dislocations, the measurements of gravity made by General Stebnitzki[1] have shown a notable deficit of gravity to characterize this marginal zone. A like threefold correspondence of seismic instability, of zones of dislocation, and of abnormal gravity has been proved for a number of other regions, notably Southern Italy and Sicily,[2] the Indo-Gangetic plain to the southward of the great protuberance of the Himalayan Highland, the North German plain, and a district in Hungary.

Evidence from India.—As the Russian province is of interest because the topographic correction is small, so the Indo-Gangetic plain at the southern base of the Himalayas offers a contrasted set of conditions and presents the best possible opportunity for testing the influence upon deflection constants of a huge protuberance of the lithosphere whose volume and probable density may be subjected to computation. It is thus of interest to find that Colonel Burrard[3] is led to ascribe the deficit of gravity in the Indo-Gangetic plain to the known zone of dislocation in correspondence with the zone of seismic instability; his view being that a great rift in the *subcrust* filled with material of low density extends to considerable depths beneath this zone.

Colonel Burrard is exceedingly favorable to the Pratt-Hayford conception of isostasy and has made computations based upon Hayford's earliest figures for the surface of compensation, yet he does not find that the residuals are thereby decreased, but, on the contrary, that they are enhanced. For the entire distance of 25 miles separating Kurseong in the outer Himalayas and Jalpaiguri

[1] M. A. de Lapparent, "Sur la signification géologique des anomalies de la gravité," *ibid.*, CXXXVII (1903), 827–31.

[2] Annibale Riccò, "Determinatione della gravità relativa in 43 luoghi della Sicilia orientale, della eolie, e della Calabria," *Mem. della Soc. degli spettroscopisti Italiani*, XXXII (1903), 173–296.

[3] Col. S. G. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India* (Calcutta, 1912), pp. 1–26. See also by the same author, "The Origin of Mountains," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 385–88; and "On the Origin of the Indo-Gangetic Trough, Commonly Called the Himalayan Foredeep," *Proc. Roy. Soc.*, A, XCI (1915), 220–38.

upon the plains, the difference in deflection is 45″, instead of 26″, which it should either equal or exceed on the conception of support by rigidity without compensation, and 15″, as it must be according to Hayford's hypothesis.[1] In a separate monograph of the Indian Survey, Major Crosthwait has discussed the application of Hayford's theory to the Himalayan area and has found that whereas for the United States as a whole the mean residual is 1″.86 and for all save the western section 1″.15, for the Himalayas it is more than eight times this amount.[2] Dr. Hayden has shown that to secure compensation the depth of the equilibrium surface must be increased from Hayford's figure of 122 km. to 330 km.[3] Applied in the region where it is most crucially tested, the Hayford hypothesis thus receives less support in the facts than does the doctrine of non-compensation.[4]

Mutual relationships of abnormal gravity, abnormal earth magnetism, dislocations, and seismicity.—In at least three widely separated provinces the coincidence of anomaly of terrestrial magnetism with that of gravity, and with that of dislocation zones, has been proved by the data from official surveys. In the earthquake province of Calabria and Sicily this result has been reached by a Royal Commission under the direction of Professor Riccò.[5]

A close correspondence between anomaly of gravity and that of terrestrial magnetism has likewise been brought out to special advantage within a province in Hungary which is relatively small, but one provided with an especially large number of stations, so

[1] Burrard, *op. cit.*, p. 4. See also Sir Thomas Holland, "The Origin of the Himalayan Folding," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 167–76.

[2] Major H. L. Crosthwait, R. E., "Investigation of the Theory of Isostasy in India," *Prof. Paper No. 13, Survey of India* (Dehra Dun, 1912), pp. 1–123.

[3] H. Hayden, "Notes on the Relationship of the Himalaya to the Indo-Gangetic Plain," etc., *Geol. Surv. India*, XLIII (1913), 138–67, Pls. 3, 4.

[4] The stations discussed by Bowie from the Indian district to indicate harmony with the Hayford doctrine are far removed from the Himalayas (W. Bowie, "Isostasy in India," *Jour. Wash. Acad. Sci.*, IV [1914], 245–49.)

[5] A. Riccò, "Anomalie del magnetismo terrestre in relatione alle anomalie della gravità nella Sicilia orientale," *Boll. dell' Accad. Gioenea di Scienze Naturali in Catania*, Fasc. 80 (1904), pp. 1–3. See also "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia," *Annali dell Ufficio Centrale Meteorologico e Geodinamico Italiano*, XIX (1897; separate printed at Rome in 1907), 1–10, plate; also, "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia in relatione alla costituzione del suelo, *Boll. della Soc. Sism. Ital.*, XII (1907), 393–407.

that the lines of equal anomaly of gravity have been drawn for each millimeter of acceleration.[1] The sharp changes—steep gradients—upon the map thus come into prominence, and these show very close correspondence with strong abnormality of the magnetic forces and with the intensity of earthquakes, the seismicity of the province having been investigated by Rethly.[2]

For the area of the North German plain, Deecke, making use of data upon magnetic constants determined by Schück and of those of gravity issued by Helmert from the Royal Prussian Geodetic Institute at Potsdam, has shown that the lines of equal anomaly of gravity correspond closely with those of terrestrial magnetism (involving both inclination and declination), and that these lines are further, in many cases, those of recent faulting, and in some cases were probably the seats of movement during the earthquake of October 23, 1904.[3] In this connection it is of interest that a resurvey of magnetic elements in Japan subsequent to the great earthquake of 1891 indicated remarkable changes in the isomagnetics of the province.[4]

In connection with a general survey of geodetic data assembled from many regions, Helmert, though approving Hayford's views, has concluded that gravity values are in many localities not completely in harmony with Pratt's hypothesis,[5] and that this is especially true for the oceanic islands, for the margins of the continental

[1] Baron Roland Eötvös, "Bestimmung der Gradienten der Schwerkraft und ihrer Niveauflächen mit Hülfe der Drehwage," *Abh. der XV. Allgemeinen Konferenz der Erdmessung in Budapest, 1906*, I, 1–59 (reprint). See also, by the same author, "Über Arbeiten mit der Drehwage ausgeführt im Auftrage der königlichen ungarischen Regierung in den Jahren 1909–1911," *Bericht an die XVII. Allgemeine Konferenz der Internationalen Erdmessung* (Budapest, 1912), pp. 1–17.

[2] *Földrajzi Közlemenyek*, XXXIX, 391–420.

[3] W. Deecke, "Erdmagnetismus und Schwere in ihrem Zusammenhange mit dem geologischen Bau von Pommern and dessen Nachbargebieten," *Neues Jahrb. f. Mineral.*, etc., Beilage Bd. 22 (1906), pp. 114–38, Pls. 1–3.

[4] D. Kikuchi, *Jour. Coll. Sci. Univ. Tokyo*, V, 149–92.

[5] Wenn Pratts Hypothese erfüllt ist, so müssen sich die Schwerestörungen Δg. lediglich aus Höhenstörungen der Massenlagerung über der Ausgleichsfläche erklären lassen. Dies gelingt aber nicht völlig; man muss daher auch noch Horizontalverschiebungen annehmen, welche die Massenlagerung gestört haben. Es treten sogar ausgedehnte Massenstörungen auf, wo die sich gegenseitig ausgleichenden Massen nicht erkennbar sind, so dass man nur schlechthin von Anhaüfungen und Defekten sprechen kann, die sich also als erhebliche Abweichungen von Pratts Hypothese darstellen" (*Sitzungsber. Berliner Akad. d. Wiss.* [II, 1908], 1060).

shelves, for mountain summits, and for intermontane valleys. He gives, as the most noteworthy of aberrant districts, Hawaii, Corsica, Sicily and Calabria, the Austrian Alps and the Carpathians, large areas in Turkestan continued eastward to the Pamirs, Lake Baikal, and localities within the valley of the Obi River in Siberia. These, with the exception of the one last mentioned, from which few seismic data are available, are notably the great earthquake zones of the Eastern Hemisphere.[1]

HAYFORD'S FIGURES ANALYZED WITH THE IDEA OF COMPENSATION ELIMINATED

Deflections corrected for topography to find attraction of hidden masses.—We have thus seen that in many regions the evidence favors the view that anomaly of gravity is connected with local irregularity and not alone with general and orderly—systematic—distribution of mass over a wide area. Hayford's gratuitous assumption has been that the distribution of mass which produces gravity anomaly ($\Delta g.$) is throughout regular and systematic; and to this he has added the additional assumption of a failing earth, which in the light of recent work does not appear to be well founded. Pratt's hypothesis of compensation was designed to meet conditions within an earth shell of supposed high plasticity, and Hayford has contributed to this theory a determination of the supposed depth of the compensation surface. His assumed proof has consisted in testing by the method of least squares a number of hypothetical *systematic* distributions of matter in the unknown region, with the use of the measurements of deflection of the vertical and of gravity within the area of the United States. His choice of the depth of 76 miles for complete compensation was based upon a reduction of the sum of the squares of the residuals to about one-tenth of that obtained upon the hypothesis of a rigid earth *without important local irregularities in distribution of matter.*

If it be true that local anomaly is to be ascribed largely to irregular local distribution of mass beneath and near the station, Hayford's method is inapplicable and can only lead to erroneous results.

[1] Cf. de Montessus, "Les tremblements de Terre," *Géographie Seismologique* (Paris, 1906), Map 1.

Let us then see from examination of his figures whether they betray evidence of large local as against broad systematic distribution only of the concealed matter beneath and about the station. For reasons already given, this test of his figures is possible only in case of the deflections of the vertical.

Distribution of residuals in excess of 50″ of arc.—Hayford has computed with considerable care the topographic deflections for each station, and this resultant horizontal pull of the *determinable* masses at the station, when deducted from the measured deflection, must leave a residual fixed by the *hidden* masses whose distribution of density is unknown. By assembling his topographic corrections and applying them we obtain residual deflections which range from zero to 89″.46 of arc.[1] We have arbitrarily selected in a first survey of the results an arc of 50″, or something more than half the maximum residual, as a *minimum of excessive anomaly* in order to determine the plan of distribution. The results are shown in Table I.

Thus it is seen that 100 stations out of a total of 774 (numbering stations separately for latitude and for longitude or azimuth) gave residuals, after correction for known distribution of matter, which are in excess of 50″ of arc. These constitute 12.9 per cent, or about one-eighth of the entire number, and it is a fact of much significance that, with the exception of two stations which are

[1] We may here ignore the sign of the residual deflection, which indicates the direction of displacement of the zenith. The topographic correction is for the coastal regions particularly large and often several times the measured deflection. It is therefore interesting to find that the uncorrected deflections are also in the Pacific coastal region the largest for the United States. Deflections of the vertical for the entire series of Hayford which are in excess of 15″ are the following, with station numbers given:

In meridian: 238, Santa Barbara (−18.38); 245, Los Angeles (−17.99); 364, Mt. Wilson (−28.50).

Prime vertical: 1, Point Arenas (+16.98); 224, Tepusquet (+20.15); 225, Arguello (+15.90); 227, New San Miguel (+20.62); 228, Santa Cruz W. (+19.71); 229, Santa Barbara (+15.04); 230, Los Angeles N.W. (+19.56); 231, Los Angeles S.E. (+21.55); 236, Sulphur Pk. (+18.82); 237, Ross Mt. (+18.18); 241, Avila (+29.93); 242, San Buenaventura (+19.38); 244, Soledad (+28.06); 245, San Diego (+32.43); 23, Genoa (−18.65); 42, Ogden (+16.25); 43, Waddoup (+24.84); 44, Salt Lake City, Long. Sta. (+15.37); 45, Salt Lake City, Az. Sta. (+18.15); 46, Mt. Nebo (+18.69); 61, Colorado Springs (−18.74).

TABLE I

"Abnormal" Deflections of the Vertical—Hayford (Corrected for Topography)

(Minimum, 50″ of Arc)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
233......	Mt. Toro..................	36°32′	121°37′	52″.34
234......	Arguello..................	34 35	120 34	53.97
236......	Santa Cruz W.............	34 4	119 55	56.62
237......	New San Miguel...........	34 2	120 23	55.30
242......	Lospe.....................	34 54	120 36	51.08
246......	Dominguez Hill............	32 52	118 14	59.03
254......	Point Pinos...............	36 38	121 56	51.00
260......	San Luis Obispo...........	35 11	120 45	52.41
261......	Avila.....................	35 11	120 43	50.22
264......	San Buenaventura..........	34 16	119 16	53.29
265......	San Pedro.................	33 43	118 17	58.61
266......	Santa Catalina............	33 26	118 30	57.90
267......	Soledad...................	32 50	117 15	50.04
361......	Harbor....................	33	118 34	54.22
362......	Wilson Peak...............	34 13	118 3	50.50
363......	Los Angeles N.W...........	33 55	118 3	53.98
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
1......	Point Arena...............	38 55	123 41	87.65
3......	Ukiah.....................	39 9	123 12	81.84
6......	New Presidio..............	37 48	122 27	79.47
7......	Lafayette Park............	37 48	122 26	80.34
8......	Washington Square.........	37 48	122 25	80.26
9......	Mt. Hamilton..............	37 21	121 38	77.84
10......	Marysville................	39 8	121 35	75.75
16......	Sacramento................	38 35	121 30	75.07
246......	San Diego 1871............	32 43	117 9	62.49
20......	Lake Tahoe S.E............	38 57	119 57	70.88
22......	Verdi.....................	39 31	119 59	66.21
23......	Genoa.....................	39	119 51	71.66
24......	Carson City...............	39 10	119 46	62.26
25......	Virginia City.............	39 19	119 39	59.71
216......	San Diego.................	32 43	117 9	63.69
217......	Los Angeles Normal Sch. 001.	34 3	118 15	61.52
243......	Buenavista................	34 3	118 15	61.26
352......	Wilson Peak...............	34 13	118 3	61.22
353......	Mare Island...............	38 6	122 16	75.54
361......	Gazelle...................	41 32	122 31	75.50
367......	Eugene....................	44 4	123 5	77.72
372......	Portland..................	45 31	122 41	63.58
376......	Tacoma....................	47 16	122 27	57.98
377......	Seattle, 1908.............	47 40	122 19	57.79
378......	Seattle, 1888.............	47 37	122 20	58.77
381......	Port Townsend.............	48 7	122 45	60.71
382......	Blaine....................	48 59	122 45	50.95

TABLE I—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
2......	Paxton....................	39° 8′	123°19′	78″79
4......	Mt. Helena................	38 40	122 38	66.59
5......	Mt. Tamalpais.............	37 55	122 36	77.95
224......	Tepusquet................	34 55	120 11	60.63
225......	Arguello.................	34 35	120 34	70.19
226......	Gaviota..................	34 30	120 12	63.38
227......	New San Miguel...........	34 2	120 23	59.65
228......	Santa Cruz W.............	34 4	119 55	56.70
229......	Santa Barbara............	34 24	119 43	58.71
234......	Dominguez Hill...........	33 52	118 14	58.01
236......	Sulphur Peak.............	38 46	122 51	66.37
237......	Ross Mountain............	38 30	123 7	72.48
238......	Point Avisadero..........	37 44	122 22	88.84
239......	Monterey Bay.............	36 36	121 53	89.46
240......	Santa Cruz...............	36 59	122 3	73.20
241......	Avila....................	35 11	120 43	54.51
242......	San Buenaventura.........	34 16	119 16	52.56
221......	Santa Lucia..............	36 9	121 25	81.74
222......	Castle Mount.............	35 56	120 20	65.75
223......	Lospe....................	34 54	120 36	71.71
11......	Monticello...............	38 40	122 11	72.19
12......	Vaca.....................	38 23	122 5	74.89
13......	Mt. Diablo...............	37 53	121 55	75.38
14......	Yolo, N.W. Base..........	38 41	121 51	68.34
15......	Yolo, S.E. Base..........	38 32	121 48	69.97
17......	Mocho....................	37 29	121 33	77.15
18......	Mt. Lola.................	39 26	120 22	75.44
19......	Round Top................	38 40	120	74.44
21......	Lake Tahoe S.E...........	38 58	119 57	63.96
26......	Mt. Conness..............	37 58	119 19	66.91
27......	Carson Sink..............	39 35	118 14	60.49
218......	Santa Ana................	36 54	121 14	72.64
219......	Mt. Toro.................	36 32	121 37	78.97
220......	Hepsedam.................	36 19	120 49	65.71
111......	Cape Henry Lighthouse (old)	36 56	76 1	52.72
116......	Wolftrap.................	37 24	76 15	51.02
351......	Harbor...................	33	118 34	72.60
354......	Snow Mountain E..........	39 23	122 45	81.50
355......	Marysville Butte.........	39·12	121 49	82.51
356......	Mt. Grant................	38 34	118 47	61.80
357......	Kent.....................	39 58	122 44	81.52
358......	Lyons....................	40 18	121 38	77.35
359......	Round....................	40 48	121 57	77.95
362......	Rust.....................	42 37	122 21	75.06
363......	Onion....................	42 41	123 14	85.05
364......	Scott....................	43 22	123 4	85.76
365......	Spencer..................	43 59	123 6	81.06
368......	Mary.....................	44 30	123 33	76.64
369......	Yam......................	45 4	123 9	76.15
370......	Barnes...................	45 32	122 45	63.31

TABLE I—*Continued*

DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
371......	Balch....................	45°32′	122°43′	63″.70
373......	Lam......................	46 8	122 28	68.56
374......	Bel......................	46 47	121 56	59.78
379......	Point Hudson.............	48 7	122 45	66.69
389......	Classet..................	48 23	124 40	52.32
390......	Beechy Head..............	48 20	123 39	56.69

located in the Atlantic Coast province (see below, p. 711), all are to be found within the intense seismic area of the Pacific coastal region, which was so recently, after the destructive California earthquake of 1906, the subject of special investigation. When now the stations showing notable anomaly are accurately plotted upon the special map of the seismic province prepared by the Earthquake Investigation Committee,[1] it at once appears that there is an apparent relationship between their distribution and that of the better-known recent faults of the province. The number of stations with corrected anomaly of deflection greater than 50″ is something more than half (58 per cent) of the total number of stations within the Pacific Coast province. In the map of Fig. 1 which shows the distribution of the abnormal stations (in dotted outlines the map of the Earthquake Investigation Committee) black circles of different diameters have been used to bring out roughly the magnitude of the corrected residuals, and it appears that those of higher order particularly are generally grouped near the known displacements of the district, some of which have been the seats of movement during recent earthquakes.[2]

Distribution of residuals in excess of 35″ of arc.—Had the minimum of abnormality of deflection been made 35″ of arc, instead of

[1] A. C. Lawson, G. K. Gilbert, H. F. Reid, J. C. Branner, A. O. Leuschner, George Davidson, Charles Burckhalter, and W. W. Campbell, *Atlas of Maps and Seismograms* accompanying the *Report of the State Earthquake Investigation Committee upon the California Earthquake of April 18, 1906* (Carnegie Institution of Washington, 1908), Map 1.

[2] The recent faults are not indicated on the area outside the dotted border. Few gravity data relatively are available for the area east of California, where many fault lines are shown.

50″, practically all of the remaining stations located within the California earthquake province would have been included, and a separate group would have been found within the Atlantic coastal

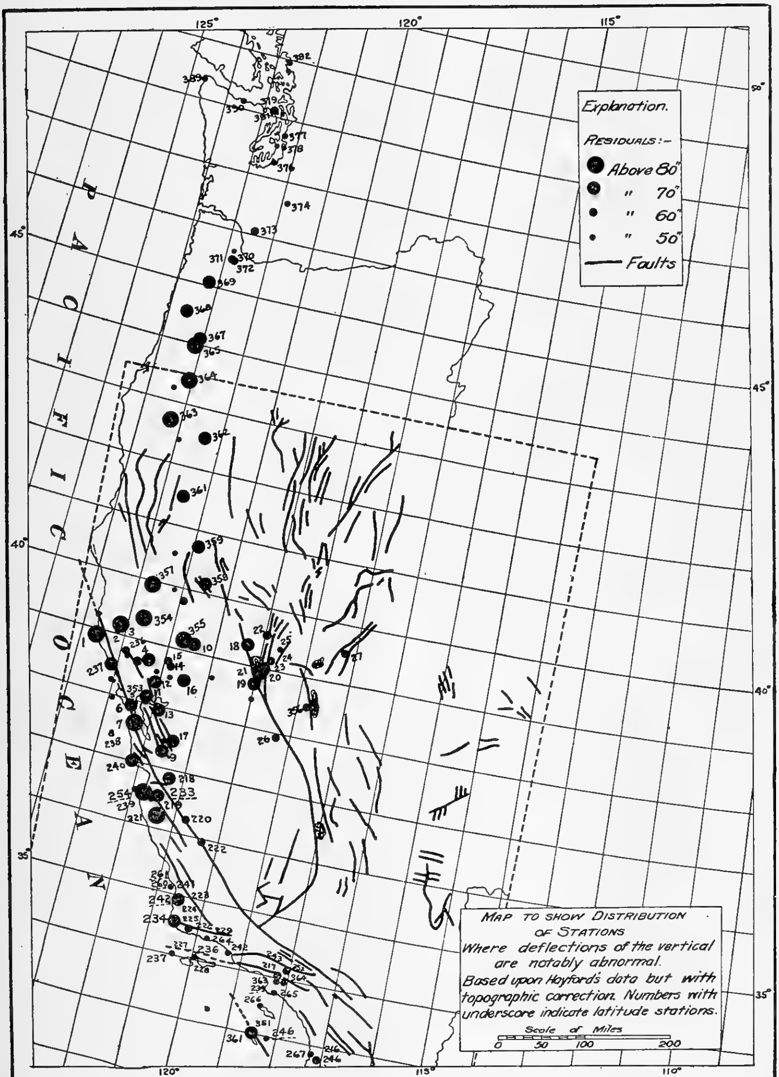

FIG. 1

province (Hayford's northeastern and southeastern groups of stations). This supplementary list prepared upon the basis of a minimum of abnormality of 35″ of arc, but without including the additional Pacific slope stations, is given in Table II, following.

The stations listed in this table have been plotted and appear in the map of Fig. 2 with some indication of the measure of abnormality, and upon the map of Fig. 3 are found the points of higher seismicity as determined by De Montessus upon the basis of recorded data,[1] which, however, of necessity give undue prominence to localities of early settlement or of later importance commercially.

General conclusion as to law of distribution of anomaly of gravity.—Hayford's own observations thus confirm the evidence derived from other regions that anomaly of deflection of the vertical and of gravity show large local defect or excess, and that these local anomalies are in some way connected with the distribution of seismicity and with zones of dislocation.[2] We believe therefore that the late Professor de Lapparent was correct when in 1903 he stated with much force before the French Academy:

> I believe, therefore, that for the present we may claim that the sea upon the one hand, and the continents upon the other, enter into the variations of gravity there only where a dislocation puts into contact two crustal compartments, one of which is depressed and one of which remains stationary or is fixed. . . . .
>
> One may add that even in countries where the surface does not reveal the dislocations, a means is found for diagnosing the deep and hidden faults. Finally, the relation of seismic regions to rapid variations in the anomaly of gravity shows that it would be eminently proper to carry out such studies in order to make known those provinces of our globe which have most to reckon with the danger from earthquakes [translation].[3]

May not the truth, as in so many other controverted questions, lie between the extreme viewpoints? It is possible to assume

[1] Count F. de Montessus de Ballore, "Les Etats Unis séismiques," *Archives des Sciences Physiques et Naturelles de Génève*, 4th period, V (1898), 201–16. See also William H. Hobbs, "On Some Principles of Seismic Geology," *Gerlands Beiträge zur Geophysik*, VIII (1907), Appendix, pp. 289–92, Pl. 2; also, *Earthquakes* (Appleton, 1907), pp. 112–16.

[2] While magnetic data are available for the territory of the United States (*United States Magnetic Tables and Magnetic Charts for 1905* [Washington, 1908]), their discussion by Bauer is still unpublished, and it would be premature to discuss them here.

[3] M. A. de Lapparent, *op. cit.*, pp. 830–31.

TABLE II

"Abnormal" Deflections of the Vertical—Hayford (Corrected for Topography) (Minimum, 35″ of Arc)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
136	Yard	39°58′	75°23′	37″.81
137	Mt. Rose	40 22	74 43	35.22
158	Howard	44 38	67 24	37.97
164	Calais	45 11	67 17	35.97
350	Folger	41 17	70 6	38.56
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
90	Charlottesville	38 2	78 31	43.20
92	Strasburg	38 59	78 22	38.42
99	Naval Observatory	38 55	77 4	37.40
100	Naval Observatory	38 54	77 3	38.28
101	C. and G.S. Observatory	38 53	77 1	35.61
108	Dover	39 9	75 31	38.69
110	Cape May	38 56	74 56	44.91
113	Roslyn	37 14	77 24	40.74
114	Staunton	38 9	79 4	39.74
118	Seaton	38 53	77	35.51
119	Statesville	35 47	80 54	36.38
157	Cambridge	42 23	71 8	41.42
158	Duxbury	42 3	70 40	42.19
172	Bangor	44 48	68 47	35.14
173	Calais	45 11	67 17	35.92
233	Provincetown	42 3	70 11	39.05
253	Kit	41 30	73 59	41.63
257	Mt. Weather	39 4	77 53	44.77
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
91	Clark	38 19	78	41.78
93	Long Mount	37 17	79 5	44.99
94	Bull Run	38 53	77 42	40.30
95	Maryland Heights	39 20	77 43	41.52
96	Sugarloaf	39 16	77 24	42.61
97	Causten	38 56	77 4	35.32
109	Cape Henlopen	38 47	75 5	46.63
111	Cape Henry	36 56	76 1	52.72
115	Knott Island, North End	36 34	75 55	47.68
116	Wolftrap	37 24	76 15	51.02
117	Tangier Island	37 48	75 59	42.32
120	Moore	36 24	80 17	37.72
122	King	35 12	81 19	35.29
142	Yard	39 58	75 23	42.26
143	Mt. Rose	40 22	74 43	46.12
144	Beacon Hill	40 22	74 14	42.50
147	Cambridge	42 23	71 8	38.24

TABLE II—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
DEFLECTIONS IN PRIME VERTICAL (ASIMUTH)—*Continued*				
149......	Spencer....................	41°41′	71°30′	45.″30
150......	Beaconpole.................	42	71 27	43.38
151......	Copecut....................	41 43	71 4	40.10
152......	Indian.....................	41 26	70 41	46.49
153......	Shootflying................	41 41	70 21	37.97
154......	Blue Hill..................	42 13	71 7	41.90
156......	Thompson...................	42 37	70 44	40.35
159......	Unkonoonuc.................	42 59	71 35	37.98
161......	Agamenticus................	43 13	70 42	41.42
235......	Davis......................	38 20	75 6	48.87
248......	Mt. Blue...................	44 44	70 31	37.15
254......	Gardiners Island...........	41 6	72 6	37.42
255......	Barnegat Inlet.............	39 46	74 6	40.78
258......	Cahas......................	37 7	80 1	38.07
338......	Chapel Hill................	40 24	74 4	44.23
383......	Sankaty Head...............	41 17	69 58	37.71
384......	High Point.................	41 19	74 40	40.99
385......	Womelsdorf.................	40 19	76 12	40.98

that a tendency to attain to isostatic adjustment exists within the earth's outer shell as a consequence of diastrophic action, and that at any given time large areas, such as the greater portion of the United States, are measurably compensated. In areas more recently disturbed and at a more rapid rate (western section of the United States or the Himalaya region), which still betray their lack of stability in earthquakes, no such state of isostatic compensation can be postulated. Such regions show a rigidity sufficient to support their excessive loads for long periods even if measured in geological units, and if they yield to some extent through eventual fatigue of the materials under strain, this effect lags far behind the degrading effects of surface erosion and transportation. Some suggestion of this idea appears to be found in the paper by Crosthwait.[1]

CRITICISM OF HECKER'S DETERMINATIONS OF GRAVITY OVER THE OPEN SEA

Helmert's claim that gravity is nearly constant over deep water of the ocean.—A line of evidence which has been held to support the conception of isostatic compensation, but for the oceanic areas

[1] *Op. cit.*, pp. 4–5.

only, is that supplied by Helmert and Hecker, who have applied the Mohn hypsometer-barometer to measurements of gravity over the open sea. Upon the basis of these studies, which were executed

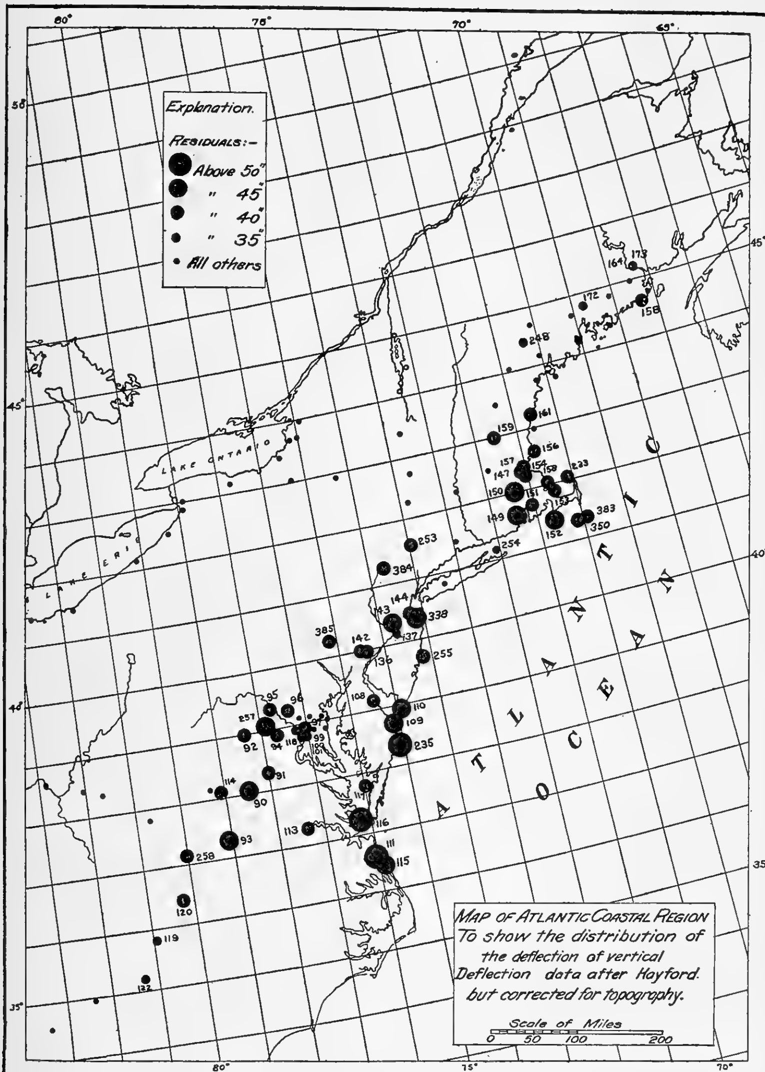

FIG. 2

by Hecker, Helmert has claimed that "the force of gravity above the deep water of the Atlantic Ocean between Lisbon and Bahia is nearly normal"—that is to say, the same as at the shore within

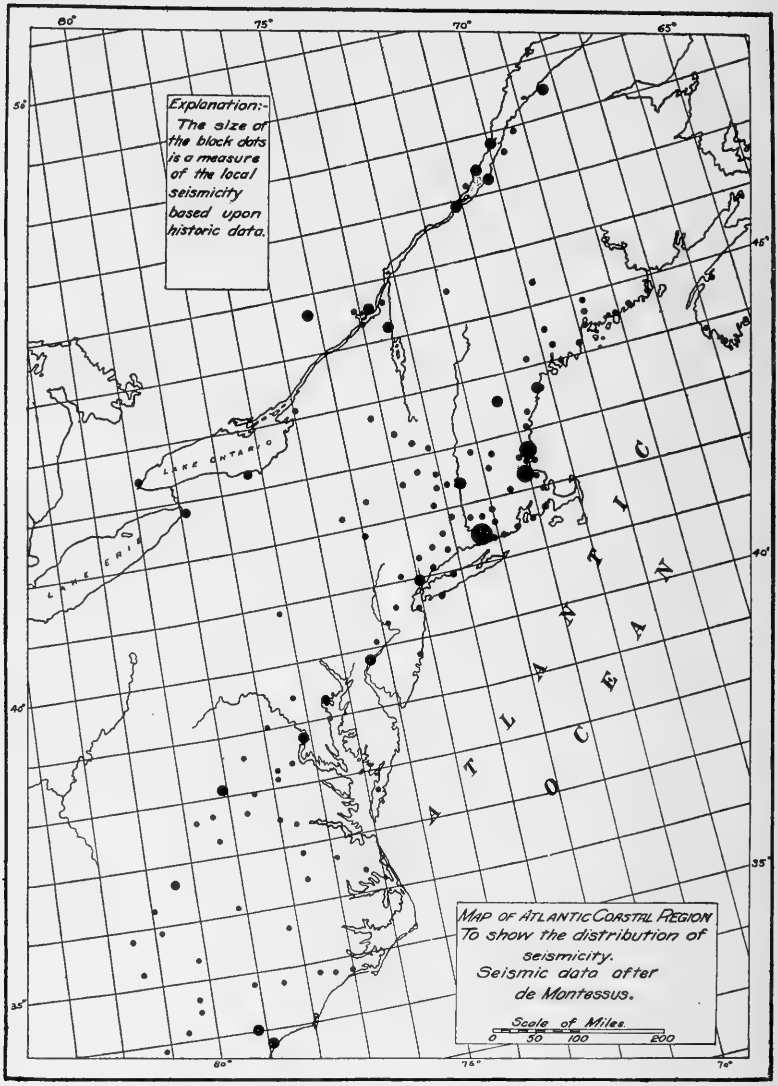

FIG. 3

the same latitude.[1] If this statement is well founded, it would be difficult to escape the conclusion that at least partial compensation exists for the oceanic areas. But from examination of the figures in Hecker's original monograph,[2] a different form of statement would seem better to express the facts. Up to the time of Hecker's Atlantic voyage geodesists, through basing their conclusions upon pendulum observations made upon a few oceanic islands, had held the belief that gravity is uniformly in excess over the oceans; and the force of Helmert's statement lay in the fact that it exploded this notion, which had received official sanction from an international geodetic congress. A better form of statement would appear to have been that Hecker's results did not in general reveal the high excess above normal values which had been expected. But values of Δg. which range from 146 units[3] of defect to 161 units of excess can hardly be called nearly constant unless errors of measurement be assumed to be excessive.

Hecker's grouping of his data objectionable in that it tends to efface significant local anomalies.—Hecker's paper is open to the objection that by a process of averaging the local significance of Δg. is made largely to disappear. Of this, two examples will suffice: the first, of measurements made over the shallow North Sea and British Channel with depths ranging from 60 to 160 meters only; and the second, a group of four measurements made between the Cape Verde Islands and the equatorial ridge over unknown but presumably large depths, which from a few not very distant soundings are probably generally in excess of 5,000 meters (Tables III and IV).

Hecker's revision of his data after the Black Sea cruise.—The figures as first published by Hecker were shown by Baron Eötvös to need correction for direction of motion of the vessel (west or east), and after having tested the magnitude of this correction in a special

[1] F. R. Helmert, "Dr. Heckers Bestimmung der Schwerkraft auf dem atlantischen Ozean," *Sitzungsber. d.k. preuss. Akad. d. Wiss. z. Berlin*, I (1902), 126–28.

[2] O. Hecker, "Bestimmung der Schwerkraft auf dem atlantischen Ozean, sowie in Rio de Janeiro, Lissabon und Madrid, *Veröffentlichung d. k. preuss. Geod. Inst.* (N.F.), No. 11 (Berlin, 1903), pp. 84–85, Pl. 6.

[3] Measured in thousandths of a centimeter of acceleration.

cruise over the Black Sea, Hecker has now so revised his figures that they are no longer recognizable, and many of the excessive values for Δg. for one reason or another have disappeared altogether.[1] This is true, for example, for the third entry in the list quoted in table III. Hecker's methods have been more sharply challenged by Bauer[2] upon the ground that his instruments were

TABLE III

NORTH SEA AND BRITISH CHANNEL

Lat.	Long.	Δg. in cm.	Hecker's Mean
51°25′N.	3°50′E.	+0.053	
51 25 N.	3 40 E.	+0.016 } (0.134)*	
49 58 N.	1 1 W.	−0.118 }	−0.015
49 50 N.	1 17 W.	−0.035	
49 45 N.	2 29 W.	0.000	
49 39 N.	2 45 W.	−0.067	

* Author's interpolation.

TABLE IV

BETWEEN CAPE VERDE ISLANDS AND EQUATORIAL RIDGE

Lat.	Long.	Δg. in cm.	Hecker's Mean
11°52′ N.	26°57′ W.	−0.065	
11 44 N.	36 59 W.	−0.146 } (0.189)*	−0.038
10 54 N.	27 21 W.	+0.043 }	
10 44 N.	27 55 W.	+0.017	

* Author's interpolation.

not sufficiently standardized and checked during the work, and because his methods were in other respects open to criticism. In his first paper Bauer has sought further to discredit Hecker's corrected figures upon the ground that the values for Δg. vary more widely from Hayford's than did those of the first series. This point of view is interesting as indicating that local anomalies in

[1] O. Hecker, "Bestimmung der Schwerkraft auf dem schwarzen Meere sowie neue Ausgleichung der Schwerkraftmessungen auf dem atlantischen, indischen und groszen Ozeane," *Veröffentl. d. Zentralbureaus d. Internationalen Erdmessung* (N.F.), No. 20 (Berlin, 1910), pp. 1–160, 4 pls. (especially pp. 151–60).

[2] L. A. Bauer, "On gravity determinations," etc., *Am. Jour. Sci.* (4), XXXI (1911), 1–18. See also Hecker's remarks on "Ocean Gravity Observations" (a reply to Hecker), *ibid.*, XXXIII (1912), 245–48.

gravity must be forced out of sight or be interpreted by specialists in the field of the exact sciences as evidence of inaccurate work.

Hecker's figures in general indicate large anomalies of gravity above submerged escarpments and near where seaquakes have been felt.—If it be assumed that the limit of error in Hecker's measurements is not too high, his data from the Atlantic (the earlier ones particularly) and from the Indian and Pacific oceans all show a maximum of anomaly above the steep slopes at the margins of the continental shelves, and in general above submerged escarpments. Examined with reference to recorded seaquakes the earlier data in particular are hardly less interesting. Above the escarpment off the mouth of the Tagus, where such excessive values were recorded, it is known that several ships received heavy shocks at the time of the Lisbon earthquake (Fig. 4). The measurement of 0.146 of defect in the British channel, where there is no visible evidence for defect of matter (this figure had nearly disappeared in the earlier table under the mean of 0.015, and had vanished completely from the later tables), is almost exactly above the spot at which a seaquake has been put on record by Rudolph[1]—the only recorded one upon his map within a radius of 500 miles. Other noteworthy correspondences between seismicity and abnormal gravity will be noticed upon comparing Hecker's figures with Rudolph's map.

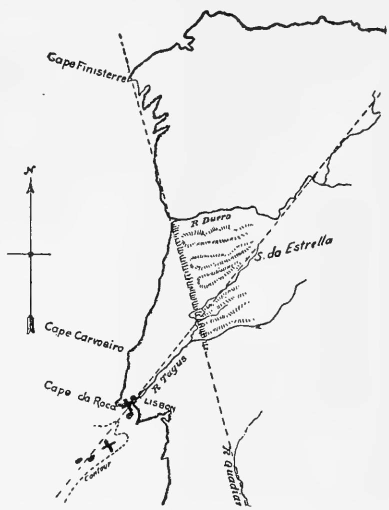

FIG. 4.—Sketch map of a portion of the Iberian Peninsula to indicate the great lineament of the Tagus, along which shocks were especially heavy at the time of the Lisbon earthquake of 1755. The positions of ships which felt the shock of the Lisbon earthquake are indicated, and also the two positions (crosses) where Hecker's measurements showed excessive values.

UNIVERSITY OF MICHIGAN
January, 1916

[1] E. Rudolph, "Über submarine Erdbeben und Eruptionen, mit Tafel iv–vii," *Gerlands Beiträge zur Geophysik*, I (1887), 133–365 (map at end).

A STAGE ATTACHMENT FOR THE METALLOGRAPHIC MICROSCOPE

ALBERT D. BROKAW
University of Chicago

A device to obviate the necessity of mounting specimens that have been polished on one side only has been found very convenient by the writer. It consists of a disk of brass with a hole about three-eighths of an inch in diameter at the center. The lower surface is plane and the upper side is turned to an inverted conical surface, shown in plan and elevation at *D* in Fig. 1. The disk is fitted into the stage aperture, where it may be held by a steep pitch screw, in which case the outer edge of the lower projection is milled. The post *P* is screwed into the stage from below, at one corner. A spring *S* is attached to a brass block, held in place by a set screw. This spring supports the specimen, which is placed with its polished surface against the lower side of the disk. The spring pressure is controlled by the position of the block. The upper side of the disk is cut away to allow the objective to come to its focal distance from the surface to be examined. The plane surface of the disk is perpendicular to the axis of the microscope; consequently the whole field is brought into focus at the same position, without the usual care necessary in mounting the specimen. The specimen may be moved around without loosening of the spring, except in the case of unusually irregular pieces.

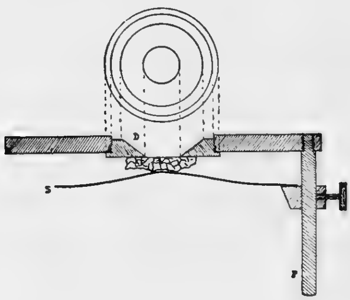

FIG. 1.—Plan and elevation of attachment.

FIG. 2.—Spring clip.

The size of the aperture depends upon the size of the specimen, but it must be large enough to permit the highest-power objective used to come to its focal distance. Where a specimen is large, a larger aperture has the advantage of exposing more of the surface to view, facilitating the finding of such features as are visible megascopically. Where the megascopic characters are of great importance, the disk may be replaced by a ring, with three converging arms attached within it. These arms have a profile like the cross section of the disk. The ring and arms must be ground to a true lower surface, and the arms must be polished to prevent scratching of soft specimens.

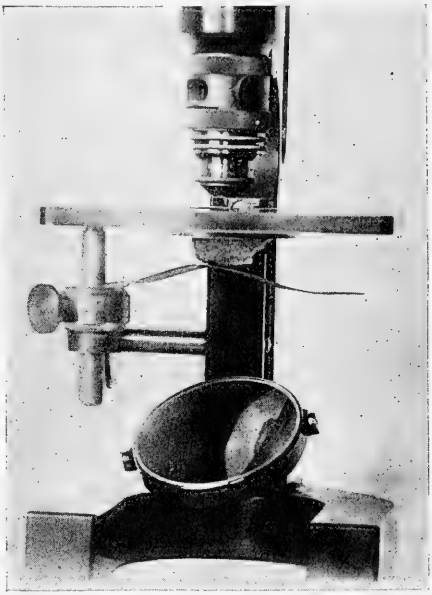

FIG. 3.—Photograph of microscope with attachment in place.

Instead of inserting the post as shown in Fig. 1, it has been found possible to use a spring clip of the form shown in Fig. 2, if the variation in the thickness of the specimens is not too great. The ends E and E' hook over the upper surface of the stage, and support the spring, which is made of thin spring brass, about one-half inch wide. If carefully fitted the disk may be forced into place, where it will stay without the necessity of threading. Using the second type of spring and the fitted disk makes the attachment very inexpensive and at the same time effective, especially if a number of springs of different curvature for different sizes of specimens are made.

It will be seen that, in addition to the fact that the necessity of mounting the specimen is eliminated, the position of the stage when in focus is the same without reference to the thickness of the specimen. This removes the necessity of stage focusing, and facilitates the work when a comparative study of two or more specimens is being made. Fig. 3 shows a microscope with the attachment as it is used.

Reviews

Geology Physical and Historical. By H. F. Cleland, Ph.D. New York: American Book Co., 1916. Pp. 718, figs. 588.

This new textbook enters the field of general geology, a field already fairly well covered by a number of excellent books. The value of this new attempt will depend upon new material, new methods of treatment, or fewer infelicities than the other books have. The book occupies in its scope a middle ground among the books on the subject, being more ambitious than some and more modest than others. It will be used properly as a textbook in first courses in general geology in colleges and universities, where the students are at least fairly well prepared and somewhat mature.

The book is about the proper length best to serve its purpose, is pleasingly written, beautifully illustrated, and well bound. The presswork is exceptionally good. The reviewer has read the book through and knows of but one typographic error. The book is printed on glossy paper, and yet it is portable and durable.

The author of the book seems to be more at home in Part II, "Historical Geology," than in Part I, dealing with physical geology. This greater familiarity with the last portion of his subject is reflected in better English, more careful treatment, more detail, and greater accuracy and definiteness in Part II than in Part I. The best part of the book is that dealing with life, although some will think that this phase of geology is overdone.

There are a few glaring omissions. The origin of dolomite is avoided on p. 249. There is a chapter on earthquakes, but no presentation of the more important aspects of diastrophism, except as the subject is scattered through the chapters on structural geology, metamorphism, and mountains and plateaus. This is a weakness which is felt throughout the book. Proterozoic glaciation in Ontario, the causes of Permian glaciation, the Pleistocene Driftless Area, are not mentioned. There is no classification of the plant and animal kingdoms, an omission which depreciates the value of the excellent paleontological material in Part II.

With the exception of a few errors, such as plural nouns with singular verbs or vice versa, indefinite antecedents of pronouns, a rather free use of "the former" and "the latter," the English is good. The author uses words denoting time where place or number is involved in a monotonously regular way. The book must contain over a thousand cases of such misused words.

The origin and derivation of technical terms introduced throughout the book is a feature of much value. This point is somewhat discounted, however, by the use of some of these terms before they have been explained. For instance, the terms "travertine," "strike," "eskers," "basal conglomerate," "feldspars," "scoriaceous," "stoping," "schistose," "systems," "fauna," "phylum," are all introduced in advance of their explanation, and some of them are used repeatedly without explanation.

The scientific and pedagogical character of the book is marred by a certain odd looseness and indefiniteness of statement, which must militate against clear thinking and expression on the part of the student. On p. 298 lava is said to be "molten" rock; on p. 300 it is made clear that lava is rock dissolved rather than melted; and on p. 329 it is stated that igneous rocks "have consolidated from a state of fusion." The first part of the last sentence on p. 253 is true only when the surface of the ground is flat or nearly so. In Part II the terms "system," "group," "period," "era," etc., are defined, but these terms are used in various ways on pp. 383, 389, 392, 401, 384, 477, and 574. On pp. 89 to 92 various points are numbered for the sake of definiteness, but points 4 and 5 are quite similar to point 1; in the same way on p. 128, 5 and 1 are practically identical. On pp. 199 and 200 there are three statements, each of which appears to be contradictory to the other two. Some of the geography is ambiguous, especially that which refers to the western portions of the United States. The author of the book does not seem to realize the magnitude and importance of the area west of the Mississippi River. An illustration is found on p. 403, where the Cambrian rocks are carefully located in the East and then are said to be exposed "in portions of the West." On p. 658 the exact meaning of the figures at the close of the second paragraph is not clear. Illustrations of this looseness and indefiniteness are found on at least thirty-three pages of the book.

Although most of the topics are treated adequately, an effort to obtain brevity has led to incomplete treatment of antecedent streams, p. 102, of tides, p. 202, of the economic importance of metamorphism, p. 351, of the Planetesimal Hypothesis, pp. 386 and 387, of the physical problems of the Ordovician, pp. 418 to 434, of the Red Beds, p. 511, of the economic products of the Miocene, pp. 579 to 580, of the glacial and interglacial stages of the Pleistocene, pp. 648 to 651, and of other equally important topics. On the other hand, many topics are treated with unnecessary detail. The relatively unimportant subjects of geysers, cirques, icebergs, coral reefs, and earthquakes are given too much space. Throughout Part II life is given a more prominent place than physical history. The physical history of the Devonian occupies 4 pages, the life-history, 13 pages; Mesozoic stratigraphy has 15 pages; life, 48 pages; Tertiary history covers 18 pages, Tertiary life, 52 pages.

Perhaps the greatest fault of the book has to do with order. The author has seen fit to exclude separate chapters on lakes, sedimentary rocks, and diastrophism, and to scatter these important subjects through other chapters. The result is disorganization. In Part II the various life-forms are discussed as life-forms rather than as earth inhabitants at stated times in geologic history, resulting in better biologic than geologic treatment. Stream erosion and stream deposition are badly mixed (monadnocks, for instance, on p. 111 belong on p. 105), lacustrine deposits, even peat, the origin of rock salt, extinct lakes, are all discussed under the work of streams; ice in lakes, cuestas, and sedimentary rocks appear nowhere save in the chapter on the ocean; chalk is found under deep sea deposits; hinge faults are separated from other types of fault and included under earthquakes; igneous rocks are classified before minerals are referred to; Pennsylvanian coal is scattered; Cretaceous sequoias are treated in the Tertiary; on pp. 545 and 646, "1. Other Continents" and "2. North America" should be in reverse order.

On the whole, the book shows an excellent attitude toward unsettled and controversial questions. In most cases both sides are fairly stated and the reader is allowed to take either view. The author is orthodox in most of his views. Geologists, however, will tend to disagree with some of his statements, such as the origin of geodes, p. 79, the history of the Tennessee River, p. 117, and the peneplaination of the larger part of North America during the Cretaceous period, pp. 518 to 520. It is doubtful if marble weathers to calcareous clay (p. 350). On pp. 417, 437, 451, and 590 there is intimation and definite statement that climatic zones did not exist until recent stages in the history of the earth; this is easy to write but not so easy to explain. There is grave doubt whether Devonian vulcanism in New England and Nova Scotia had anything to do with Permian diastrophism in the Appalachian Mountains (p. 455). The author of the book will hardly convince the majority of geologists of the unimportance of diastrophism and the relative importance of life-changes in stratigraphic classification and correlation, and especially of the truth of his statement on p. 582 that "the separation of the history of the earth into chapters should be based, not upon the unconformities, however great, but upon the changes which life has experienced." There may be disagreement with the theory of isostacy as explained on pp. 365 to 368 and applied on pp. 132, 472, 478, and 651.

Little but praise should be expressed for the illustrations in the book, for almost all of them are clear and well chosen. Most of them are new, and this feature will be appreciated. There are, however, a few mistakes connected with the illustrations. Fig. 103 pictures as a peneplain a surface which is now known not to be a peneplain. Figs. 142 and 145 seem to be misplaced; they do not illustrate the work of mountain glaciers. Figs. 396 B and 414 B are both labeled "Receptaculites ohioensis"; fig. 414 B illustrates R. oweni. The illustrations of various principles described in words, which occur throughout the book, are numerous, well chosen, and altogether laudatory.

There is no general plan for presentation of references in the book. Footnotes giving definite references on specific points are practically wanting. A few general references are given at the ends of chapters in Part I and at the ends of smaller divisions within chapters in Part II. In some cases previously published material is quoted, with or without the name of the author, but without specific reference. Much material is taken from classic geological literature without reference; for instance, material on the geomorphology of the Appalachian Mountains, Murray's classification of marine sediments, metamorphism, the bar theory for salt formation, and the Lafayette formation. The book would be of much greater value as a work of reference if more care had been taken with sources.

As in the case of any such work, Professor Cleland's book has its good points and its points of weakness, in which the good points outnumber and outweigh those of the opposite character.

A. C. T.

Mine Waters. By A. C. Lane. Ann. Rept., Board Geol. and Biol. Surv. (1911), pp. 774–779.

The study of mine waters in the copper district of northern Michigan is of practical interest, first, owing to the effect on boilers of the admixture of the lower strongly saline waters with those of upper levels; secondly, because it seems clear that the character of the water has had a considerable importance in the deposition of the copper. Observation covering most of the eastern portion of the peninsula indicates that beneath (1) the layer of relatively free circulating soft surface waters there is (2) an important horizon of sodium chloride waters, beneath which (3) the water is nearly saturated, in many places, with calcium chloride. It is suggested that the lowest waters are connate, indicating therefore the composition of sea water at the time of deposition of the rocks. The presence of copper chlorides in the lower water, the mode of occurrence of the copper deposits, the chemical character of the alterations of the rock, and the low temperature gradient of the region are all thought to be consistent with the theory that the copper has been deposited in zones of relatively low oxidation by the waters. The ultimate source of the copper must be the formation itself, which as a whole carries about 0.02 per cent copper.

R. C. M.

Le Revermont, étude sur une région karstique du Jura méridional. By GEORGES CHABOT. Ann. d. Géog., XXII (1913), pp. 339–415. Maps 2.

The Revermont is a fragment of the southern Jura Mountains more or less separated from the main part of the range by the valley of the river Ain. While physiographically and structurally an integral part of the Juras, by reason of its position bordering the fertile plains of La Bresse, it is geographically a dependent of the latter. Coralline and foraminiferal limestone of Sequanien to Kimeridgien (Jurassic) age forms the floor of the Revermont valleys, most of which are in the synclines of the highly folded strata. Local conditions make the work of ground-water very important. Large inclosed depressions or sinks into which surface waters drain are characteristic, and comparatively recently the Suran River has dried up completely in the lower part of its course, the water disappearing beneath the surface. The soil is poor and cultivation difficult. Consequently for a number of years there has been a depopulation of the district.

R. C. M.

A New Gypsum Deposit in Iowa. By G. F. KAY, U.S. Geol. Surv., Bull. 580, pp. 59–64, Fig. 11.

The discovery of a deposit of gypsum in the Mississippian rocks of the central southern portion of Iowa is of scientific interest. The gypsum, with some anhydrite, occurs at a depth of more than 500 feet. Whether it will prove to be of economic importance is undetermined.

R. C. M.

The Geology of the County of Jervois, and of Portions of the Counties of Buxton and York, with Special Reference to Underground Water Supplies. By R. Lockhart Jack. Geol. Surv. South Australia, Bull. No. 3, 1914. Pp. 47, pl. 1, figs. 6, maps 3.

A Review of Mining Operations in the State of South Australia during the Half-Year Ended December 31st, 1913. No. 19. By Lionel C. E. Gee. 1914. Pp. 66, pls. 6, figs. 3.

The Geology of the Aroha Subdivision, Hauraki, Auckland. By J. Henderson, assisted by J. A. Bartrum. Geol. Surv. New Zealand, Bull. No. 16 (New Series), 1913. Pp. 127, pls. 10, figs. 7, maps and sections 10.

Hauraki is on the northwestern coast of North Island. The report is noteworthy for the description and full analyses of thermal springs of the region. Economically Hauraki is a rich gold- and silver-producing district.

Temiskaming and Northern Ontario Railway Commission. Toronto, 1914. The Mining Industry in That Part of Northern Ontario Served by the Temiskaming and Northern Ontario Railway, Ontario Government Railway. By Arthur A. Cole. Pp. 74, pls. 21.

The Geology of Steeprock Lake, Ontario. By Andrew C. Lawson.

Notes on Fossils from Limestone of Steeprock Lake, Ontario. By Charles D. Walcott. Geol. Surv. Canada, Memoir No. 28, 1912. Pp. 23, pls. 2.

Lawson reports the rock to consist of basement complex of granite and gneisses, unconformably overlain by the Steeprock series. This series consists of interbedded traps and volcanic ash, limestone, and conglomerate. Unconformable upon the Keewatin, and in different structural relations from those of the Steeprock series, lie the Seine series of quartzites and conglomerate. These are cut by granite gneiss. Before the deposition of the Seine series, the Steeprock series had been folded down into the older Archean rocks. The Steeprock limestones, 500–700 feet thick, are very fossiliferous. These fossil-bearing strata are placed well down in the Archean, as in the following tabulation:

Algonkian..........	10. Keweenawan.
	Erosion interval.
	9. Animikie.
	EPARCHEAN INTERVAL
Archean............	8. Granite gneiss, intrusive in the Seine series.
	7. Seine series.
	6. Acute deformation and erosion interval.
	5. *Steeprock series. Fossil-bearing.*
	4. Erosion interval.
	3. Granite gneiss, intrusive in the Keewatin.
	2. Keewatin.
	1. Coutchiching.

Walcott first identified the fossils as Archaeocyathinae, which are found elsewhere in the Lower Cambrian formations. Later, on the strength of microscopic examination, he called them a new genus, *Atikokania.* He found them apparently related to both the Archaeocyathinae and to the sponge *Syringocnema.* They are quite unlike any of the Beltina fauna. If their stratigraphic position were not surely determined, Walcott would consider them to be of Lower Cambrian age.

T. T. Q.

The Huronian Formations of Temiskaming Region, Canada. By W. H. Collins. Geol. Surv. Canada, Museum Bull. No. 8, 1914. Pp. 33, pl. 1, figs. 2.

The formations in the "Original Huronian" district have been correlated with the well-known sections at Sudbury and Cobalt. Six type localities were successively studied in the region, and the formations were traced across the intervening spaces. It was certified that the original Huronian sedimentaries consist of two distinct series, separated from one another by a large erosion interval, and separated from the pre-Huronian rocks by a great interval of diastrophism, granite intrusion, and erosional peneplaination. It has been determined that the Cobalt series of Cobalt, the Ramsey Lake conglomerate of Sudbury, and the slate conglomerate of the upper of the two series in the original Huronian are equivalents.

Instead of Upper and Lower Huronian, Collins calls the upper of these series Cobalt and the lower one the Bruce series. Elsewhere, the name Huronian has been applied to quite different series; by using these local names for the Temiskaming region one avoids confusion.

The Bruce series consists of quartzites, conglomerates, limestones, and greywackes. The Cobalt series contains quartzites, conglomerates, both basal and slaty, and cherty limestone. As at Cobalt, so at Bruce the Cobalt slate conglomerate carries striated bowlders.

T. T. Q.

Über die Parallelstruktur des Gletschereises. By AXEL HAMBERG. 9e Cong. Internat. d. Géog., 1908, Compte rendu II. Pp. 7, pls. 4.

In general two sorts of parallel structure are to be observed in glaciers, that due to the original snow bedding in the collecting area, and that of secondary origin which is vertical and parallel to the longitudinal axis of the glacier. By some it has been thought that the vertical parallel structure was only the original horizontal snow bedding turned up on edge through pressure. It is desirable to know whether "regenerated" glaciers show the vertical parallel structure and how it is formed. The author after a study of a number of glaciers in Sweden and Spitzbergen concludes that the structure in question has relation to the movement of the ice. When there is a downward slope in an ice sheet, the very great downward pressure of the ice from gravity has a forward component which tends to cause movement along the valley. Friction of the sides and bottom of the valley retards the motion of ice layers next to them, so that the ice is broken into parallel bands which move forward at differential rates, the upper central bands moving the more rapidly. The planes of differential motion are influenced by every irregularity of the containing valley and may be trough-shaped.

R. C. M.

The Grain of Igneous Rocks. By A. C. LANE. Ann. Rept., Board Geol. and Biol. Surv., Michigan (1911), pp. 145–71. Figs. 5.

The grain of an igneous rock depends on a number of factors, among which may be noted the chemical and mineralogical composition of the rock, its retention of solvent gases and mineralizers, pressure, and rate of cooling. The last named is one of the most important, and it is observed that there is a direct ratio between the size of the grain and distance from the cooling surface, the effect being most advantageously studied in the mineral grains which are last to crystallize. With due consideration of certain variable factors, such as the power of crystallization of the magma, diffusivity of heat, production and absorption of latent heat, and undercooling, it is possible to make mathematical determination of the size of grain that should form at a given distance from the cooling surface. Gradual change in the temperature of the margin is one of the factors most difficult to estimate. It seems obvious that the margins of certain even-grained dikes were near the temperature of the magma at the time of crystallization.

R. C. M.

Temperature of the Copper Mines. By A. C. LANE. Ann. Rept., Board Geol. and Biol. Surv., Michigan (1911), pp. 757–73, Fig. 1.

The temperature at various depths in the copper mines is of practical interest because of its importance in determining to what extent men may work with efficiency, and of scientific interest because of its relation to the circulation of mine waters and possibly to the formation of native copper, as indicated by the result of recent experimentation. The mean annual surface temperature in the copper region is about 39° F., that in the upper levels of the mine at the depth of "no variation" between 43° and 44° F. Careful measurements of the rate of increase of temperature downward have been recently made which give an average of 1° F. for 105 feet descent, or in certain cases as low as 1° in 111 feet. This rate is below the normal and may be due to a number of causes. The more important factors are thought to be (1) endothermal reactions connected with the deposition of copper, (2) the high diffusivity of the strata, permitting the free escape of heat, (3) downward absorption of water carrying the cooler surface temperatures, and (4) relative exhaustion of the internal supply of heat by the Keweenawan and earlier eruptions.

R. C. M.

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THE RÔLE OF INORGANIC AGENCIES IN THE DEPOSITION OF CALCIUM CARBONATE

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Organic agencies are doubtless the predominant occasion of the deposition of calcium carbonate, yet certain inorganic factors may not safely be left out of account. The mode of action of the former, which is in part a biological question, we shall not enter into, but we shall limit ourselves to a discussion of the effects producible by variation of certain inorganic factors which affect directly the solubility of calcium carbonate. The question of the concentration of calcium relative to the limiting saturation concentration of calcium carbonate under the particular conditions—in other words, the relative degree of saturation with respect to calcium carbonate—has not received adequate consideration; this is largely the consequence of faulty data and of contradictory and erroneous statements regarding the solubility of calcium carbonate under various conditions. It is our purpose to direct attention to the quantitative effect, as deduced from laboratory study, producible by variation of those factors which, by affecting directly the degree of solubility of calcium carbonate, induce its precipitation from a solution saturated with it; and to emphasize the fact that many of the points now ambiguous may be settled by means of systematic and accurate investigation of a certain group of properties of sea-water, properties which, moreover, are of high importance in connection with certain biological problems. The mode of treatment is similar to that employed by Stieglitz,[1] who, at the instance of Chamberlin, carried out series of calculations to ascertain the proportion of $CaCO_3$ which one might expect to find in gypsum that had been deposited from solutions saturated with respect to both $CaSO_4$ and $CaCO_3$ at different partial pressures of CO_2 in the atmosphere in contact with the solution. The principles, therefore, are not new, though the point of view differs somewhat; and we now have the advantage of more extensive data than were available in 1907.

The data bearing on the solubility of pure calcite have been collated and discussed at length in two recent papers,[2] to which the reader desirous of fuller information on the chemical side is referred. As it would lead too far to discuss here all details of the solubility-product constant and of its mode of calculation, we shall give only the established conclusions which are pertinent to the present discussion, premising that a symbol inclosed within brackets represents the concentration (expressed in moles per liter) of that particular ionic or molecular species.

1. In a solution at a fixed temperature saturated with pure calcite, the solubility-product—i.e. $[Ca^{++}]\,[CO_3^{=}]$, the product of the respective concentrations of calcium-ion and carbonate-ion—is a constant, independent of the proportion of free CO_2 in the solution and of the presence of other salts. This characteristic solubility-product constant is to be carefully distinguished from the solubility which, as ordinarily measured, is the concentration of *total* calcium in a solution in equilibrium with solid calcite; and this calcium is associated with bicarbonate and hydroxide (and with any other anion present, e.g., chloride or sulphate) as well as with carbonate—indeed, under ordinary atmospheric conditions but a small fraction of the total

[1] J. Stieglitz, "The Relations of Equilibrium between the Carbon Dioxide of the Atmosphere and the Calcium Sulphate, Calcium Carbonate, and Calcium Bicarbonate in Water Solutions in Contact with It," in "The Tidal and Other Problems," by T. C. Chamberlin *et al.*, *Carnegie Inst. Publ. No. 107* (1909).

[2] J. Johnston, *Jour. Am. Chem. Soc.*, XXXVII (1915), 2001, hereinafter designated for convenience as *op. cit.;* Johnston and Williamson, *ibid.*, XXXVIII (1916), 975.

calcium is ever associated with carbonate. The fact of the constancy of this solubility-product in presence of solid calcite[1] enables us to calculate, with all the accuracy required for the purposes of this paper, the solubility of calcite under any specified conditions, e.g., in presence of calcium-ion or carbonate-ion from whatever source derived, provided only that we can ascertain what these ionic concentrations actually are.

2. The concentration of H_2CO_3 ("free" CO_2)in solution is regulated by the partial pressure (P) or proportion of CO_2 in the layer of atmosphere in contact with the solution, and conversely; and, for a given value of P, it diminishes with rising temperature, since the absorption coefficient (solubility) of CO_2 diminishes.

3. At a given temperature the total solubility as usually measured —i.e., the total concentration of calcium in the solution—varies with the concentration of H_2CO_3 (hence with P), owing to the fact that the latter determines the proportion of carbonate-ion $CO_3^=$, hydrocarbonate-ion HCO_3^-, and hydroxide-ion OH^- in accordance with definite mathematical expressions; and since the product $[Ca^{++}]\,[CO_3^=]$ remains constant $[Ca^{++}]$ must vary inversely as $[CO_3^=]$. The presence of other salts also affects this total solubility; so long as pure calcite is the stable solid phase in equilibrium with the solution, the magnitude of this effect is readily calculable, since the several concentrations always adjust themselves until the solubility-product $[Ca^{++}]\,[CO_3^=]$ attains its characteristic value.

4. The solubility-product constant of calcite diminishes with rising temperature; it is not affected to an appreciable extent by change of *hydrostatic* pressure.

The mathematical expressions are given below:

$$[H_2CO_3]=cP$$
$$[Ca^{++}]\,[CO_3^=]=K_C \text{ (in presence of solid calcite)}$$
$$[HCO_3^-]^2/[CO_3^=]=l[H_2CO_3] \quad =lcP$$
$$[OH^-]^2/[CO_3^=]=m/[H_2CO_3]=m/cP$$

where c, K_C, l, and m are constants at any given temperature.[2] We may note, moreover, that the free CO_2 and the total CO_2 (i.e.,

[1] Similar remarks apply, *mutatis mutandis*, to impure calcite or to aragonite; to this point we revert later.

[2] For their values and significance, see Johnston, *op. cit.*, p. 2011.

$[H_2CO_3]+[CO_3^{=}]+[HCO_3^{-}]$) determine $[OH^-]$, the degree of alkalinity (or acidity) of the solution; and that no change can be made in any one of these quantities without affecting each of the others.

Accordingly the solubility of calcite is significant only if the concentration of free CO_2 is controlled and measured, for changes in the latter, such as may easily occur, exert a large influence on the amount dissolved.[1] This is evident from Table I, which gives the solubility

TABLE I

SOLUBILITY OF CALCITE AT 16° FOR VARIOUS VALUES OF *P*

CO_2 in the Atmosphere Expressed		Free CO_2 or H_2CO_3 in Solution, Parts per Million	Solubility of Calcite, Parts $CaCO_3$ per Million
As Partial Pressure *P*	As Parts per 10,000 (by Volume)		
0.0001	1.0	0.18	44
.0002	2.0	.36	55
.00025	2.5	.45	59
.0003	3.0	.55	63
.00035	3.5	.64	66
.0004	4.0	.73	69
0.0005	5.0	0.90	75

at 16° for various values of *P* not far removed from the proportion normally present in the atmosphere (about 3 parts per 10,000). Calculation shows that except for very small partial pressures of CO_2 the calcium in solution is associated almost entirely with bicarbonate—thus even when *P* is only 0.0005, the proportion as carbonate is only about 2 per cent, whereas when *P* is 1.0, the proportion is less than 1 part in 30,000; nevertheless, carbonate is still the solid phase which separates out, an excellent example of the fact that it is the solubility relations and not the "affinity" relations in solution that determine which of the possible stable solid phases shall appear.

[1] Neglect of this factor or, in general, a failure to secure equilibrium conditions is responsible for erroneous statements in the literature. For instance, the solubility as given by Treadwell and Reuter (*Z. anorg. Chem.*, XVII [1898], 170) is not a real solubility at all; acceptance of their figure (238 parts per million) has led several writers astray. Cf. *op. cit.*, p. 2009. Thus on this basis J. C. Jones (*Science*, XX [1914], 829) concluded that the waters of the Lake Lahontan basin are only about one-twentieth saturated with $CaCO_3$.

The change of solubility with temperature, the proportion of CO_2 being constant, is evident from Table II, which contains values interpolated from the curve expressing the observations by Wells,[1] as well as the molar absorption-coefficient (c) of CO_2 and the calculated value (K'_C) at each temperature. There is a slight error involved in identifying K'_C with the solubility-product constant $[Ca^{++}][CO_3^{=}]$ except at temperatures close to 18°, because in calculating K'_C we have—for lack of better knowledge—assumed that the ratio (nr) of the first to the second ionization-constant of H_2CO_3 is independent of the temperature; nevertheless, since these values of K'_C were obtained from actual measurements of solubility, they enable one to calculate[2] for any temperature up to 30° the solubility of calcite under any conditions of CO_2 pressure or salt-concentration.[3]

TABLE II

THE SOLUBILITY OF CALCITE UNDER ATMOSPHERIC CONDITIONS (P=0.00032), AND THE SOLUBILITY-PRODUCT CONSTANT AT SEVERAL TEMPERATURES

Temperature t	Solubility of Calcite Parts $CaCO_3$ per Million	Molar Absorption Coefficient of CO_2 at t c	Solubility-Product Constant $K'_C \times 10^8$
0	81	0.0765	1.22
5	75	.0637	1.14
10	70	.0535	1.06
15	65	.0455	0.99
20	60	.0392	0.93
25	56	.0338	0.87
30	52	0.0297	0.81

From the foregoing it follows that in order to decide definitely if a natural water is saturated with respect to calcite one must know: (a) the concentration of free CO_2 in the water, (b) the temperature, (c) the concentrations of the other constituents present. Of these the third is the only one which has in general been satisfactorily ascertained, but it is only of subsidiary importance; experimental data on the two important factors are commonly either lacking or

[1] R. C. Wells, *Jour. Wash. Acad. Sci.*, V (1915), 617.

[2] For the mode of calculation see Johnston, *op. cit.*, p. 2011.

[3] This holds only so long as *calcite* is the stable phase. If the salt-concentration is such that some other carbonate (e.g., a double carbonate) is the stable phase, the appropriate constant must be employed in place of that characteristic of calcite.

untrustworthy.[1] On the other hand, the concentration of free CO_2 in any water, at a given temperature, can be calculated by means of the known absorption coefficient of CO_2, if the proportion of CO_2 in the atmosphere with which it has been in contact is known;[2] and as at the present time this proportion is usually close to 3 parts in 10,000 the corresponding solubility of calcite in natural waters should be close to the values given in Table II. Consideration of the published analyses[3] from this standpoint leads to the conclusion that the surface layers of the warmer portions of the sea (in so far as they have been investigated), as well as many river waters,[4] are substantially saturated with calcite. Murray,[5] in adverting to this question, states the opinion that "the ocean as a whole remains just about saturated for calcium carbonate"; but this statement is without doubt too sweeping, except in the sense that the concentration of $CaCO_3$ throughout the ocean is probably as great as it is in the warm surface layers. But there is also more direct evidence. Thoulet[6]

[1] The titration methods which have usually been employed for the determination of free CO_2—and to some extent of combined CO_2—are altogether untrustworthy, since the results depend upon the amount of indicator added and upon other factors which have not been adequately controlled. This question is discussed at length in another paper (J. Johnston, *Jour. Am. Chem. Soc.*, XXXVIII [1916], 947). Cf. also Morgulis and Fuller, *Jour. Biol. Chem.* XXIV (1916), 31.

[2] With regard to the solubility of CO_2 in a sea-water see C. J. J. Fox, *Trans. Faraday Soc.*, V (1909), 68.

[3] See F. W. Clarke, *Data of Geochemistry;* but especially a paper by E. Dubois, "The Amount of the Circulation of $CaCO_3$ and the Age of the Earth." (*Proc. Acad. Wetenschappen Amsterdam* [1901], pp. 43–62). Cohen and Raken (*ibid.* [1901], p. 63) have determined directly the solubility of $CaCO_3$ in an artifical sea-water at 15° and found about 55 parts per million; but their method of experiment is not unexceptionable and would tend to yield low results; they also conclude that this sea-water is saturated with $CaCO_3$. Wells also (*Jour. Wash. Acad. Sci.*, V [1915], 621) points out that the amount of carbonate carried by the Mississippi River diminishes steadily as it flows southward, i.e., in the direction of rising temperature.

[4] Indeed, the amount carried by many rivers is much in excess of the true solubility, indicating that some of it is in suspension. Where such a river reaches the sea, the salts cause the flocculation of this and any other suspended material, and in this way induce the formation of deposits there.

[5] Murray and Hiort, *The Depths of the Ocean* (1912), p. 180.

[6] J. Thoulet, "Etude bathylithologique des côtes du Golfe de Lyons," *Annales de l'Institut Océanographique*, IV, fasc. VII (1912), pp. 32–35.

studied silt grains taken from various parts of the Gulf of Lyons, and observed upon them films of calcium carbonate which had been precipitated during the process of sedimentation; this shows, therefore, that the water of the Gulf of Lyons is substantially saturated with $CaCO_3$. Recent experiments of A. G. Mayer[1] show that the sea-water about the coast of Florida is likewise substantially saturated, for shells exposed to it for a year lost no significant weight. Moreover, the investigations of T. W. Vaughan[2] on coral reefs "show that submarine solution is not effective there [about Florida] as all the bays, sounds, and lagoons are being filled with sediment," a conclusion which accords "with the conclusions reached by numerous investigators in the Pacific, which are that the more or less continuous walls inclosing lagoons have been formed by constructional geologic processes and that lagoon channels and atoll lagoons are not due to submarine solution."

The evidence just presented leads us, therefore, to the opinion that the surface layers of the ocean, except in the polar regions and within currents of cold water—in other words, the warmer portions of the ocean water—are substantially saturated with $CaCO_3$. We wish to point out specifically, however, that this belief cannot be regarded as established (or indeed disproved) until trustworthy determinations of the several quantities concerned have been made; indeed, to emphasize the necessity of such investigations is the prime purpose of this paper. But in this connection it may be remarked that a *permanent* deposit of limestone can hardly result unless (1) the *final* solution locally in contact with it is saturated, or (2) the precipitated carbonate is protected from the water by an organic tissue or otherwise, or (3) the process of deposition is rapid, in water circulating very slowly or not at all, under which conditions re-solution by diffusion is very slow.

In this paper, which is dealing primarily with the chemical arguments, it would be out of place to take up the geologic lines of evidence which indicate that the ocean as a whole is not saturated with $CaCO_3$, for this point is not at issue; but we may fitly advert to the

[1] A. G. Mayer, *Proc. Nat. Acad.*, II (1916), 28.

[2] T. W. Vaughan, *Am. Jour. Sci.*, XLI (1916), 133. See also his earlier papers, especially in the *Year Books* of the Carnegie Institution of Washington.

chemical arguments which have been adduced in favor of this position. Thus Tolman writes:[1]

> As direct evidence that the ocean is not saturated with calcium acid carbonate, we find (1) of the many hundred bottles of the Challenger's samples of sea-water, from all depths and collected at all temperatures, kept several years, only one or two showed deposit of lime.[2] (2) Sea-shells from the bottom of the Pacific show corrosion and re-solution.[3] The Pteropod shells are not found below fifteen hundred fathoms, and two thousand eight hundred fathoms is the limit for the globigerina ooze.[4] (3) Thoulet found by actual experiment that sea-water will dissolve calcium carbonate from shells, corals, etc.[5] (4) Usiglio, studying the evaporation of the Mediterranean water at Cette, found that no precipitate was formed until the specific gravity of the sea-water increased from 1.02, the specific gravity of the unevaporated water, to 1.0503, when the first precipitation begins, composed largely of calcium carbonate with ferric oxide.[6]

Let us now consider these arguments severally. (1) That samples of surface water did not deposit $CaCO_3$ on standing is not good evidence one way or the other unless conditions were carefully controlled, for change of temperature or of concentration of CO_2 would influence the result. (2) This shows, of course, that the lower (and colder) layers are not saturated; to this point we revert later. (3) Reference to Thoulet's paper shows that his work proves nothing as to the point in question, for neither the temperature nor the partial pressure of CO_2 was controlled. Indeed, he writes: "In the case of marble . . . . and of coral, the loss [of weight] in sea-water was *negative*. This result arises from the fact that small algae appeared . . . . the weight of which confuses the result." (4) This observation also is no proof, in view of the well-known fact that solutions of calcium carbonate exhibit a great tendency to supersaturation when no solid $CaCO_3$ is already present; therefore it shows only that, when the density was 1.05, the degree of supersaturation had become so great that precipitation took place. From

[1] C. F. Tolman, *Jour. Geol.*, VII (1899), 604.

[2] *Challenger Reports*, p. 221.

[3] *Jour. Geol.*, I, 504.

[4] *Challenger Reports*, p. 221.

[5] *Comptes rend.*, CVIII, 753.

[6] *Encycl. Brit.*, XXI, 229.

this discussion, then, it follows that three of these arguments are not conclusive as to the point at issue.

Let us now consider the modes in which $CaCO_3$ may be precipitated. We shall for convenience arrange them under three heads, which, however, cannot be sharply differentiated: (1) direct evaporation of the water; (2) through organic agencies; (3) change of conditions, especially of temperature and concentration of free CO_2, these being the predominant inorganic factors.

1. *By direct evaporation.*—When natural waters evaporate, $CaCO_3$ is commonly (though not necessarily) the first substance to be deposited, and may be very largely precipitated before any of the other salts separate;[1] the more soluble salts, moreover, will tend to be leached out of such deposits. But since all such deposits are of obvious origin and of minor importance, they need not detain us further.

2. *Deposition through organic agencies.*—The agencies which come under this category are of the greatest importance and are predominantly responsible for the deep-sea deposits, yet little as to their mode of action can be definitely stated until more is known about the biologic processes involved. This question is altogether beyond the scope of this paper; we shall mention merely two established effects of organic agencies, reverting to them later: viz., the abstraction of free CO_2 from fresh water by growing plants,[2] and the production of ammonia in sea-water by decaying organisms or by bacteria.[3] Both of these effects disturb the equilibrium in a solution originally saturated with $CaCO_3$, the former by diminishing the concentration of H_2CO_3, the latter by increasing the concentration

[1] Cf. Van't Hoff's *Ozeanische Salzablagerungen.*

[2] Various references to these effects are given in Clarke's *Data of Geochemistry* under "Limestone." See especially C. A. Davis, *Jour. Geol.*, VIII (1900), 485, 494; IX (1901), 491. According to Murray, the calcareous algae common in the warmer oceans no doubt secrete their skeletons in the same way. See also S. T. Powell, "Effect of Algae on Bicarbonates in Shallow Reservoirs," *Jour. Am. Waterworks Assoc.*, II (1915), 703.

[3] This question has been discussed recently by G. H. Drew (*Carnegi ,Institution Publ. No. 182* [1914], p. 7), and by Kellerman and Smith (*Jour. Wash. Acad. Sci.*, IV [1914], 400), and so need not be treated here. Many decaying organisms and bacteria (as well as the respiration of animals) produce CO_2, and to this extent they would act as an adverse influence on the deposition of $CaCO_3$.

of $CO_3^=$ directly,[1] the net result in either case being the precipitation of an amount of $CaCO_3$ which could readily be calculated by means of the equilibrium equations if the amount of CO_2 abstracted, or of ammonia produced, were known. But by this we do not imply that an organism cannot secrete calcium carbonate except from a solution already saturated with it. Nevertheless the possibility is open that the effects just considered may sometimes be in reality examples of the changes in conditions to be next considered—that the organism may be merely the agency which localizes the process, the mechanism which occasions the precipitation. It may even be that certain bacteria are abundant where $CaCO_3$ is being precipitated because there they can easily secure material—particularly CO_2—needed for their life-processes; on this basis they would be concomitants, rather than causes, of the deposition of the carbonate.

3. *Change of conditions.*—The important physico-chemical factors are temperature, and concentration of free CO_2, of the water; in comparison with these two all other such factors are entirely subsidiary. As an illustration of the magnitude of the effect producible by change of these factors, a change in the proportion of CO_2 in the air in actual contact with the solution from 3.3 down to 3.0 parts per 10,000—a change[2] which may occur at the present time—of itself decreases the solubility from 65 to 63 parts per million, and so will cause the ultimate precipitation of the corresponding quantity of $CaCO_3$ from a solution already saturated with it. A similar amount will be deposited[3] if the temperature of the saturated solution rises about 2° C., the proportion of CO_2 in the air remaining constant; under these circumstances the concentration of free CO_2 in the water falls, and its diminution is responsible for the larger part of the diminished

[1] The production of free ammonia causes an increase in the concentration of OH^- and therefore an increase in $[CO_3^=]$, since the quotient $[OH^-]^2/[CO_3^=]$ is constant when P is constant, in accordance with the equation already given. It may be noted that the production by the decaying organisms of an ammonium salt such as NH_4NO_3 or $(NH_4)_2SO_4$ would tend to increase the solubility of $CaCO_3$ and hence would not favor its deposition.

[2] The range of variation in the course of geologic time has in all probability been very much greater than this with correspondingly larger possible consequences.

[3] This of course implies that supersaturation does not take place; but in the sea supersaturation is highly improbable by reason of the great abundance of appropriate nuclei always present.

solubility, since the diminution of the solubility-product constant of calcite with temperature is, as we have seen, proportionally less than that of the absorption coefficient of CO_2.

The abstraction of CO_2 from a saturated solution results ultimately, then, in the deposition of $CaCO_3$, no matter what the agency which abstracts the CO_2. This agency may be a diminished proportion of CO_2 in the air, or a higher temperature, or both; or it may be organisms which make use of the CO_2 in their vital processes, or the production by bacterial action of ammonia, which indirectly achieves the same result; or, in short, it may be any way in which the concentration of CO_2 may possibly be diminished. Consequently, if the surface layers of the sea are saturated, as we believe they are, precipitation of $CaCO_3$ will be brought about wherever any of the foregoing agencies are operative.

In this connection two points which are the consequence of accepting erroneous chemical data are to be noted. Thus Davis[1] in his excellent work on marls has made a slight slip. He observed that on bubbling oxygen gas through a solution containing $CaCO_3$ the latter was precipitated, and he attributed this effect to a specific action of the oxygen; but any other gas would have produced the same effect, which was actually due to the sweeping out of the CO_2 from the solution. Nor is it necessary to consider, when ammonia is being produced, whether it appears as hydroxide or as carbonate, or whether there is a subsequent metathesis with calcium sulphate or chloride or some other reaction; in either case the net result can be predicted immediately from a consideration of the effect of the added substance upon the concentration of calcium-ion and of carbonate-ion,[2] and of the magnitude of the product $[Ca^{++}]$ $[CO_3^{=}]$ in relation to its precipitation value.[3] To some this procedure may appear complicated; in reality, while it pays no heed to those easily derived arithmetical equations so often considered as representing reactions, it takes into account the several equilibria which must be adjusted,

[1] C. A. Davis, *Jour. Geol.*, VIII (1900), 487.

[2] Change of concentration of $CO_3^{=}$ affects, and is affected by, the concentration of HCO_3^{-} and OH^{-}, these being all dependent variables; see Johnston, *op. cit.*

[3] Provided that calcite is still the stable solid phase in equilibrium with the solution; cf. footnote 3, p. 733.

and is the only procedure which will yield accurate results and lead to correct conclusions. Moreover, a comprehension of this question is desirable because this apparently complex equilibrium is typical of what takes place in many other systems, aqueo-igneous and igneous as well as aqueous; it is in but very few cases, however, that we know even what molecular species are important factors in the equilibrium, and in still fewer is any information available as to the quantitative relations at equilibrium.

There has, moreover, been considerable misapprehension as to the rôle of hydrostatic pressure in increasing the solubility of $CaCO_3$; thus in a recent paper Daly[1] writes: "On account of the higher temperatures and lower bottom pressures (*pressure increasing the solubility of the carbonate*) of the shallower water we should expect the rate of chemical precipitation of calcium carbonate at the bottom to be concentrated in the neritic (epicontinental) and shallower bathyal regions." And many smiliar statements relative to the effect of hydrostatic pressure might be quoted. As a matter of fact, the hydrostatic pressure[2] acting on the water is of itself an absolutely negligible factor; thus water a mile below the surface of the sea will hold in solution an amount of $CaCO_3$ which does not differ by an appreciable quantity from the amount the same water at the surface will hold, provided that the concentration of free CO_2 and the temperature be the same in both cases. The increased solubility with depth in the ocean is due entirely to the lower temperature of the water and to the increased proportion of free CO_2, but not at all to the increased hydrostatic pressure there prevailing.

The only pressure which does affect the solubility is the partial pressure, i.e., the proportion, of CO_2 in the layer of atmosphere[3] in

[1] R. A. Daly, *Bull. Geol. Soc. Am.*, XX (1909), 156; also in "Geology of North American Cordillera," *Memoir No. 38, Geol. Survey of Canada*, Part II (1912), p. 651. Italics are ours.

[2] Increase of hydrostatic pressure *decreases* the solubility of some substances. In any case the effect is very small indeed; its magnitude and direction can be calculated if the appropriate data on volume changes are known. Cf. Johnston and Niggli, *Jour. Geol.*, XXI (1913), 504, where references are given.

[3] The proportion of CO_2 in the air increases, *ceteris paribus*, as we pass from higher to lower levels; but this is a factor of no moment to the present discussion because the diffusion downward through the water is in all probability very slow in comparison with the natural circulation of the water.

contact with the solution, for there is a definite and quickly attained equilibrium between the proportion of CO_2 in the adjacent atmosphere and the concentration of free CO_2 in the water, the factor of proportionality being the absorption coefficient (the solubility) of CO_2 in the solution at the particular temperature. It is true that water at depth can hold more CO_2 in solution, if it gets hold of it, for in that case bubbles of CO_2 gas cannot form until its virtual pressure just exceeds the hydrostatic pressure; but slow diffusion upward would tend to equalize the concentration at various depths. In the ocean, on the other hand, the content of CO_2 is only what it was able to absorb when at the surface, supplemented by that which has been produced by organic processes—the latter being in all probability but a small fraction of the whole in deep water.[1] However this may be, it is manifest why the water at depth should contain more CO_2, for its present low temperature, retained from its polar days, establishes the fact that when at the surface in contact with the atmosphere it was cold, and lowering of temperature increases very markedly the amount of CO_2 which water can absorb through contact with an atmosphere containing a constant proportion of CO_2.[2] This fact, combined with its present low temperature —for, as we have seen, lowering of temperature of itself increases the solubility of $CaCO_3$—suffices to account for the well-known fact that all shells and tests disappear in the depths of the ocean.[3]

Now let us revert to the consequence of abstraction of CO_2, and consider what will happen when, in the course of the oceanic circulation, this cold water, which carries more CO_2 and more $CaCO_3$ than the warmer surface waters,[4] reaches the surface and is slowly warmed.

[1] Buchanan (*Proc. Roy. Soc.*, XXII [1874], 483) writes: "Down to nearly 2,000 fathoms life is still abundant; below this depth, however, the amount rapidly decreases till, at about 2,800 fathoms, it is, for carbonic acid producing purposes, practically extinct."

[2] Thus in contact with any atmosphere, water (or a dilute salt solution) absorbs about twice as much CO_2 at 0° as at 20°.

[3] See the report of the Challenger expedition or the work of Sir John Murray. In the present connection it is immaterial whether these shells consist of calcite or aragonite, although assertions to the contrary may be found.

[4] This appears a necessary prerequisite, no matter what be the mechanism of precipitation. Dittmar, in his article in the *Encyclopaedia Britannica*, states that there is a slight but indubitable increase in concentration of calcium with depth. Moreover,

In the first place, it will gradually lose CO_2 to the air, the residual concentration of free CO_2 being dependent at any moment upon the temperature of the water and the proportion[1] of CO_2 in the air at that place. The consequence of this loss is that the amount of calcium in solution will at some point exceed the concentration which the water is able to hold in solution—or, in other words, the product $[Ca^{++}][CO_3^{=}]$ reaches its characteristic precipitation value—whereupon precipitation[2] sets in, and continues thereafter so long as the temperature continues to rise. This process is without doubt taking place now in tropical and subtropical regions wherever and whenever the necessary conditions are fulfilled. It has been correlated[3] with the abundant bacterial and planktonic life found under such circumstances, and there would seem to be little question that the organisms are a factor in the process, if only in the sense of catalyzing it. But may it not be, in some cases at least, that the organisms are abundant there because of the abundance of the CO_2 available for their life-processes in such water? For it is to be borne in mind that the precipitation of $CaCO_3$ is accompanied by the setting free of an equivalent quantity of CO_2 which, if not used up in the sea, will pass into the atmosphere. Be this as it may, the physico-chemical factors are in themselves competent to account for the precipitation[4] of $CaCO_3$ on a large scale, and the prerequisite conditions for deposition by this means do not differ materially from the postulates required for precipitation by bacterial action or by organisms generally.

Buchanan (*Proc. Roy. Soc. London*, XXIV [1876]) writes: "There is usually more CO_2 in waters taken from the bottom and intermediate depths than in surface water; but if regard be had to the temperature of the water, it will be seen that there is but little difference in the amount in waters of the same temperature from whatever depth they have been derived." It is to be observed that these determinations all refer to low latitudes; conditions in the Polar regions may well be different.

[1] All experiments indicate that this proportion departs in general very little from 3 parts in 10,000, except in or near large towns. Off the west coast of Greenland, however, amounts up to 7 parts in 10,000 were observed by Krogh (*Meddelelser om Gronland*, XXVI [1904], 409).

[2] Supersaturation is under these conditions obviously a negligible factor.

[3] G. H. Drew, *Carnegie Inst. Publ. No. 182* (1914), p. 7; Kellerman and Smith, *Jour. Wash. Acad. Sci.*, IV (1914), 400. See also recent papers by T. Wayland Vaughan.

[4] Likewise for its re-solution.

Indeed, there are several facts which point to a parallelism between the amount of lime secreted by organisms and the degree of saturation of the sea with respect to $CaCO_3$; thus the animals of the warm seas secrete more lime, on the average, than the same types in cold seas;[1] and, according to Murray,[2] "on the whole, lime at the present time appears to be accumulating toward the equator." These observations directly corroborate the idea that solubility is a significant factor even in the secretion of lime by organisms; that the decreasing abundance of calcareous organisms toward the polar regions is a question not only of the decrease of general vitality (rate of growth and of reproduction) with lowering of temperature, but also of the decreasing capacity[3] of the organism to secrete $CaCO_3$ from colder sea-water, this being associated with the fact that, though the concentration of lime is no smaller in the colder water, the degree of unsaturation is greater the colder the sea-water.

According to Murray, "a limited amount of purely inorganic precipitation does, indeed, take place in coral reefs and some shallow water deposits and in the Black Sea."[4] Now it has been argued[5] that chemically precipitated limestones are due to the production of ammonia by decaying organic matter; according to this view such limestones could form only when conditions were such that a long-continued process of persistent decay was possible. According to the view emphasized in the present paper—and, be it noted, this is primarily a chemical, rather than a geological, question—chemical

[1] See citations from the *Challenger Reports*, in Chamberlin, *Jour. Geol.*, VII (1899), 576–77.

[2] *The Depths of the Ocean*, p. 180. "In very deep water, even within the tropics, the calcareous shells do not accumulate on the bottom, being apparently removed through the solvent action of sea-water, and with increasing depth the Globigerina ooze passes gradually into another pelagic type, usually Red Clay" (p. 164). "Pteropod ooze is limited to the tropical and subtropical regions, usually in the neighborhood of oceanic islands and on the summits and sides of submarine elevations; it is found in relatively shallow water, and covers a relatively small extent of the ocean floor" (p. 167).

[3] It would be of interest to know if these calcareous organisms could secrete $CaCO_3$ from colder water kept saturated with calcium carbonate.

[4] *The Depths of the Ocean*, p. 178.

[5] Most recently by R. A. Daly, *Bull. Geol. Soc. Am.*, XX (1909), 153; in more extended form in *Memoir No. 38, Geol. Survey Canada* (1912), pp. 643 f.

precipitation would take place wherever, and so long as, a current of water saturated with calcite was being warmed. These views are not at all mutually exclusive; but their implications differ, and it ought to be possible to decide by appropriate observation and deduction in how far either has been a dominant cause on a large scale.

The magnitude of the scale of this presumed process of precipitation through purely inorganic agencies depends primarily upon the rate of circulation and upon the amount of calcium carried by this water rising to the surface. We shall now consider the competence of these agencies as geologic factors. In doing so let us suppose that a cold current of sea-water is not saturated with $CaCO_3$ until it has reached a temperature of 15°, and that this current after traveling 1,000 kilometers (600 miles) has attained a temperature of 20°; further, that the water in this stretch of 1,000 km. is changed 10 times a year, corresponding to a current speed of $1,000 \times 10/365$ or 27.4 km. a day. Now this water in being warmed from 15° to 20° would precipitate 5.4 parts $CaCO_3$ per million by weight, or 2 parts per million by volume; on these assumptions,[1] therefore, in the course of a year the mean thickness of the deposit (presuming that all of the precipitate finally settles to the bottom within this stretch) would be 2/1,000,000 of the depth of the current. Hence if the depth of the current is 100 m., the average deposit over the whole area would be, on the specific assumptions just mentioned, 2 mm. yearly.[2] This estimate is probably a minimum, particularly because we have supposed that deposition would take place over the whole area, whereas in reality deposition would be localized (e.g., if there is, as is likely, a more rapid warming up at some places) so that the deposits actually formed would be thicker. Moreover, the deposit would be redissolved whenever the current is underlain by colder unsaturated water; therefore actual deposits belonging to this category should occur only in localities bathed by currents which are

[1] The numerical values adopted were chosen as being reasonable; in any case these calculations will serve as an illustration, and anyone may make similar calculations using whatever numerical values he deems most consonant with the facts.

[2] This corresponds to about 5,000 tons $CaCO_3$ per square kilometer per year, or to a thickness of about 8 inches in a century.

warm and hence comparatively shallow and rising in temperature as they proceed. Consequently, if deposits of $CaCO_3$ are being formed in this way—and there is no direct evidence at hand which contradicts this view—it should be possible to correlate the position and rate of formation of such precipitated deposits with other things by means of series of bathymetrical observations on the manner of flow of the currents, the temperature of the water, and, above all, the concentration of free CO_2. As regards the latter, it may be said that the methods hitherto in vogue are very faulty indeed,[1] and that systematic, accurate determinations of the free CO_2 (which can be made by proper choice of method) are very much to be desired, not only on account of their bearing on the present question, but because an accurate knowledge of the concentration of free CO_2 is of high importance[2] in connection with many biological problems, both theoretical and practical.

Nor would the establishment of this presumed correlation between deposits of $CaCO_3$ and the physico-chemical conditions prevailing in the ocean be of importance only in relation to present-day formations belonging to this category; it would also be of use in interpreting past deposits of this character which have persisted and in co-ordinating them with other factors. For the rate of formation of such deposits (including the limiting case of zero rate) depends obviously upon the mode and rate of circulation of the ocean and the amount of calcium carried by the water rising to the surface, secondarily, therefore, upon the amount of calcium carbonate brought down by the rivers to the sea; all of which depend ultimately upon the physiographic and petrologic character of the land surface, upon the magnitude of the seasonal variations and regional differences, upon the climate over the whole earth, and upon the proportion of CO_2 in the atmosphere. It would lead too far to discuss this question in all its bearings;[3] in order to show the importance of the

[1] See Johnston, *Jour. Am. Chem. Soc.*, XXXVIII (1916), 947.

[2] The free and combined CO_2 and the alkalinity of the solution are not independent variables, a fact often forgotten; and doubtless many effects ascribed to a change in alkalinity are due equally, or primarily, to a change in the CO^2 equilibrium in the solution.

[3] The discussions of Chamberlin (*Jour. Geol.*, VII [1899], 545, 667, 757), Tolman (*ibid.*, p. 585), Krogh (*Meddelelser om Gronland*, XXVII [1904], 334), and others, require some revision in the light of data available since that time.

last factor—apart altogether from the influence of CO_2 as an agency disintegrating the rocks—we have calculated the concentration of the free and combined CO_2 in sea-water at three temperatures for several proportions of CO_2 in the atmosphere. The specific assumptions made in these calculations are: (*a*) that the molar absorption coefficient (*c*) of CO_2 is the same as in a 0.6 *N* (3.5 per cent) solution of sodium chloride; (*b*) that the water is always saturated with respect to calcite, so that we are justified in using the solubility-product constant (K'_C) corresponding to the temperature; (*c*) that the degree of ionization of the carbonate is 0.6, a value which is probably high rather than low.[1] On this basis the formula becomes

$$A = \text{total } CO_2 = cP + \sqrt{11200cK'_C P}/0.6,$$

where the first term represents the free CO_2 and the second the total combined CO_2, each expressed in moles per liter; whence by multiplication by the factor 0.044 one obtains the result in grams CO_2 per cubic meter (parts per million) as given in Table III.

TABLE III

THE CONCENTRATION OF FREE (*f*), COMBINED (*b*), AND TOTAL (*A*) CO_2—EXPRESSED IN GRAMS CO_2 PER CUBIC METER (PARTS PER MILLION)—IN SEA-WATER AT SEVERAL TEMPERATURES AND SEVERAL PARTIAL PRESSURES (*P*) OF CO_2 IN THE ATMOSPHERE; CALCULATED ON THE BASIS OF THE SPECIFIC ASSUMPTIONS MENTIONED ABOVE

CO_2 in Adjacent Atmosphere as		10° $c=0.0463$ $K_C=1.06\times10^{-8}$			20° $c=0.0335$ $K_C=0.93\times10^{-8}$			30° $c=0.0260$ $K_C=0.81\times10^{-8}$		
Parts per 10,000	Partial Pressure *P*	*f*	*b*	*A*	*f*	*b*	*A*	*f*	*b*	*A*
2.5	0.00025	0.51	81.5	82	0.37	70.0	70	0.29	61.5	62
3.0	.0003	0.61	86.6	87	0.44	74.5	75	0.34	65.5	66
3.5	.00035	0.71	91.1	92	0.51	78.3	79	0.40	68.8	69
30.0	.003	6.12	187.6	193	4.4	160.3	165	3.43	140.8	144
300.0	0.03	61.2	402.	463	44.0	345.	389	34.3	303.	337

The figures for total CO_2, derived in this way, are in substantial agreement with the results of analyses of sea-water; in any case the

[1] Murray and Hjort (*The Depths of the Ocean* [1912], p. 175) estimate the aggregate degree of ionization in sea-water to be 0.9; but this is undoubtedly much too high.

relative values for the different conditions are probably good even if the absolute values are inaccurate. According to the table, the concentration of total CO_2 in water at constant temperature varies practically as the cube root of P, for the small values of P; in other words, a change of 3 per cent in the present proportion of CO_2 (e.g., from 3.1 to 3.0 parts per 10,000) will produce a change of but 1 per cent in the concentration of total CO_2 in the sea-water. Likewise under present conditions (i.e., $P=0.0003$) the total CO_2 in the ocean decreases about 1.5 per cent of its value for each degree of rise in temperature. At the higher pressures of CO_2 the proportion of free CO_2 in the water becomes relatively much more important; but a hundred-fold increase in the proportion in the adjacent air would cause only a fivefold increase in the total CO_2 in the sea. In this estimate and in the subsequent discussion, be it noted, the assumption is implicit that the water is continuously saturated with $CaCO_3$ at 15° for all values of P, which in turn implies that conditions were such that the rivers transported to the sea sufficient lime to achieve this. On this basis, therefore, if the present amount of CO_2 in the atmosphere were increased a hundred fold, the total amount of CO_2 in atmosphere and ocean would be only six times as much as it is now; the conditions of equilibrium always being such that a chance in the proportion of CO_2 in the atmosphere is minimized, not through a permanent change in the proportion of free CO_2 in the sea (and of its alkalinity), but ultimately by means of the precipitation or solution of a definite quantity of $CaCO_3$.

Let us now make a computation of the ratio of the total amount of CO_2 in the whole ocean to that in the whole atmosphere, this being, of course, a measure of the capacity of the ocean to regulate the proportion now present in the atmosphere. We assume again that the ocean as a whole would be saturated with $CaCO_3$ if its temperature were 15°,[1] and that its mean depth is 3,600 meters;[2] on this basis the mean amount of CO_2 under each square meter of surface of the sea is $81 \times 3,600$ gm. or 290 kg. The mean amount above each square

[1] This is just equivalent to the assumption that the average proportion of $CaCO_3$ throughout the ocean is that which corresponds to its solubility at 15°, about 60–70 parts $CaCO_3$ per million for values of P not far removed from 0.0003. Cf. Table I.

[2] See *Encycl. Brit.*, article "Ocean."

meter of the earth's surface (sea and land together) is 3 kg.; for if the proportion of CO_2 in the air at the earth's surface is 3 parts per 10,000, the proportion in the whole atmosphere is 2 in 10,000 by volume, hence 3 in 10,000 by weight, or 3 kg. per square meter. Consequently, since the ocean covers about 71 per cent of the total surface of the globe, the ratio

$$\frac{\text{total } CO_2 \text{ in ocean}}{\text{total } CO_2 \text{ in air}} = \frac{290 \times 0.71}{3} = 69 .$$

In other words, the ocean contains about 70 times[1] as much CO_2 as the air, on the basis of the assumptions specified above. On this basis the total CO_2 now present in the ocean and atmosphere combined would form a layer of $CaCO_3$ only about 17 cm. thick over the whole globe, or about 86 cm. (nearly 3 feet) over one-half the present land area; likewise if the amount of CO_2 in the atmosphere were 100 times as much as at present, the corresponding values would be slightly more than 6 times as large, namely, 110 cm. over the globe, or 550 cm. (18 feet) over one-half the present land area. The possible deductions, however, must remain uncertain until series of simultaneous accurate determinations of free and total CO_2, temperature, and salinity in the sea at various depths and in different localities shall have been made.

The precipitation of $CaCO_3$ in forms other than calcite.—Besides calcite, which is the stable crystalline form of $CaCO_3$ under all ordinary conditions, there are two unstable crystalline forms, aragonite and μ-$CaCO_3$, which may precipitate under certain circumstances. This whole question is discussed at length in another paper, to which the reader desirous of further information is referred;[2] we shall here merely recapitulate the conclusions relevant to the present discussion. The existence of the μ-form in nature has not been definitely established, possibly by reason of the fact that some of the criteria which have been used to differentiate the several forms of $CaCO_3$ have not been unexceptionable, possibly on account of its

[1] This estimate is higher than that (27 times) of Krogh (*Meddelelser om Gronland*, XXVI [1904], 420) or that (55 times) given in Chamberlin and Salisbury's *Geology*, II, 661, which see, with respect to the whole discussion.

[2] "The Several Forms of Calcium Carbonate," Johnston, Merwin, and Williamson, *Am. Jour. Sci.* (4), XLI (1916), 473.

instability, for in presence of water the μ-form transforms to calcite in a few days. Calcite also appears as spherulites and as "amorphous" $CaCO_3$; but there is little question that the divergent properties of the latter are due entirely to its fineness of grain, i.e., to its extent of surface in proportion to its mass. Consequently the only form other than calcite which we need consider here is aragonite.

Apparently aragonite is formed in nature (*a*) through organic agencies (e.g., in certain shells), (*b*) by deposition from hot springs, (*c*) when an isomorphous carbonate is present to serve as nucleus, and (*d*) by chemical precipitation in saline waters, even at ordinary temperatures, under circumstances which we are unable to specify except by saying that the presence of sulphate appears to be a favorable factor. But *pure* aragonite cannot persist for any length of time in presence of water and calcite, hence only in special circumstances will it be found persisting in the sea. There is, however, the possibility that aragonite may take up in solid solution enough material to bring its own solubility below that of calcite, and hence in the saline solution in equilibrium with the solid solution to render the latter stable with respect to calcite; on this basis it is possible that such impure aragonite may persist in contact with sea-water under certain circumstances, although when exposed to the action of meteoric waters it would soon transform to calcite. However this may be, the circumstance that $CaCO_3$ precipitates otherwise than as calcite would not of itself affect appreciably anything stated in this paper, since the whole effect would be that ensuing upon the substitution for the solubility-product constant of calcite of the corresponding value for the other form, the latter being certainly no more than twice as great as the former; so the precipitation of the less stable forms is therefore of only subsidiary importance in the present connection.

Summary.—Though organic agencies are predominantly responsible for the deposition of calcium carbonate, yet the purely inorganic factors should also be taken into account in discussions of the mode of deposition. In this paper emphasis has been laid on one point which has not received adequate recognition; namely, the concentration of calcium relative to the limiting saturation concentration of calcium carbonate under the particular conditions, or, in other

words, the relative degree of saturation with respect to calcium carbonate in the ocean. The importance of this factor is obvious if we recollect that the chance of a permanent deposit is, *ceteris paribus*, greater the more nearly saturated the surrounding water is; its neglect is doubtless due to the erroneous and misleading statements as to the solubility of $CaCO_3$ which have been prevalent. The solubility under specified conditions can now be calculated with the requisite accuracy; it is affected materially by variations of temperature and of concentration of free CO_2 such as occur in nature. For example, a change in the proportion of CO_2 in the adjacent air from 3.2 to 3.0 parts per 10,000, or an increase of temperature of 2° C. would result ultimately in the precipitation of about 2 gm. $CaCO_3$ from every cubic meter of a solution saturated with it. Comparison of the solubility as calculated with the available analytical data indicates that the warmer surface layers of the sea are substantially saturated with respect to calcite, and consequently that precipitation is to be expected wherever the water is being warmed or is losing CO_2, or both, and this independently of any other agencies. Indeed, these inorganic factors must be considered no matter what may be the agency inducing precipitation; for example, there is ground for believing that calcareous organisms are more abundant the more nearly saturated with $CaCO_3$ the water is. The view here advocated, that a somewhat greater rôle be assigned to the inorganic factors than has hitherto been usual, does not conflict with other views—it merely shifts the emphasis a little; nor does it conflict with any facts that have been definitely ascertained. Its precise importance can be determined only by accurate determination of temperature, salinity, and particularly of concentration of CO_2—free and total—of the water carried out systematically over the ocean; the results of such an investigation, properly carried out, would have an important bearing on many outstanding biological, as well as geological, problems.

NOTES ON THE STRUCTURAL RELATIONS OF AUSTRALASIA, NEW GUINEA, AND NEW ZEALAND

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INTRODUCTION

The accompanying brief note is an attempt at the co-ordination of our increasing knowledge of the structural development of Australia and the neighboring islands.

The ideas given in this note are intended only as a temporary viewpoint from which to consider the work of the great pioneers of geology in Australia and as an inference or tentative hypothesis to stimulate interest in those magnificent field problems in Australasia, New Guinea, New Caledonia, and New Zealand, which call so urgently for solution. In this way it is hoped that the scheme here proposed will serve as a rough clue to the unraveling of certain vexed questions in the stratigraphic and structural history of Australia.

Several difficult points need explanation before any simple account of the building of Australia would be possible. Thus in the discussion of the Devonian it must not be forgotten that folds supposed to be of this age occur in *Northwest* Australia. Highly altered rocks of unknown age and of large area occur also in Northern and Northeastern Queensland, and the occurrence of these has not been explained in the present note. Then again, it must not be forgotten that our knowledge of some of the Permo-Carboniferous rocks, such as the Gympie of the Queensland geologists, is far from satisfactory.

Again, it is not known how many of the observations of the older workers in connection with the strike of folds were merely local and how many were conducted on a large scale.

Acknowledgments.—The writer is deeply indebted to Professor Leo A. Cotton and Dr. W. N. Benson, of Sydney University, for their kindness in reading the report in manuscript and for supplying additional information as to literature on the pre-Cambrian and Ordovician, and for kindly criticism of the notes on the Devonian, the Permo-Carboniferous and the Trias-Jura.

Previous workers.—It is the desire of the writer at this stage of our scientific development in Australia to draw attention to the work of the pioneers of geology in the great island continent. Australian pioneer geologists, in common with Australian explorers and miners, and in common also with American pioneers, have breathed the inspiration of their own mighty surroundings. Foremost among the pathfinders of geology in the country under consideration—men who crossed trackless wastes and endured untold discomforts in their pursuit of knowledge—were W. B. Clarke, R. Daintree, and A. R. C. Selwyn; others who followed in the track of these giants, but who nevertheless bore much of the heat and burden of the day and were either worthy successors or contemporaries of the pioneer trio, were H. Y. L. Brown, J. E. Carne, T. W. E. David, W. Howchin, R. Logan Jack, A. Gibb Maitland, R. Murray, S. Stutchbury, R. Tate, W. H. Twelvetrees, and C. S. Wilkinson. Among them also must be named the paleontologist, R. Etheridge, Jr., whose labors in the cause of Australian paleontology have done so much to simplify the task of the field workers. A whole group of younger enthusiasts have built and are today building on the work laid down by these pioneers.

PREVIOUS WORK DONE AND SCOPE OF PRESENT NOTE

The earliest definite statement known to the writer concerning the building of Australia as a whole was made by T. W. E. David.[1] In this detailed account Professor David's descriptions imply

[1] Presidential address on "The Growth of Australia," *Proc. Linn. Soc. N. S. Wales*, 1893, pp. 547–607.

the growth of Australia as from west to east. In 1911 the same writer amplified his earlier statement and said:[1] "Since the close of Paleozoic time Australia has been subjected to broad warps, but not to true folding except in the direction of New Guinea, where Cretaceous, and even early Tertiary, strata are highly folded. New Guinea is thus a new fold region; and even in Australia tectonic movements are newer as New Guinea is approached" (p. 59).

H. I. Jensen[2] also, in a later note, discussed the gradual growth of the eastern portion of the continent.

Like David's earlier reports, this paper of Jensen's is important and suggestive. Jensen approaches the problem of Eastern Australian history also from the viewpoint of "petrological unity." He, however, considered that the folding of the Permo-Carboniferous sediments was sporadic and had died out practically in Northern New South Wales.

In 1914 David[3] presented an epitome of Australasian geology. In this he said: "The latest folding to which the earth's crust in Australia has been subjected belongs to late Carboniferous time" (p. 256). He qualified this, however, by the statement: "The strata in the Permo-Carboniferous system are either perfectly horizontal or disposed in broad open troughs and arches. Only in the case of the strata of Drake and Undercliffe in New England and the Ashford areas [New South Wales] and the Gympie area in Queensland, are the strata of this system highly disturbed near granite intrusions" (p. 267).

The reader is referred for a consideration of this statement to the discussion of the field evidence in connection with the Permo-Carboniferous. It will then be seen how incomplete is our knowledge of the age of the sediments of Eastern Australia lying to the north of Sydney, and hence how great the need for caution to be exercised in coming to any definite conclusion as to the scheme of structure.

[1] T. W. Edgeworth David, "Presidential Address," *Proc. Roy. Soc. N.S. Wales*, 1911, pp. 15–76.

[2] "The Building of Eastern Australia," *Proc. Roy. Soc. Queensland*, July, 1911, pp. 149–98.

[3] T. W. Edgeworth David, "The Geology of the Commonwealth" (Federal Handbook), *Brit. Assoc. Adv. Sci.*, Australian meeting, 1914, pp. 241–325.

Origin and scope of present note.—The idea of writing a paper similar to the present one was conceived as far back as 1905–6, when the writer was surveying an area of folded sediments in Northern New South Wales. Previous workers had considered these beds as belonging to the older Paleozoic because they were strongly folded, whereas the beds of known Permo-Carboniferous type in Australia at that time were either horizontally bedded or only moderately domed.

David, however, in connection with these beds, had pointed out as far back as 1893: "I have, however, lately come to the conclusion that the whole of the Paleozoic sedimentary rocks of the Vegetable Creek district, provisionally classed by me as Upper Silurian or Devonian, are referable to the Gympie horizon"[1] [presumably Carboniferous.—E. C. A.].

During the progress of the survey these beds were discovered to contain many characteristic Lower Marine (Permo-Carboniferous) fossils, as probably also some Upper Marine types. The area of these Permo-Carboniferous types was proved to extend far to the north and west afterward by the field work of Carne and the writer.[2]

In Southern Queensland, near Warwick, these two observers found Lower Marine rocks folded in the most complicated manner,[3] while in 1908 during a visit to Mount Morgan, about 500 miles north of the New South Wales border, they saw rocks indicated on the Queensland geological map[4] as of the same age as the Warwick types, also highly folded.

In 1901 Mr. C. Hedley and the writer traced rocks at intervals from a little north of Townsville to near Cooktown, all highly contorted, and all shown on the Queensland geological map as of the same age as the Warwick beds. This caused the writer to consider

[1] "Presidential Address," *Proc. Linn. Soc. N.S. Wales*, 1893, pp. 586–87.

[2] J. E. Carne, "The Tin-Mining Industry of New South Wales," *Mineral Resources No. 14, Dept. Mines, Sydney, N.S.W.*, 1911, pp. 54, 70, 71; E. C. Andrews, "The Drake Copper and Gold Field, N.S. Wales," *Mineral Resources No. 12, Dept. Mines, Sydney, N.S.W.*, 1908, pp. 3–11.

[3] Drake Report. See plate opposite p. 10.

[4] R. L. Jack and R. Etheridge, *Geology of Queensland*, Brisbane (by Authority), 1892, plate 69.

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the significance of the peculiar problem of the Permo-Carboniferous, inasmuch as the whole of the work of the field officers of the geological survey of New South Wales had proved that the Permo-Carboniferous strata south of the Hunter River (lat. 33° S.) lie almost horizontally.

The independent testimony of the ore deposits of New Zealand and Australasia was then examined, and the problem of Australasian growth was formulated in the following terms:

During the progress of geological time folding movements in Australasia retreated north and east, while ore deposition moved parallel with these movements.

The growth of New Zealand does not appear to be known definitely, but the New Guinea and the New Caledonian movements appear to have opposed the Australian direction of growth.

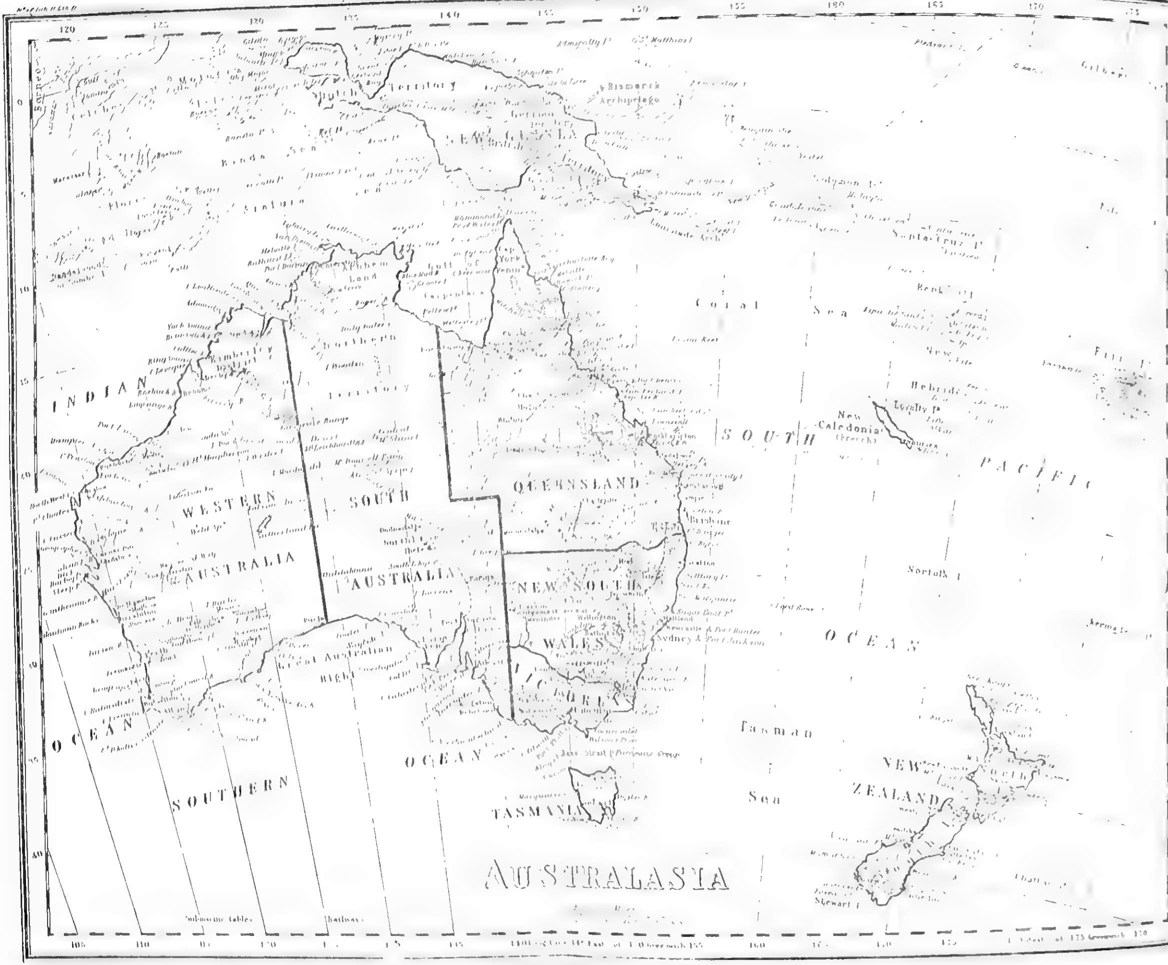
A study both of structure and of ore deposits suggests that New Zealand, Australia, and New Guinea have had independent origins.

GROWTH OF AUSTRALASIA FROM PRE-CAMBRIAN TO RECENT TIME

Pre-Cambrian —The greater portion of Australia, which stretches to the west of a line drawn from the southwest of Tasmania to the center of North Queensland,[1] is composed of pre-Cambrian schists, gneisses, granites, and allied rock types. The dominant strike of the foliations is northwest and southeast, approximately, with a marked tendency to show large local, or even regional, corrugations in the eastern portion of the area. This is well shown on David's map accompanying his report of 1911[2] to the Royal Society. It is possible that at the close of the pre-Cambrian period in Australia the land surface extended across the southeastern or even the eastern portion of the continent. This is suggested, not only by the schists of Cloncurry in Northern Queensland mentioned by Woolnough, but also by the presence of great masses of schists and gneisses of unknown age in Eastern Victoria extending northward into the Cooma district.

[1] W. G. Woolnough, *Bulletin of the Northern Territory,* No. 4, Dept. External Affairs, Melbourne, 1912, p. 51.

[2] "Presidential Address," *Proc. Roy. Soc. N.S. Wales,* 1911. See large map accompanying the paper.



AUSTRALASIA
INDIAN
OCEAN
SOUTHERN
OCEAN
WESTERN
AUSTRALIA
SOUTH
AUSTRALIA
Northern
Territory
QUEENSLAND
NEW SOUTH
WALES
VICTORIA
TASMANIA
Great Australian
Bight
Gulf of
Carpentaria
Bismarck
Archipelago
Dutch
Territory
German
British
Banda Sea
Coral Sea
SOUTH
PACIFIC
OCEAN
Tasman
Sea
New
Caledonia
(French)
Loyalty Is.
Norfolk I.
Brisbane
Sydney & Port Jackson
Newcastle & Port Hunter
NEW
ZEALAND
Stewart I.

Browne,[1] however, inclines to the belief that a portion of this area, at least, is of Ordovician age. Other schist masses exist in Queensland.

The possibility of sediments and other rock masses being molded onto, or being wrapped round, these resistant blocks is thus suggested.

Cambro-Ordovician.—Since the momentous pre-Cambrian period the greater portion of the area mentioned appears to have been a positive or buoyant element till the present day. A great negative area appears to have existed at this time over Eastern Tasmania, Victoria, and New South Wales. It is possible, however, that a positive element existed in this period in Southeastern Victoria and New South Wales. The Cambrian sediments are more in evidence on the western strip of this area, while the Ordovician are common on the southeastern and eastern portions. It is possible that the Ordovician sediments of the more eastern areas are conformable to the Cambrian, but there is an unconformity between the shallow water forms of the two in the MacDonnell Ranges of Central Australia.

Silurian.—At the close of the Ordovician there was a very powerful folding movement. Wherever the Ordovician occurs in New South Wales or Victoria, it is strongly folded and altered. The new land surface was carried far to the north and east by this folding movement. Ordovician sediments occur quite near the coast about 100 miles south of Sydney, and they outcrop within 120 miles (lat. 33° S.) of Sydney in a direction west-northwest. Thence to the pre-Cambrian outcrops of the more western areas they may be seen in many places, exposed by the stripping of their Devonian cappings.[2] In the majority of the localities observed the strike of the sediments is west of north.

During the Silurian the old negative area which had been occupied by the Cambro-Ordovician sediments once more sank, and the sea transgressed far to the west, almost to Broken Hill (long. 141°

[1] W. R. Browne, "The Geology of the Cooma District, N.S. Wales," *Jour. Proc. Roy. Soc. N.S. Wales*, XLVIII (1914), 172–222.

[2] E. C. Andrews, "The Canbelego Gold and Copper Field," *Mineral Resources, No. 18, Dept. Mines, N.S. Wales*, 1913. See maps and sections.

E.), not nearly so far west, nevertheless, as the Ordovician sea had transgressed. This sea was shallow in places and full of islands. As in the Cambro-Ordovician period, sandy sediments and conglomerates also were deposited in the west, while great areas of coralline limestone were deposited in the eastern portions. Much of the area colored on the geological map as Devonian in the west of New South Wales may be found hereafter to be Silurian or Cambro-Ordovician in age. No fossils have been found in these beds, and they have been referred to the Devonian because of their lithological resemblance to the eastern Devonian quartzites and sandstones. The strikes of the sediments are similar to those of the Ordovician.

Devonian.—A strong movement of folding closed the Silurian and ushered in the Devonian sedimentation. The Devonian problem in Australia is complicated much in the same way as are the Carboniferous, the Permo-Carboniferous, the Trias-Jura, and the Tertiary. The work of the pioneer geologists suggested that there were two, if not three, divisions in the Devonian period, with an unconformity between two of the sets of sediment.

Mr. W. S. Dun has made a study of the Devonian in Australia and he has supplied the following notes for this report. He states that the Buchan and Bindi sediments in Victoria appear to be of Middle Devonian age, and that they are the equivalents, in great measure, of the Murrumbidgee beds in Southern New South Wales, the two groups containing types of fossils in common. In this case, however, Mr. Dun points out that it is probable that after detailed examination, Lower Devonian sediments would be found developed in these regions passing into Middle Devonian.

The Upper Devonian series of sediments are characterized by the forms *Lepidodendron australe*, *Spirifer disjuncta*, and *Rhynchonella pleurodon*. The Upper Devonian series occur both at Mount Lambie and at Tamworth (New England). In the latter locality, however, *Spirifer disjuncta* and *Rhynchonella pleurodon* do not appear to have been found.

Sussmilch,[1] in dealing with the Devonian, says: "An alternative explanation of the relations between the Lower and Upper Devonian

[1] C. A. Sussmilch, *Geology of New South Wales*, 1914, pp. 77–80.

formations, however, suggests itself, and that is that the two formations were deposited more or less contemporaneously, the former in an open but comparatively shallow continental sea, at some distance from a shoreline; the latter in the shallow coastal waters of the same sea" (p. 80). He suggests that the marked differences so well established by R. Etheridge, T. W. E. David, and W. S. Dun between the faunas of the two formations would be due in such case to the unlike environments.

To Benson's field work, however, we are indebted for one definite piece of knowledge which may be expected to help in clearing up the tangle which has gathered round the Devonian in Eastern Australia. He[1] showed that the Carboniferous in New England is actually conformable with the Devonian in that region, the sediments of each age being strongly folded, the strike of the folding being north-northwest approximately, as traced for 200 miles at least.

During various geological surveys in the western, southern, and northern parts of New South Wales, the writer has noted that the Devonian sediments vary in appearance and structure, and the results of those observations would suggest that in very great measure the Devonian sea transgressed the area of folded Silurian sediments as far west as the Darling, without extending, however, as far in that direction as had the Silurian sea. A movement of folding apparently occurred in the Devonian which affected the eastern portions of Southern New South Wales strongly, being more marked as a whole in the northern portion of that area than in the southern, and more marked in the east than in the west. This movement may have been revived still later, with a tendency to cause Australia to grow northward and eastward as it had at the close of both the Silurian and Ordovician periods, the movement of sea transgression to the west and south being less during each succeeding period.

This brings us to a mention of the long zone of weakness extending from a point somewhat south of Sydney to Queensland in a direction slightly west of north. The great negative area which had received the Ordovician and Silurian sediments had been changed to a positive element with the close of the Devonian sedimentation in the south and west. The negative area by this time had shifted

[1] W. N. Benson, *Proc. Linn. Soc. N.S. Wales*, 1913, pp. 490–517.

to the position mentioned above, and such a zone of weakness appears to mark the boundary of two geological provinces in Eastern Australia. Benson has shown that in this heavy area the Devonian and Carboniferous accumulated conformably, none of the series apparently being folded until the close of the Carboniferous. Carboniferous sediments are believed by some geologists to exist in Australia south of this zone, but Mr. W. S. Dun, in a personal communication, has informed the writer that in his opinion the fossils from such sediments are to be referred to the Devonian rather than to the Carboniferous.

It is advisable, at this stage, to consider the general scheme of folding for the Devonian in Eastern Australia, inasmuch as what obtains for the Devonian in a general way, as regards its structure, is true also of the Silurian and the Permo-Carboniferous with this difference, that the analogies of form in rocks of the various periods considered are to be sought in areas which succeed each other to the north-northeast approximately in succession of time. Thus if the Silurian has been folded strongly over a large area, it may be found that the strongest folding of Devonian might be expected to be found north and east of the southern Silurian folds, whereas in certain areas of the strongest Silurian folding the Devonian is to be found bedded almost horizontally.

Thus in Tasmania the Devonian is missing; in Victoria it is folded, apparently in two series separated by an unconformity; in Eastern New South Wales it is strongly folded, whereas in Western New South Wales it occurs as a series of gentle rolls and folds, with small areas, however, exhibiting local nipping or sharp folding within the complex basement of Cambro-Ordovician and Silurian.[1] Reference to forms very similar will be made in the chapter dealing with the Permo-Carboniferous.

It may be mentioned here that a peculiar occurrence of so-called Devonian sediments has been recorded from Northwestern Australia by H. V. Woodward.[2] This observer mentions Devonian

[1] E. C. Andrews, "Canbelego Gold and Copper Field," *Mineral Resources, No. 18, Dept. Mines, N.S. Wales.* See maps and sections.

[2] *Report on Gold Fields of the Kimberley District* (by Authority), Perth, 1891, p. 10. Quoted from T. W. E. David's "Presidential Address," *Proc. Linn. Soc. N.S. Wales,* 1893.

sediments at Kimberley (Northwestern Australia), which are said to possess a strike almost northeast and southwest, and a dip of 70°, while so-called Carboniferous sediments lying immediately above are almost horizontal.

Carboniferous.—Benson's great contribution concerning the conformability of the Carboniferous with the Devonian in Northeastern New South Wales allows us to infer that the Devonian south of lat. 33° S. was folded prior to the tilting of the New England Devonian, and it suggests also that not only Middle Devonian but also Upper Devonian is to be expected in this New England series.

Permo-Carboniferous.—The Permo-Carboniferous period was a most interesting one in Australia, but only the salient points dealing with its history are here recorded so far as they deal with the main thesis of this report.

A great period of submergence is indicated over wide areas throughout peripheral Australia, but the strong folding to which certain sediments of this age were subjected at the close of the sedimentation was confined to a relatively narrow area within Eastern Australia north of the Hunter River, lat. 33° S. Thus the sediments of this age in Tasmania and Western Australia are almost horizontal; in Victoria they appear to be flexed only in the neighborhood of Tertiary faults or monoclinal folds; in Southeastern New South Wales they exhibit corrugations scarcely recognizable;[1] in the coastal region 100 miles north of Sydney they are moderately domed,[2] whereas to the west and southwest they are almost horizontal.[3] In Northeastern New South Wales, as shown by Carne, Woolnough, and the writer, the Permo-Carboniferous sediments are much folded and intruded by granite, whereas at a distance of 200 miles to the west the strata lie almost flat. In Southern Queensland the Permo-Carboniferous is intensely folded, as mentioned elsewhere in this report.

[1] E. C. Andrews, "Yalwal Gold Field," *Mineral Resources No. 9, Dept. Mines, N.S. Wales,* 1901; L. F. Harper, "The Southern Coal Field," *Memoir No. 7, Dept. Mines, N.S. Wales,* 1916.

[2] T. W. E. David, "The Hunter River Coal Measures," *Memoir No. 4, Dept. Mines, N.S. Wales,* 1907.

[3] J. E. Carne, "Western Coal Fields," *Memoir No. 6, Dept. Mines, N.S. Wales,* 1908.

Farther north, as, for example, at Gympie[1] and Mount Morgan,[2] the sediments are strongly folded and are Permo-Carboniferous in age. Along the north coastal area of Queensland there is a very long belt of sediments which are highly contorted and which appear to be Permo-Carboniferous.[3] Nevertheless, less than 100 miles inland the Permo-Carboniferous[4] dips at an angle of 12° only. All this indicates that the close of the Permo-Carboniferous period was accompanied by a strong folding movement in areas north and slightly east of the areas affected by the great closing Carboniferous movement in New England. Additional evidence of this is adduced when dealing with the regions of ore deposition in Australia.

The strikes of these foldings may be considered as subparallel to the Carboniferous lines of Benson, namely, northwest to north-northwest.

It may be pointed out here also that the area of Permo-Carboniferous sediments in Tasmania, South Australia, and Western Australia is very large; nevertheless the beds there are horizontally bedded.

Trias-Jura.—In this period there appears to have been a tendency for the old heavy, or negative, area of Central-Eastern Australia to sag again, or for the long zone of weakness separating New England from the land to the west and south to be broadened. In the northeastern portion of New South Wales and in Southern Queensland another area of sagging received a great thickness of Trias-Jura sediments.

The geographical conditions under which the two sets of sediment were deposited differed in certain well-marked features. This

[1] Jack and Etheridge, *Geology of Queensland* (by Authority), 1892, pp. 72–84. B. Dunstan has also produced detailed geological maps of this area in a late number of the *Queensland Survey Publications.*

[2] Jack and Etheridge, *Geology of Queensland*, p. 598.

[3] Lionel C. Ball, "Wolfram, Molybdenite, and Bismuth at Bamford, Northern Queensland," *Queensland Mining Journal,* 1914, p. 568. Mr. Ball has made a more definite statement as to the Permo-Carboniferous age of the beds in this district in a recent communication to the writer.

[4] J. H. Reid, "Permo-Carboniferous at Bett's Creek," *Queensland Government Mining Journal,* July, 1914, pp. 408–12.

has been indicated most clearly by Carne,[1] who calls attention to the fact that massive conglomerates, coal seams, and abundant fossil trees characterize the northern sediments as to their lower members, while tuffs and sandstones without heavy conglomerates, coal seams, or abundant tree stems characterized the southern and western sedimentation (Triassic). Cross-bedded sandstones of warm-brown color and intercalated black shales characterize the southern, middle, or Hawkesbury series, while cross-bedded sandstones are very common in the northern or Clarence series. In both series the later stages of the Trias-Jura appear to be dark shales in the main.

It is possible that the great folding at the close of the Carboniferous in Northeastern New South Wales was responsible, in great measure, for the heavy conglomerates of the Clarence series as well as of the Triassic of the Upper Hunter valley, and it is probable that very high land barriers separated the two sinking areas during a moderate part, at least, of the period. This might be expected to have caused variations in local floras. As an example, the Clarence series contains a characteristic fossil, namely, *Taeniopteris Daintreei*, whereas it is absent from the Hawkesbury. On the other hand, however, *Taeniopteris Daintreei* is found in the Victoria Trias-Jura, so that Carne and others consider the Clarence to be of different age from that of the Hawkesbury.

The southern or Hawkesbury (Triassic) area does not appear to have been dominated to the west and south by high land, inasmuch as the adjacent and subjacent Permo-Carboniferous in those directions does not appear to have been disturbed except by a gentle movement of sagging. The earlier period of the Trias-Jura appears to have been one of moderate to fair precipitation, but the middle period appears to have been subarid. In the Sydney district massive cross-bedded sandstones predominate in these middle beds, with relatively thin layers of dark-gray shales. In places layers of grit and subangular pebbles are interspersed with large blocks of these dark-gray shales, all mixed confusedly, apparently marking

[1] J. E. Carne, "Western Coal Field," *Memoir No. 6, Geol. Survey, N.S. Wales*, 1907, pp. 26–41; see also E. F. Pittman, *Ann. Report N.S. Wales*, 1880, p. 244. Quoted by Carne, *op. cit.*, p. 26.

periods of short-lived floods (sheet floods) which broke up the clays and mixed them with the pebbles and grits carried downstream by the local cloud-bursts or heavy rains. This appears also to have been the opinion of Professor H. E. Gregory, of Yale, from an examination by him in 1916 of the Sydney and Blue Mountain exposures. The upper portion of the period appears to have been one of greater precipitation in which actual lakes were in existence.

At Sydney, and a little south of that area, the Triassic beds dip inland at a very gentle angle, but, as Carne has shown, the whole southern area of these sediments has a dip averaging only from 1° to 2°. In the northeastern part of New South Wales, however, the Mesozoic coal measures and the conglomerates dip from 10° to 20°, while in Southern Queensland they have been still more disturbed. In the western portions of Eastern Australia, however, as also in Western Australia, they lie practically horizontal.

There appears to be no consensus of opinion among Australian geologists as to the origin of the Hawkesbury beds. Rev. J. E. Tenison Woods considered them to be of wind-blown origin[1] with lakes and swamps between the dunes.

In an unpublished paper R. S. Bonny considers them to be of estuarine origin. On the whole they may be said to be continental in origin, being formed in a sinking area mainly by water strains in a rather dry period.

Cretaceous.—The Cretaceous period marked a spilling over of the ocean with the formation of great epicontinental seas, especially during the Upper Cretaceous period. The area most affected was the northern portion of the old heavy area separating Eastern and Western Australia. It is probable that, during the Upper Cretaceous, the epicontinental sea extended from the Gulf of Carpentaria to the Southern Ocean. The eastern area occupied by the Triassic sediments, however, consisted of dry land during the Cretaceous. At the close of the period the whole center of Australia appears to have been raised to a moderate height above sea-level. Dunstan and Richards have recorded pronounced folding (40°–55°)

[1] "The Hawkesbury Sandstone," *Proc. Jour. Roy. Soc. N.S. Wales*, XVI (1882), 53–90.

of Lower Cretaceous rocks on the coast of Queensland at some distance north of Brisbane.[1]

Reference will be made later to this local evidence of folded Trias-Jura and Cretaceous rocks along the coast of Central and Northern Queensland.

Tertiary period.—The Eocene sea was not large and appears to have been confined to areas, relatively small, in the north and south of the continent. Indeed, the continent as a whole, except in the northeast, appears to have been growing in size subsequently to the close of the Cretaceous, although a submergence, postdating the recent Glacial period, appears to have isolated New Guinea and Tasmania from the mainland.

It is as if there has been a general tendency in Australasia and New Zealand to move in a vertical direction in post-Cretaceous time, the movement being subject to two great laws:

1. That elevation, or vertical movement, of the land was emphasized in an easterly direction, as from Western Australia to New Zealand, due allowance being made for the lagging behind differentially of the two great and relatively heavy portions, namely, Central Australia and the suboceanic mass separating Australia from New Zealand.

2. That the uplifts after the widespread peneplanation of the Cretaceous period did not proceed continuously, but were saltatory in their action, and, moreover, that the periods of time separating these uplifts became less as the present time approached, and that, nevertheless, the amounts of individual uplifts became greater as the periods marking the pauses between the uplifts became less in duration. This has given rise to great "valley-in-valley" structures owing to the interrupted work of the streams.

Thus in Australia, during what appears to be the Cretaceous period, great peneplains were formed in the land areas lying east and west of the Cretaceous sea, and only the hardest rock structures remained to show the existence of former plateaus or hills. In the various Tertiary divisions of time the streams carved valleys with

[1] B. Dunstan, *Queensland Government Mining Journal*, December, 1912; H. C. Richards, "The Cretaceous Rocks of Woody Island," *Queensland Aust. Assoc. Adv. Sci.*, Melbourne meeting, 1913, pp. 719–88.

widths so great as to appear as local peneplains, although they are only very broad, shallow valleys in whose bases other broad and shallow valleys have been excavated. The great uplifts of the later Kosciusko period allowed the streams to form profound canyons which receded along these older shallow valleys. In other words, the main Tertiary land history has consisted of repeated elevations with stream revivals. During one or more of the Tertiary divisions of time, particularly in what may be the Miocene, the land appears to have sunk with the formation of lakelike expanses along the stream courses and the burial, later, of deep-river deposits beneath basalt floods covering thousands of square miles in Eastern Australia. This led to great modifications in the stream drainage, but the dominating lesson of the repeated revival of stream action must not be overlooked, the modifications due to lava floods being only an incident in the great geographical unity of Australia in Tertiary and post-Tertiary times.

New Guinea.—If attention be turned, however, to the north-eastern part of Australia, it will be found that as geological time progressed, the area occupied now in part by New Guinea was built to the south and west. An excellent epitome of the main features of structure known to date has been supplied by Professor T. W. E. David.[1] Schists outcrop at very high altitudes along its northern portion, while strongly folded Cretaceous Strata are reported to occur at the highest altitudes in the north, their steep dips ending abruptly against a high and deeply dissected plateau surface. For 50 or 60 miles inland from the south, the area consists of middle and late Tertiary strata, all intensely folded, and all beveled off by a high plain, probably one of submarine erosion. The knowledge of this strong orogenic movement in late or closing Tertiary time and the excavation of a plain of erosion within folded sediments of this age was established by Carne while doing pioneering work in the oil industry.[2]

[1] "Geology of Papua" (Federal Handbook), *Brit. Assoc. Adv. Sci.*, Australian meeting, 1914, pp. 316–25.

[2] J. E. Carne, *Bull. of the Territory of Papua, No. 1*, Dept. External Affairs, Melbourne, 1913, pp. 19–29.

David's conclusion is:

In regard to the broad tectonic features of Papua it may be suggested, very tentatively, that the mainland of Australia has functioned as a "foreland massif," Torres Straits, the Gulf of Carpentaria, the Arafura Sea, and the deep Mesozoic and Tertiary basins with their thick strata as a *Senkungsfeld.* Possibly the crystalline schists forming a great part of the backbone of the island have played the part of an inner, or *rück-land* massif which has helped to roll up the Mesozoic and Tertiary sediments.[1]

In passing, it may be mentioned that this simply raises the question again as to the origin of the forces of crumpling. Do they act from the land as suggested by Suess in his discussion of the Asiatic framework, or do they act from the oceans? If the movements be assumed to act as from Central Australia toward the oceans, then it is difficult to understand the stability and rigidity of such central area of force. If the source of energy is suboceanic and directed toward the continents, then it is difficult to explain the growth of Australia north and east, while that of New Guinea appears to be south and west, unless, indeed, it be assumed gratuitously that the later foldings in Northeastern Australia are simply the expressions of orogenic movements dying away in a southwesterly direction from the Pacific. Even so the intense contortions evidenced in the Miocene and Pliocene beds might be expected on the northeastern aspect of New Guinea rather than on the south and southwestern. It would seem, indeed, as though each negative or heavy area had played a part in the movements.

New Caledonia.—In New Caledonia the Mesozoic sediments have been intensely folded, especially on the western and southwestern aspects, and the overfolding appears to have been directed toward Australia, according to Peletan, Depiet, Piroutet, and others as quoted by Suess.[2]

New Zealand.—In turning to a consideration of New Zealand we meet with a certain amount of disappointment, inasmuch as there is no consensus of opinion among the workers on certain fundamental points. Thus a glance at Dr. J. W. Gregory's map in the article on New Zealand in the eleventh edition of the *Encyclopaedia*

[1] T. W. E. David, "Geology of Papua," *op. cit.*, pp. 324–25.

[2] *Die Antlitze der Erde* (Eng. tr.), IV, 314–15.

Britannica suggests that this island group was built principally as from southwest to east and north, or at any rate that with the progress of geological time folding movements retreated to the north by east. Marshall, however, in a personal communication, under date of April, 1916, states that much of the New Zealand Jurassic has been confused with the Maitai (so-called Carboniferous) by older workers. Marshall, however, adduces sound reasons for considering New Zealand as being the true boundary of the Pacific Ocean[1] in that portion of its area. Cotton in a recent paper states that the "most profound deformation of this vast sedimentary group [Paleozoic and Mesozoic] took place in Later Jurassic or Early Cretaceous times."[2] He also states that the average trend of the strike of this older mass appears to be west of north (p. 245). And again he writes: "It is apparent that during the period of their deposition [that is, the Tertiary Andes] a great part of the site of the present islands of New Zealand was continually submerged" (p. 247).

Cotton also speaks of orogenic movements in the Pliocene in the northern and more eastern portion of the group, and it is known, moreover, that great volcanic activity has taken place in the northeastern portion of the group with the formation of important gold deposits.

In a personal communication dated August 22, 1916, Cotton writes:

> The early geological history [of New Zealand] is much obscured by the later happenings—a great deal more so, it would appear, than is that of Australia. We cannot even be sure that we have any considerable area of Paleozoic rocks. The small areas of Ordovician and Silurian in northern Nelson we can be certain of, but we know nothing whatever of the relations of these, either to each other or to rocks of later Paleozoic or Mesozoic age. It is the opinion of the present director of the Geological Survey that the greywacke rocks extending southward along the West Coast are of Aorere (Ordovician) age; but they contain no paleontological evidence of age and are part of the "Maitai" system of other writers. As for the "Maitai" rocks throughout

[1] P. Marshall, "Presidential Address," *Geological Section Aust. Assoc. Adv. Sci. Sydney*, XIII (1911), 90–99.

[2] "The Structure and Later Geological History of New Zealand," *Geol. Mag. London*, No. 624, June, 1916.

New Zealand, there seems to be no reason now for classing them as Paleozoic. As regards the Manapouri rocks of southwestern Otago, they may, of course (with the exception of some intrusives), be very ancient; but their relations to other systems are absolutely unknown. It may be that this is an upfaulted block from which a Mesozoic cover has been removed. So far as I know there is no evidence of later formations having been folded against it.

The remarkable flat-lying schists of central and eastern Otago are, again, of indefinite age. Marshall regards them as metamorphosed Mesozoics. He traces a transition to the unaltered "Maitais," but in eastern Otago, along the junction of the schist and greywacke rocks there is a complex of faulted blocks (greywacke now forming the surface in some and schist in others) which had, there can be no doubt, been planed down before the deposition of what I call the "covering strata." Later faults, which affect the cover also, have sometimes followed the lines of the older breaks, *but have reversed the throw.*

As to the direction of folding in New Zealand I have formed no opinion. The latest or Kaikoura folding was accompanied by the formation of great reverse faults in the northeastern part of the South Island, and these hade to the northwest. Many small reverse faults in the Wellington neighbourhood, which intersect (?) Triassic rocks and were *perhaps* developed during the Mesozoic period, hade in the same direction.

One question of great importance is that of the source of the enormously thick "Maitai" sediments, which consist, from end to end of New Zealand, almost universally of the little-worn detritus from acid igneous rocks. Evidently these deposits accumulated not far from a great land mass, but I know of no evidence as to the position of that land mass. Apparently the New Zealand area sometimes formed a part of the continent, for at a number of places there are deposits containing Mesozoic plants.

So far as I know there was no strong folding accompanying the formation of the Hauraki gold deposits, but there have been considerable "block" movements since.

EVIDENCE OF THE ORE DEPOSITION

It is proposed here to see what light may be thrown on the possible structural relations or differences of Australasia, New Guinea, and New Zealand, by a study of the peculiarities of ore deposition in certain areas within these regions. In this connection it is proposed to deal principally with one set of minerals only, namely, the tin group, although conclusions equally interesting would have been forthcoming from a consideration of the gold and copper, together with the silver-lead and zinc groups.

Thus with regard to gold it would have been possible to elaborate with a wealth of detail the knowledge that the gold deposits of

West Australia are found in the great area of pre-Cambrian rocks there developed, and, moreover, that they occur in belts arranged more or less parallel and relatively narrow in width, although in certain localities they appear as small isolated areas or patches; that these narrow and well-defined belts have a general northwest and southeast direction, with divergences in certain instances of several degrees on either side of this direction; that the ore deposits in these belts or zones, owing to certain activities, do not crop out in long and unbroken lines, but are cut up into relatively short lenticles, arranged *en echelon.*

Table I gives the approximate values of the several metals mined in these countries.

TABLE I

Approximate Total Values, in Millions of Pounds Sterling, of the More Important Metals Mined in Australasia and New Zealand

	Gold	Copper	Silver-lead	Zinc	Tin	Wolfram	Bismuth	Molybdenite
West Australia..	73.00	11.00	....	....	1.00	....	....	....
North Territory.	2.10	0.20	....	....	0.33	0.04	....	....
South Australia.	1.00	30.00	0.33	....	....	....	....	....
Tasmania.......	7.50	11.50	6.50	....	12.00	0.05	0.02	....
Victoria.......	300.00	0.25	0.006	....	0.80	0.005	....	....
New South Wales........	62.00	13.50	74.00	12.00	10.50	0.25	0.166	0.10
Queensland.....	80.00	11.50	2.25	....	8.50	0.80	0.125	0.25
New Zealand....	85.00	0.02	....	....	....	....	....	....

The general direction of these auriferous belts almost everywhere coincides with the strikes of the schists, which, with one or two exceptions, invariably form the matrices of the gold-bearing reefs. . . . . The quartz reefs are of two distinct types, namely, white quartz reefs and laminated quartz and jasper veins approaching very closely the hæmatite-bearing quartzites which invariably form a conspicuous feature in most of the gold fields of the State. Some of the laminated quartz veins range from almost-pure quartz, through banded jaspers, with crystals of magnetite, to bands appearing to the eye to be virtually pure haematite. The quartz reefs, of what may be called the massive types, occur plentifully in both the schists and the granites.[1]

Like the gold deposits of Western Australia those of the Northern Territory and of South Australia appear to be pre-Cambrian

[1] A. Gibb Maitland, "Mining Fields of Australia" (Federal Handbook), *Brit. Assoc. Adv. Sci.*, Australian meeting, 1914, pp. 447–48.

in age, although there are certain indications of relative youth in the gold deposits of the Northern Territory and South Australia. Eastward, in the old trough lying within New South Wales and Victoria, now filled with Cambro-Ordovician and infolded Silurian sediments, occur the most important gold deposits of Australasia, especially the famous saddle reefs of Bendigo, Ballarat, Canbelego, and other localities. Immediately to the east and north lie the ore deposits beyond the Hunter zone of weakness where Benson's line of serpentine occurs with its gold deposits of Carboniferous age. Beyond, but parallel, or subparallel, with these, are the great gold fields of the closing Paleozoic period in New England and Eastern Queensland, as, for example, at Hillgrove, Gympie, Mount Morgan, and the Palmer. It might be mentioned that, although no gold deposits appear to have been formed in Australia since that momentous period, nevertheless the important gold deposits of the North Island of New Zealand are of *late Tertiary age.* It might be mentioned here that the gold deposits of Southwestern New Zealand appear to occur in Paleozoic rocks.

Or it would have been interesting to enlarge upon the facts connected with the copper deposits of Australia: how in the west they are of pre-Cambrian age, according to Maitland and his geological staff; how the nature of the deposits there suggests deposition at a great depth below the old land surface; how the copper deposits of great but of unknown age, in the Northern Territory, South Australia, Western New South Wales, and Tasmania, as, for example, at Wallaroo, Moonta, Burra Burra, Cobar, Nymagee, and Mount Lyell, do not appear to be dependent upon ordinary igneous rock types, but, from an examination of the reports of Ward, Jack, J. W. Gregory, and the writer, they appear to be the equivalents themselves of igneous rocks because of their peculiar mineral assemblages; how with these famous deposits might be mentioned the great Broken Hill deposit of silver-lead and zinc which is apparently a replacement of schists by garnet, rhodonite, feldspar, and sulphides, owing to the action of vapors arising along a shear zone;[1] how the arrangement *en echelon* of these metalliferous areas and the individual ore lenses within such areas must be sig-

[1] E. C. Andrews, "Broken Hill Lode," *Economic Geology*, October, 1908, pp. 643–45.

nificant in the extreme. It would be instructive also to tell how, in New England, the copper and the gold which were introduced during the Carboniferous folding of Benson occur in the same deposits as a rule, as also do those of the closing Paleozoic both in New England and in the more coastal portions of Eastern Queensland (examples, Drake and Mount Morgan); how also in the Carboniferous of New England the copper and gold depend upon the serpentine belt for their existence, whereas in the Permo-Carboniferous they are related to lamprophyric dykes and basic granitic types.

In New Guinea the copper deposits appear to be in very ancient rocks, whereas in New Zealand copper is practically absent.

The tin group of minerals.—Turning, however, from these interesting points to the tin-wolfram–molybdenite-bismuth group of minerals in Australia, it may be noted that all four may occur together in certain ore deposits in this continent, but as a rule the deposits of commercial importance may be classed under two main heads. Thus tin is frequently associated with wolfram, whereas molybdenite is associated with bismuth. Should molybdenite and bismuth be associated with other minerals of the group, the preference is for wolfram rather than for tin. Indeed, the minerals associated with tin and wolfram, such as tourmaline, topaz, beryl, and quartz with rutile, are practically unknown to the writer in connection with molybdenite deposits.

All these minerals in Australia—tin, wolfram, molybdenite, and bismuth—are associated with siliceous granites or their equivalents. In New South Wales the typical tin-wolfram granites range from 75 to 79 per cent silica, while the typical molybdenite-bismuth types range from 72 to 74 per cent silica. These various granites may be distinguished easily by their peculiar vegetation, and appear to have been the hosts of the tin-molybdenite minerals in Australasia. The vapors which conveyed the minerals of the tin group to the marginal portions of the granites, preferably the roofs, or upper and lateral portions, appear to have varied in their power of penetration. Thus the tin and wolfram deposits, with their boric and fluoric associates, are found in many places at slight distances from the siliceous granites themselves, in rocks such as slate, basic igneous rock, or quartz-porphyry. Always, however, the tin minerals may be seen to be intimately related to the siliceous granites. The molybdenite deposits are almost always within the marginal development of the siliceous granites, while tourmaline, topaz, and allied minerals are characteristically absent. Contact deposits of molybdenite in Australia, as, for instance, at Yetholme (New South Wales), are rare.

Although these granites in Australia accompanied strong folding movements, and although ore deposits in that continent appear to have been dependent upon strong folding phenomena, nevertheless it must not be inferred that all periods of folding in Australasia have been associated with the formation of ore deposits on a commercial scale, but simply that all ore deposits of commercial importance in Australasia are intimately related in some way to periods of folding. This statement refers, naturally, only to deposits of the metallic minerals.

a) Western Australia: The vast area of Western Australia consists, in the main, of highly altered rocks of pre-Cambrian age. These schists and allied types are intruded by siliceous granites and allied rocks, which also are considered to be pre-Cambrian in age. "The old granite rocks are traversed by many large ice-like quartz reefs. . . . . These older granite rocks . . . . form the matrices of the tin and allied deposits of the state."[1]

This mineral has been found to the extent of about 14,000 tons in Western Australia, while wolfram is subordinate in amount. Molybdenite has been recorded in small scattered flakes from this area.

b) Northern Territory: The rocks of the Northern Territory are extremely old, probably pre-Cambrian in many places. Tin and wolfram to the values respectively of £400,000 and £40,000 approximately have been won from the Northern Territory. Molybdenite has been reported, but it has not been worked as yet.

c) South Australia: The ore deposits of South Australia are very old. Tin, wolfram, and molybdenite have been found in this state, but the amounts won are too negligible to be considered.

[1] A. Gibb Maitland, "Mining Fields of Australia" (Federal Handbook), *Brit. Assoc. Adv. Sci.*, Australia meeting, 1914, pp. 446–47.

d) Tasmania: The tin, wolfram, molybdenite, and bismuth deposits of Tasmania are considered to be of closing Silurian or early Devonian age.[1]

The tin production exceeds £12,000,000 and the wolfram £50,000 in value. Molybdenite has not been worked, but bismuth to the extent of about £200,000 value has been won.

e) Victoria and Southeastern New South Wales: In Victoria the age of the tin, wolfram, molybdenite, and bismuth deposits is not known definitely. The value of the tin won is slightly less than £1,000,000, that of the wolfram about £5,000, while molybdenite and bismuth have been found only in very small quantities.

Probably Victoria and Southeastern New South Wales form one geological province, and in the latter area the tin and allied minerals may be considered as of post-Devonian and of pre-Permo-Carboniferous age. Tin is relatively rare, but molybdenite and bismuth are abundantly represented.

f) Northeastern New South Wales and Eastern Queensland: The northeastern portion of New South Wales appears to be a province geologically distinct from that of the southeastern portion of the state, and the tin, wolfram, molybdenite, and bismuth deposits found there appear to be closing Paleozoic in age. These deposits are confined to a strip less than 150 miles from the coast. The commercial molybdenite and the bismuth occur within the eastern zone, while the commercial tin occurs within the western zone. The small deposits of the far west, near Broken Hill, for example, apparently are of very early Paleozoic age, and they really belong to the South Australian region or province.

The value of the tin won from New South Wales exceeds £10,500,000, the wolfram values approximate £200,000, the bismuth £150,000, and the molybdenite about £100,000.

In this connection it should be remembered that until 1902 molybdenite was considered as an impurity in the bismuth, its

[1] W. H. Twelvetrees, "The Scamander Mineral District," *Bull. No. 9, Geol. Survey, Tasmania,* 1911, p. 23–24; other official reports of great interest dealing with the subject of mineral deposits in Tasmania are by L. K. Ward, Loftus Hills, and L. L. Waterhouse.

inseparable associate in New South Wales; thus great amounts of the molybdenite have been lost.[1]

Queensland, in its eastern portion, should be considered as belonging, probably, to the same geological province as New England, or Northeastern New South Wales.

The tin, wolfram, molybdenite, and bismuth deposits are found only within the eastern strip of the state, and their age appears to be the close of the Permo-Carboniferous. The granites and mineral associations of the two areas are almost identical also. Thus this great province of Eastern Queensland and New England, which has yielded the bulk of the world's supply of molybdenite, lies on a great flat arc having a general trend of northwest to north-northwest. These ore deposits are associated with strong movements of folding, the age of which appears to be closing Paleozoic.

The approximate values of the tin, wolfram, molybdenite, and bismuth won from Queensland are respectively £9,000,000 to £10,000,000, £1,000,000, £250,000, and £150,000.

It would thus appear that the deposits of the tin and molybdenite group of minerals in the great geological province of Western Australia, South Australia, and the Northern Territory are of great age, but that they are almost negligible in commercial value. It is not known, however, what proportion of this absence is due to removal by erosion of the upper portions of the granites. The deposits of this group in Tasmania may be of closing Silurian or early Devonian age, the tin values being very large, but wolfram, molybdenite, and bismuth are unimportant; the deposits of the geological province of Southeastern Victoria and Southeastern New South Wales are important and are post-Devonian and pre-Permo-Carboniferous in age; while the deposits of the province of New England and Eastern Queensland, forming a coastal fringe to Northeastern Australia, are highly important from a commercial point of view and appear to be closing Paleozoic in age.

[1] Official reports have been written on the tin and molybdenite areas of New South Wales by T. W. E. David, J. E. Carne, and the writer, while Professor Leo A. Cotton has published reports on the tin of New England in the *Proc. Linn. Soc. N.S. Wales* XXXIV (1909), 738–81; Cotton intends to continue the study of tin genesis in Australia in the near future.

All of these Australasian deposits are intimately related to strong movements of folding, accompanied by intrusions of very siliceous granite.

No molybdenite, bismuth, wolfram, nor tin of any commercial importance whatever appears to have been found in New Guinea, New Caledonia, or New Zealand, although molybdenite and allied minerals have been recorded as curiosities in older Paleozoic granites in New Zealand. Neither are there in New Zealand any important copper deposits similar to those which are so intimately associated with the gold, tin, and molybdenite in Australasia.

CONCLUSION

It is therefore permissible, perhaps, to infer that each of the three great groups, namely Australia, New Guinea, and New Zealand, is a distinct geological province, but whereas in New Guinea the movements appear to have opposed the Australian growth with a tendency to fill the intervening negative area; on the other hand the growth of Australasia and New Zealand appears to have been intimately related in some manner, as though each had grown sympathetically in response to some simultaneous dominating agency. The folding action ceased in the Australasian area long before it did so in the New Zealand area. The foldings in New Guinea also were maintained right into recent geological time.

Here again the ore deposits proclaim the independence of the three centers. The oil fields of New Guinea suggest the Burmese or Malaysian origin of the New Guinea lines of structure,[1] and in a similar way the tin-wolfram–molybdenite-bismuth group of minerals appears to mark the real limits of Australasia. A little of the molybdenite group occurs in the New Zealand area, in the very old rocks, but the group as a whole, with its grand suite of siliceous granite horsts, may be said to end at the east side of Australasia. Moreover, as the folding movements retreated east and west, with progress of time they appear to have passed away finally to the northeast from Southwestern Australia toward New Caledonia.

[1] T. W. E. David, "Geology of Papua" (Federal Handbook), *Brit. Assoc. Adv. Sci. Australia*, 1914, p. 320.

It is therefore permissible, perhaps, to infer that the Tasman Sea is of great age, especially in its more southern portions, inasmuch as it appears to have been a barrier to common or related ore deposition between Australasia and New Zealand through the ages.

This of course does not imply that Australasia and New Zealand have not been closer together in the past, nor that Australasia has not extended considerably farther to the east in former times, especially in its northeastern portions; it simply suggests that some great agency which controlled the growth of Australasia and New Zealand appears to have admitted a negative or relatively sunken area from early times in the region of the Tasman Sea, and that this agency had faded away to epeirogenic movements in the Australasian area while yet it was vigorously folding the New Zealand rocks.

All this appears to be in harmony with the general contention of Marshall[1] who maintains that New Zealand, and not Australia, lies on the real border of the Pacific. Marshall, however, approaches the subject from a point of view entirely different from that taken in the present note.

[1] P. Marshall, "Presidential Address," *Geological Section, Australian Assoc. Adv. Sci. Sydney*, XIII, (1911), 90–99.

A BOTANICAL CRITERION OF THE ANTIQUITY OF THE ANGIOSPERMS

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As to the origin of the angiosperms, that group of seed plants which is now such a dominant element in the earth's vegetation, we know almost nothing. They first appear as fossils in the deposits of the lowest Cretaceous in eastern North America, Alaska, Greenland, and Portugal, but just where they actually originated, and how long ago, are still matters of great uncertainty. The aim of the present paper is to throw a little light on the antiquity of this great plant group by studying the rate of evolution displayed by its members.

Evolution has not been a uniformly rapid process. The fact that plants recognized as "primitive" and others recognized as "recent" exist together at the present time makes it evident that certain vegetable types have changed but little throughout long geological periods, whereas others have for one cause or another become altered much faster. The degree of inherent "variability" and the frequency of hybridization have doubtless been influential in determining this rate of change, but a more important factor perhaps than either seems to be the length of the generation or period from seed to seed. A plant in which this cycle is completed in a year or two is able to multiply its generations more rapidly, and thus to accumulate heritable changes much faster, than one which requires a longer time for the attainment of reproductive maturity. This length of generation is definitely correlated with the growth habit of the plant, being greatest in trees—which usually reach an age of from fifteen to twenty years (in many cases much more) before bearing fruit—less in shrubs, and shortest of all in herbs, where one or two seasons from seed suffice to produce a fruiting plant again. In a given length of time, therefore, a herbaceous species will pass through a much larger number of generations than a woody one, and will consequently tend, other factors being equal, to become changed in type much more rapidly. We should thus expect the herbaceous element in the vegetation to have been evolved at a much faster rate than the woody element. The establishment of this as a fact, taken with what we know as to the history and present numerical status of herbs and woody plants, will provide us with a valuable clue as to the antiquity of the angiosperms.

That herbs are indeed subject to more rapid changes than any other plant type is indicated by the fact that the first local species and genera to develop in a region subsequent to its isolation have apparently almost always been herbs. This is well illustrated by a comparison of the floras of temperate North America and of Europe. On these continents today there are many local or "endemic" genera which are limited in their distribution to one or to the other. Certain of these are evidently "relict" endemics, isolated survivors of types once much more widely disseminated. They may be recognized from the fact that they stand without near relatives in the floras; and many of them, such as sassafras and hickory, occur as fossils on both sides of the Atlantic. These relicts doubtless constitute a very ancient floral element, and it is significant that among them are practically all the genera of trees and shrubs which are local to either North America or Europe. The majority of the endemic genera, however, seem to belong to quite a different category, for they occur in groups of from three to twenty genera, the members in each of which are closely related to one another, each group apparently to be looked upon as a separate center of evolution and the nucleus of a new family. The genera centering around *Lesquerella* in the Cruciferae, around *Eriogonum* in the Polygonaceae, around *Godetia* in the Onagraceae, around *Pentstemon* in the Scrophulariaceae, and around *Solidago* in the Compositae, are a few of the sixty or more such groups in the dicotyledonous flora of North America, and there are as many in Europe. These "indigenous" endemic genera most probably had their origin on their respective continents, since a free interchange of plants between America and Europe was interrupted, presumably in the Early or Middle Tertiary; for had they existed before that date in anything like their present numbers and importance, it is highly unlikely that they would now be represented in the floras of both hemispheres. During the time since the isolation of the two continents, and while the rest of the flora have remained unchanged or have been developing endemic species merely, these plants have evidently undergone much wider changes, until they have finally given rise to new generic types. We are thus forced to conclude that the indigenous endemic genera constitute the most rapidly evolving members of their flora; and it is significant that they include practically nothing but herbaceous species—surely excellent evidence that the herb changes in type more rapidly than the tree or the shrub.

Further evidence pointing to the same conclusion is presented by a study of the distribution of herbs and of woody plants in the modern scheme of botanical classification, for herbs are found to occur in larger groups than woody plants, their genera containing more species and their families more genera. Monotypes and very small genera and families are very much less common among herbs than among woody plants. These facts are what one might expect on the supposition that herbs are changing faster than the rest of the angiospermous vegetation, for the more rapid production of new forms leads to the building up of larger aggregations, and enables genera or families which have become reduced in size through extinction to repair these ravages quickly.

A study of the structure, distribution, and ancestry of herbaceous angiosperms[1] indicates that they have been evolved in comparatively recent times from a woody ancestry, and have undergone practically their whole course of development since the beginning of the Tertiary. As opposed to this rapid change among herbs, we know from fossil evidence that very many woody genera have existed with very little alteration for a much more extended period than the length of the Tertiary—a convincing demonstration of the slowness with which trees and shrubs undergo evolutionary change. Almost all our woody genera bear evidence, in present

[1] E. W. Sinnott and I. W. Bailey, "The Origin and Dispersal of Herbaceous Angiosperms," *Annals of Botany*, XXVIII (1914), 547–600.

distribution or fossil remains, of a considerable degree of antiquity.

To corroborate this testimony as to the relative rapidity of evolution in herbs and in woody plants, data as to their actual rate of change today would be highly desirable; but this is very difficult to obtain. As far as differences in "variability," using the term in its broadest sense, are concerned, the two growth forms seem nearly equal. In both there are many highly variable types and many of great constancy. In the floras of three representative regions—Eastern North America, Australia, and Ceylon—the proportion of varieties and named forms among the woody species is found to be practically the same as among herbs. Nor is there a radical difference between the two in the extent of cross-pollination by insects, although in temperate regions this is somewhat more common among herbs than among trees and shrubs. The difference in length of generation to which we have called attention is probably the most important factor in determining the rate at which they have evolved.

To whatever cause we may attribute it, however, there seems to be little doubt that during the evolution of the angiosperms the primitive, woody element has been developed very much more slowly than the more recent, herbaceous one; and it is this difference which gives us a hint as to the antiquity of the whole group. We find in the angiosperm flora today (dicotyledons alone considered) over 4,200 genera of trees or shrubs, as opposed to only 2,600 genera of herbs. We may be reasonably sure that practically all of these 2,600 genera of herbs have been developed since the beginning of the Tertiary; and if we assume that herbs are producing new types only twice as fast as trees and shrubs—surely a conservative estimate—we must believe that only about 1,300 woody genera have been evolved during the same time. The evolution of the 4,200 genera of woody plants at present existing, to say nothing of the great numbers which have been lost through extinction (by which trees and shrubs have suffered much more than herbs), would therefore require a period at least thrice the length of the Tertiary. If the common assumption that the Tertiary was approximately as long as the Cretaceous is correct, the origin of the angiosperms would thus be thrust back to a date much earlier than the beginning of the Cretaceous.

Of course such an estimate is hypothetical in the extreme; but by indicating that the history of the woody members of the group extends back over a period many times as long as that during which herbs have existed, it serves to give us a clue as to angiosperm antiquity, and it emphasizes the fact that our present huge array of trees and shrubs, types very slow in changing, must have required an enormous length of time for their evolution. There is evidence, moreover, that evolution took place even more slowly in former times than it does at present, since flower-loving insects, to the agency of which many attribute the rapid development of the angiosperms, did not appear on the scene, at least in numbers, till the dawn of the Tertiary.[1] All this makes it highly probable that these now dominant seed plants did not begin their existence in the early Cretaceous, where they first appear as fossils, but that they had already undergone a long course of evolution before that time. Indeed, the external features, and more particularly the internal anatomy, of these earliest fossil angiosperms are not at all those of primitive types, but exhibit a considerable degree of specialization.[2] To regard such plants as having sprung suddenly into being from gymnospermous ancestors is to overtax the imagination of even an ultra-mutationist.

As to why the earliest members of the group apparently failed to be preserved we cannot be sure, but evidence is at hand that they were upland forms which would tend less frequently to become fossilized. This predilection of primitive angiosperms for an equable, reasonably cool climate, if it can be proved, will lead us to look back to the era of low temperatures in the Jurassic, or perhaps even to as remote a period as the cataclysmic refrigeration of the Permian, for the date when the first angiospermous stock began to be differentiated from its gymnospermous ancestry.

The botanical evidence is therefore overwhelmingly in favor of the conclusion that angiosperms existed for a considerable period

[1] Handlirsch, *Die fossile Insecten.*

[2] M. C. Stopes, "Petrifactions of the Earliest European Angiosperms," *Phil. Trans. Royal Society*, B, 203, pp. 75–100.

previous to the Cretaceous, although this cannot be said to be absolutely proved till they are brought to light as fossils from the earlier periods of the Mesozoic, a discovery which diligent search may reasonably be expected to yield. The establishment for the angiosperms of an antiquity greater than that usually accorded them at the present time will be of some importance geologically, since the occurrence of fossil members of the group in a given formation will no longer be regarded as a demonstration of the post-Jurassic age of the latter.

ARE THE "BATHOLITHS" OF THE HALIBURTON-BANCROFT AREA, ONTARIO, CORRECTLY NAMED?

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The large areas, composed essentially of banded red gneiss, which are found throughout the Haliburton-Bancroft area have been called by Adams and Barlow "batholiths."[1] These appear on maps of this region as circular or oval masses more or less completely surrounded by sediments or schists of sedimentary origin. The stratification of these sediments follows in strike the boundaries of the adjacent gneiss. Moreover, within the gneissic areas are layers of amphibolite or gray gneiss which conform in dip and strike to this same boundary. The gneissic areas, therefore, may be described as domes of red granite gneiss containing gray gneiss and amphibolite in layers striking concentrically to points more or less fixed within the mass and dipping quaquaversally at angles which vary from 37° to 45°.

In his earlier writings, F. D. Adams stated three views as to the origin and method of emplacement of the "Fundamental Gneiss."

1. The Fundamental Gneiss may be the remains of a primitive crust which was penetrated by great masses of igneous rocks and subjected to successive dynamic movements. The Grenville series may be an upward continuation of the Fundamental Gneiss under altered conditions, marking a transition from a primitive crust to normal sediments.

2. The Grenville series may be considered as distinct from the Fundamental Gneiss and reposing on it unconformably, being a highly altered series of clastic origin; the Fundamental Gneiss having some such origin as suggested above or being an older intrusive series of still more highly altered sediments.

3. The fundamental Gneiss may be considered as a great mass of eruptive rock which has eaten upward and penetrated the Grenville series, while the

[1] *Geol. Surv. Can., Mono.*, VI (1910), 12.

Grenville series represents a series of altered sediments of Laurentian, Huronian, or subsequent age.[1]

Adams in the same article stated that the last hypothesis was untenable.

The world-wide distribution of the Fundamental Gneiss (forming, as it does, wherever the base of the geological column is exposed to view, the foundation upon which all subsequent rocks are seen to rest) is opposed to this view as is also its persistent gneissic or banded character.[2]

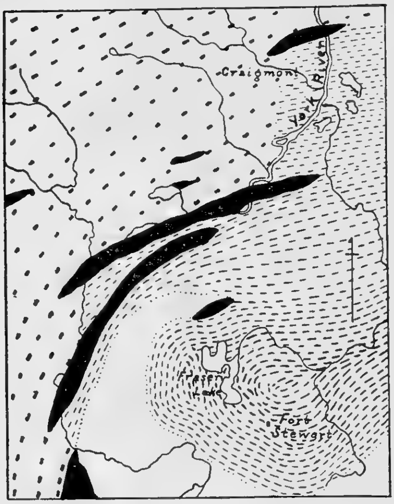

FIG. 1.—Map of the corundum syneite district of Craigmont, Ontario.

Black, limestone; white, amphibolite; dashed, gneissic granite; dotted, gneissic granite with amphibolitic inclusion.

Later, in 1897, Adams altered his earlier view. He writes:

The batholiths are undoubtedly formed by an uprising of the granitic magma from below, and these foci indicate the axes of greatest upward movement. These centers are not all areas of most rapid uplift, however. On the contrary, the gneissic foliation in some cases dips inward in all directions toward the center, thus marking them as places where the uprise of the magma was impeded, that is to say, places where the overlying strata have sagged down into the granite magma.[3]

A striking fact concerning these so-called batholiths is that they do not cut across the structure of the invaded rocks, a fundamental characteristic by which post-Cambrian batholiths are recognized. While it is true that there are bodies within the district which cut across the structure of the country rock, they are unusual, and concordant relationships are much more common.

A glance at the map (Fig. 1) which shows the corundum syenite district of Craigmont, Ontario, makes clear the concentric arrangement of the sedimentary rocks within the gneiss areas.

[1] *Journal of Geology*, I (1893), 330–32.

[2] *Op. cit.*, 332.

[3] *Am. Jour. Sci.*, III (1897), 173–80.

The granite was intruded between the layers of limestone. As in the present case, long narrow layers of limestone are often found isolated in the gneiss. These layers are in parallel bands and the strike of their stratification conforms to the strike of the gneissic structure of the surrounding granite.

If the boundary between gneiss and pure limestone is sought, it will invariably be found that there is a transitional contact zone. The distinction between areas which may be designated as "Gneiss with amphibolitic inclusions" or "Amphibolite" or "Limestone invaded by much gneiss" depends upon the degree to which the granite has invaded the limestone and altered it to amphibolite. In general, on crossing the strike from limestone to amphibolite, there is a gradual transformation of one rock into the other. The amphibolite in turn is transitional to red gneiss through the intermediate stage of gray gneiss. Xenoliths of amphibolite within the gneiss are in no degree so abundant as stringers of amphibolite varying from a few centimeters to a meter in diameter and the schistose structure of which conforms to the gneissic structure of the granite and the stratification of the limestone.

Adams[1] attributes the parallel arrangement of these bodies to movements of the granite after intrusion. He conceives that the limestone blocks, stoped from the roof of the batholith, were softened by heat and pulled out into lenses by flowage.

The parallel banding of pre-Cambrian rocks is not a local feature, illustrated only in the rocks of the Haliburton-Bancroft area. It is, rather, characteristic of most pre-Cambrian terranes. The interbanding of gneiss of igneous origin with sediments is shown by Lawson in his study of the Lake of the Woods. Högbom[2] has described similar relationships which are shown by the rocks about Upsala, Sweden.

The gneiss of the pre-Cambrian of the Adirondacks is so mingled with limestone and other sediments that for years it has been a mooted question whether to consider it of igneous or sedimentary origin. It forms lenses and sheets in the sediments, or traverses them so irregularly that an exact interpretation is difficult.

[1] *Can. Geol. Surv., Memoir No. 6* (1910), 73–78.

[2] *Bull. Geol. Instu., Univ. Upsala*, X (1910–11), 39.

However, C. H. Smyth, Jr.[1] and H. P. Cushing[2] now consider them igneous.

The gneisses of the Highlands of New Jersey may be described in similar language. These are considered by W. S. Bayley[3] and C. N. Fenner[4] to be sediments invaded by granite.

G. M. Dawson writes as follows concerning the Shuswap Terrane of British Columbia:

> The Shuswap rocks proper evidently represent highly metamorphosed sediments with perhaps the addition of contemporaneous bedded volcanic materials. . . . . These bedded materials are, however, associated with a much greater volume of mica-schists and gneisses of more massive appearance, most of which are evidently foliated plutonic rocks, and are often found to pass into unfoliate granites. The association of these different classes of rocks is so close that it may never be possible to separate them on the map over any considerable area. . . . .
>
> A distinct tendency to parallelism of the strata or foliation with adjacent borders of the Cambrian system has been noted in a number of cases. This might imply that the foliation was largely produced at a time later than the Cambrian, but materials of some of the Cambrian rocks show that the Shuswap series must have fully assumed their crystalline character before the Cambrian period. *It seems, therefore, probable that the foliation of the Shuswap rocks may have been produced rather beneath the mere weight of superincumbent strata than by pressure of a tangential character accompanied by folding.*[5]

R. A. Daly, in a recent report on this same series, states that it has been injected by innumerable sills and laccoliths. He concludes:

> The extraordinary prevalence of sills and other concordant injections is explained by the extreme fissility of the Shuswap sediments and greenstones. This feature is due to static metamorphism.[6]

Two hypotheses are offered, therefore, to explain the parallel banding of pre-Cambrian rocks. In the Haliburton-Bancroft area, Adams conceives that, in the process of intrusion by magmatic

[1] *N.Y. State Mus., 41st Ann. Rept.*, II (1899), 469–97.

[2] *Bull. No. 115*, N.Y. State Mus. (1907), 451–531.

[3] *U.S.G.S., Raritan Folio*, No. 191.

[4] *Journal of Geology*, XXII (1914), 594 ff.

[5] *Bull. Geol. Soc. Am.*, XII (1901), 63–64.

[6] Ann. Rept. Dept. Mines, *Can. Geol. Surv.* (1911), 3–12.

stoping, blocks of limestone were torn from the roof of the invading granite batholiths and elongated parallel to the contact of the granite and limestone by movements of the granite as it consolidated.

Daly believes that static metamorphism produced planes of weakness within the Shuswap series and that sills of granite were intruded along these planes.

Fenner,[1] discussing the method of intrusion of the granites of the New Jersey Highlands, states that in his opinion gaseous emanations from the granite magma penetrated the sedimentary rocks along planes of weakness and prepared the way for the intrusion of granitic fluids. The intrusion of these fluids produced banded gneisses.

It is, of course, entirely possible that intrusion in the Haliburton-Bancroft region took place by magmatic stoping and that this region is not analogous to the others described. The rock types vary within the several areas and there is, necessarily, a corresponding change in the structural relations. The limestones of the Grenville series would undoubtedly be more altered by the metamorphic effects of the granite than the quartzose rocks of the New Jersey Highlands and the Shuswap series.

It seems to the writer, however, that the facts shown by the study of the Glamorgan gneissic area favor the theory of intrusion by parallel penetration along planes of weakness rather than the theory of intrusion by magmatic stoping.

If intrusion took place by magmatic stoping, the following conditions must be postulated. The objections to each of these conditions are noted.

1. The blocks from the roof of the batholith were stoped off and elongated parallel to the contact.	1. Intrusion by magmatic stoping usually produces an irregular molar contact. The igneous rock cuts the sediments. Though the blocks were elongated parallel to the contact, this would not, except by chance, be parallel to the stratification of the sediments, and yet this is the relationship of the banded structure of the rocks of the Haliburton-Bancroft area.

[1] *Journal of Geology*, XXII (1914), 594 ff.

2. Adams postulates that the elongation of the blocks occurred in the later stages of batholithic intrusion as the granite solidified.

2. It would seem necessary that this should be true; for a hot, fluid magma, if too hot would melt the blocks and incorporate them into a homogeneous magma. If it were too cold it could not elongate them. The necessary conditions for the production of parallel elongation, therefore, is a narrow temperature range within which the blocks remain viscous. This would be found, it would seem, at a more or less constant distance from the molar contact of the intruding batholith with the country rock. As the magma progresses upward, the central heat of the batholith must likewise progress upward and hence the parallel banding of the batholith produced at any stage would be destroyed in a later stage by the complete solution of the blocks into a homogeneous magma. The so-called "batholiths" are in all stages of dissection yet the parallel structure is persistent from center to edge. The structure is not, therefore, a border phenomenon as Adams' theory would demand.

3. The limestone blocks, stoped from the roof of the granite batholith, floated and so were elongated by the movements of the granite parallel to its contact.

3. Daly[1] has shown that limestone blocks at high temperatures are much heavier than fluid granite. Hence these blocks should sink and leave a clear contact which would be progressively attacked by the hot granite magma. This would not give rise to the parallel structure observed. If, however, they floated they would impede the attack of the granite magma at the contact and their solution or partial solution and elongation would cause an enormous loss of heat and render the further upward progress of the batholith very difficult.

It is estimated by Adams and Barlow that 20 per cent of the "batholithic" areas consist of gray gneiss and amphibolite. This estimate is low for the districts visited by the writer. Not only these rocks but also bands of pure limestone are often found near

[1] *Igneous Rocks and Their Origin* (1914), 202.

the center of the gneissic areas, where, it would seem, by Adams' theory, that the pure gneiss of the intruding batholith should be found.

This fact makes it easy to believe that the granite was intruded along planes of slight resistance, and that the limestone terrane of the Grenville series became an immense steam pack, at the time of the intrusion of the granite, with layers of gases followed by fluid granite alternating with layers of limestone. The pre-Cambrian granites were probably accompanied by an immense amount of pneumatolytic gases. The loss of these gases at higher levels due to decreasing pressures accounts for the gradual lessening of the interaction of granite and limestone away from the main granite mass, while within the gneissic areas the retention of the gases allowed the granite to effect a complete change of the limestone to gray gneiss and amphibolite. At certain places the granite failed to penetrate great lenses of the limestone. The gases from layers of fluid magma at the top and bottom of these lenses metamorphosed their borders but failed to affect their centers. Lenses of pure limestone were, therefore, preserved in the midst of gray gneiss and amphibolite.

It has been inferred that the intrusion of the granite occurred along planes of weakness. These, as the structure now shows, were parallel to the stratification of the limestones. Daly and Dawson have stated that in the Shuswap area these planes were due to static metamorphism. Fissility produced in this way would be less apparent in limestones than in the quartzose rocks of British Columbia. However, the fact that the gneissic structure of the Laurentian gneiss is parallel to the stratification of the Grenville series would favor the view that the granite solidified under conditions of stress similar to those which produced the parting planes along which it was intruded. A vertical dike near Baptiste Lake, west of Bancroft, Ontario, shows horizontal schistose structure similar to certain dikes described by Daly[1] in the Shuswap area. Adams and Barlow[2] ascribed the gneissic structure of the Laurentian gneisses to the pressure of intrusion of the granite magma. This,

[1] Cf. to figure in *Guide Book No. 8*, Part II, Internat. Geol. Cong., Can (1913), 130.

[2] *Can. Geol. Surv., Memoir No. 6* (1910), 78–81.

however, would not explain a phenomenon such as that shown by the dike just described (Fig. 2). It is believed that the fissility which allowed the granite to intrude the sediments and the gneissic structure of these granites were both results of a persistent force, the static pressure of the overlying sediments. The Grenville series is said by Adams and Barlow to be approximately 50,000 feet thick. This series compares with the Shuswap Terrane which is 30,000 feet thick.

The elongation or compression of the amphibolitic layers and the presence of amphibolitic inclusions may be explained as easily by the theory of Daly and Fenner as by that of Adams. The granitic gases and fluids must have had their origin at certain definite points. At these points they were pushed upward and sideways along planes of easy parting and a pine-tree structure was produced. In general, the increase of material due to the addition of granite would produce a doming at the center of intrusion with quaquaversal dips away from these points. However, the subsidence of the magma on cooling might very possibly cause a collapse of the dome and irregular dips would result.

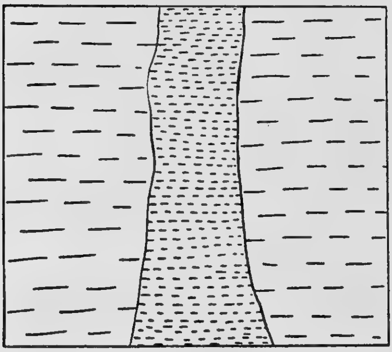

Fig. 2.—A vertical dike showing horizontal schistose structure.

The mechanism of lit-par-lit intrusion, as explained by Fenner,[1] is dependent on the fluxing power of the pneumatolytic gases given off by the granite. These go before and prepare the way for the later intrusion of the granite magma. The prevalence of lit-par-lit rather than batholithic intrusions in pre-Cambrian terranes may be due, therefore, to the greater abundance of magmatic gases in the earlier periods of the earth's history. The vast amounts of pegmatitic granite associated with pre-Cambrian areas lends support to this theory.

[1] *Journal of Geology*, XXII (1914), pp. 594 ff.

The facts presented above do not mean that cross-cutting bodies are lacking in the Haliburton-Bancroft areas. They are found but are by no means as common as concordant injections.

It seems fair to conclude, therefore: (1) that the so-called "batholiths" were formed by the concordant injection of granite into a fissile limestone terrane; (2) that this fissility was produced by the pressure of the overlying sediments; (3) that the layers of

FIG. 3. "Stromatolithic" structure (C. N. Fenner, *Jour. Geol.*, XXII [1914], p. 596).

limestones, lying between layers of molten granite, were permeated by the pneumatolytic gases and fluids given off by the granite and transformed to amphibolites or gray gneisses; (4) that the concordant injection of the granite produced the dome-like character of the "gneissic" areas; (5) that the term "batholithic" does not describe the true character of these areas and the term "stromatolithic"[1] is suggested in its place (Fig. 3).

[1] From Greek στρωμα, "a layer," and λιθος, "a stone." The noun "Stromatolith" may be defined as a rock mass consisting of many alternating layers of igneous and sedimentary rocks in sill relationship.

A CONTRIBUTION TO THE OÖLITE PROBLEM

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INTRODUCTION

At the present time there are two prevalent theories of oölite formation, namely, the inorganic, or chemical precipitation theory, and the organic theory. Prior to the year 1890 the inorganic theory was generally agreed to and it is to this day the most widely accepted of the two.

In the year mentioned, however, Wethered[1] pointed out a close relationship between the concretionary structure of the calcareous algae *Girvanella* and that of true oölite, and showed that certain so-called oölites of the Carboniferous and Jurassic of England really consist, in part at least, of rounded calcareous masses secreted by this organism, since they possess in addition to the concretionary structure the vermiform tubules which characterize the genus. But in this and again in a succeeding paper, entitled "The Formation of Oölite," which appeared in 1895,[2] Wethered was unable to demonstrate the presence of the *Girvanella* tubules in typical oölite spherules showing both radial and concentric structure, although he was led to believe that these were also of algal origin.

Following closely upon Wethered as a champion of the organic theory came Rothpletz, who published a paper on the origin of oölite in 1892.[3] This investigator upon studying the recent oölites of Great Salt Lake found that where these were still in the water they were usually covered by a bluish-green algal mass consisting of the cells of *Gloeocapsa* and *Gloeothece*, forms which are known to secrete carbonate of lime; and, when the oölite grains and rodlike

[1] *Quar. Jour. Geol. Soc. London*, XLVI, 270–83.

[2] *Ibid.*, LI, 196–209.

[3] *Botanisches Centralblatt*, No. 35, pp. 265–68 (English translation by F. W. Cragin, *American Geologist*, X, 279–82).

calcareous bodies on the shore were dissolved in acid, they all yielded dead and shriveled fission algae. Rothpletz, therefore, concluded that the oölites of Great Salt Lake are the product of lime-secreting fission algae, and that their formation is proceeding day by day.

Furthermore, a study of the recent and near-recent oölites of the Red Sea showed these also to contain minute grains of organic material suggesting fission algae. But these differ from the Great Salt Lake oölites in that their nuclei always consist of sand grains and in that their concentric structure is less well developed. They also possess small vermiform canals filled with calcite, which are interpreted as imprisoned algae of another type.

Rothpletz also remarks that certain elongated corpuscles possessing oölitic structures, which he interprets as organic, occurs in the Lias limestone of the Vilser Alps, and concludes as follows: "According to the present stage of my researches, I am inclined to believe that at least the majority of the marine calcareous oölites with regular zonal and radial structure are of plant origin; the product of microscopically small algae of very low rank, capable of secreting lime."

In spite of these discoveries by Wethered and Rothpletz, later students of the oölite problem have tended to drift back to the inorganic theory and to regard the association of oölites with algae as accidental. Thus Linck[1] has shown by experiment that oölites similar to natural ones may be produced artificially by the action of sodium carbonate and ammonium carbonate on the calcium sulphate of sea-water. He points out that these carbonates are formed by decomposition of animal and plant tissues in the sea, and favors the view that oölites have been formed in this way. That natural oölites can be formed chemically is demonstrated by Vaughan,[2] who points out that oölitic structure is now being developed in the calcareous muds precipitated through the agency of bacteria off the coasts of Florida and the Bahamas.

In a recent review of the whole question of oölite formation, T. C. Brown[3] has endeavored to substantiate Linck's conclusions

[1] *Neues Jahrb.*, Beil. Bd. 16 (1903), pp. 495–513.

[2] *Jour. Washington Acad. Sci.*, III (1913), 302–4.

[3] *Bull. Geol. Soc. America*, XXV (1914), 745–80.

and to discount the importance of the algal theory. To quote from him: "The dead algal cells in the Salt Lake oölite are regarded as cells which had selected the oölite as a point of attachment. They became imprisoned within it by the further accretion of aragonite by chemical precipitation." He suggests that the decay of the attached algae furnishes Na_2CO_3 which acts as a precipitating agent and thereby aids the growth of the oölite.

As regards the importance of algae in the production of the oölites of Great Salt Lake, future studies may be expected to throw additional light on the problem. Microscopic examination of these by several investigators has failed to reveal any indications of algal structure in the calcareous grains themselves. On the other hand, they exhibit highly developed radial and concentric structure.

THE PRAIRIE DU CHIEN OÖLITE

Some time ago the writer had occasion to examine microscopically a siliceous oölite which marks the base of the Ordovician in northeastern Iowa, and found to his surprise that the oölite grains of this showed undoubted algal structures. The bed in question constitutes the so-called transition member between the Prairie du Chien dolomite and the Saint Croix sandstone. With reference to this bed Leonard, in his "Geology of Clayton County," says:

> The lower Magnesian is not marked off sharply from the underlying Saint Croix, but there is a transition from the one to the other through from fifteen to twenty feet of calcareous sandstone or siliceous oölite. The rock is composed of clear rounded grains of quartz cemented by lime carbonate. In some beds this cementing material is quite abundant, in others there is only enough to hold together the grains. The ledges vary in thickness from a few inches to two or three feet. This siliceous oölite is well exposed in an old quarry in the river bluff one and one half miles above North McGregor. The transition beds are also seen in the section at Point Ann, just below McGregor. Here there are alternating layers of sandstone and limestone and some oölite similar to that described above.[1]

A bed of similar character and thickness has been described by Calvin[2] as occurring at the same horizon in Allamakee County, which lies directly north of Clayton. The writer has examined

[1] *Iowa Geol. Survey*, XVI (1905), 239–40.

[2] *Ibid.*, IV (1894), 61.

the member at the Point Ann exposure only, and the samples here described and figured are entirely from that locality.

Microscopic examination of the rock shows it to consist of imperfectly preserved siliceous oölite grains in a dolomitic matrix. The history of the rock is briefly as follows: Subsequent to the formation of the oölite, dolomitization set in, transforming the calcareous matrix completely, and many of the calcareous oölite grains either wholly or in part, to dolomite. Alteration then ceased and silicification of the unchanged, or only partly changed, oölite grains ensued. The irregular areas of dolomite within the interiors and the frayed-out borders of many of the silicified oölite grains are in this way accounted for. The structure of grains which were completely dolomitized prior to silicification is almost entirely obliterated, and these are often only with difficulty distinguished from the matrix.

The oölite grains range from 0.1 mm. to 1.13 mm. in diameter, and when well preserved show, in addition to the concentric and radial structure, minute sinuous, enwrapping fibers very similar to the tubules which characterize the *Girvanella* type of calcareous algae. A comparison of the microphotographs of the oölite grains with that of *Girvanella problematica* Nicholson, described and figured by Rothpletz, in his memoir entitled "Ueber Algen und Hydrozoen im Silur von Gotland und Oesel,"[1] will bring out this striking similarity (Figs. 1–6).

It should be recognized that the interwoven fibers of the oölite have been partly obliterated by silicification. Doubtless these consisted of hollow tubules filled with calcite, like those shown by *Girvanella problematica* prior to silicification.

The fibers of the organism of the oölite have an average diameter of 0.015 mm. which agrees very closely with the diameter of the tubules of *Girvanella problematica*, which varies from 0.01 to 0.018 mm., according to Rothpletz.

Typically the well-preserved oölite grains consist of an inner structureless nucleus, followed by a narrow intermediate band showing radial structure, and this again by an outer band bearing

[1] *Kungl. Svenska Velenskapsakademiens Handlingar*, Band 43, No. 5 (1908), Pl. I, Fig. 1.

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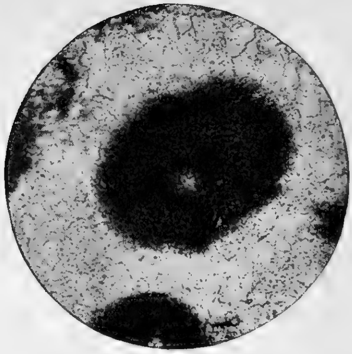

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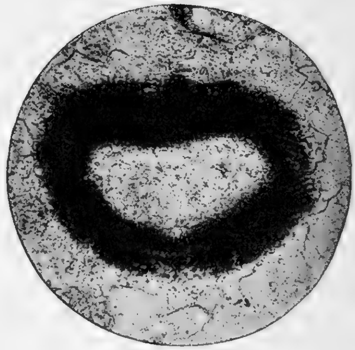

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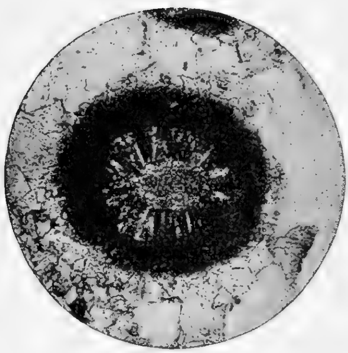

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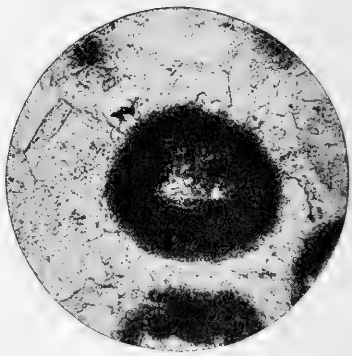

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FIG. 1.—Microphotograph of *Girvanella problematica* Nicholson. About ×42. After Rothpletz.

FIG. 2.—Microphotograph of peripheral section of a silicified oölite grain from basal Ordovician at McGregor, Iowa. About ×45.

FIG. 3.—Cross-section of another grain from the same locality. About ×45. Note the well-developed algal structure in the outer portion and the band showing radial structure within this. The interior is not preserved.

FIG. 4.—Imperfectly preserved oölite grain. About ×45. The interior and peripheral portions of the grain were replaced with dolomite, with obliteration of structure, prior to silicification.

FIG. 5.—Silicified grain showing well-developed radial structure but with algal fibers nearly obliterated. About ×45.

FIG. 6.—Another grain showing fine concentric structure but with no distinct algal fibers preserved. About ×45.

sinuous fibers. In some instances, however, the two outer bands grade gradually into each other without any distinct line of demarkation; or indeed the radial structure may be entirely wanting and the concentric structure may continue into the nucleus. The fibers are best shown in peripheral sections of the grains. In these they appear to enwrap the bodies.

Some of the grains, however, show little or no trace of algal fibers, but there is convincing evidence that this fact has resulted in most, if not all cases, from the obliteration of original structures as an accompaniment of silicification. All stages of such obliteration may be traced under the microscope.

SOME EFFECTS OF CAPILLARITY ON OIL ACCUMULATION[1]

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All rocks in the upper crust of the earth contain pore space. The percentage by volume of this space varies from a fraction of 1 per cent in the case of most fresh crystalline rocks[2] up to 40 per cent in some sandstones.[3] Below ground-water level these openings are more or less saturated with water, which moves about from points of higher to points of lower pressure.

The movement of water thus entombed does not exactly follow hydrostatic laws, as can be observed by the small loss of head in artesian flow. For example, an instance is cited by Van Hise[4] where water traveled under ground 150 kilometers with a loss of only 50 m. in head. This shows that the movement was very slow (perhaps a few feet per year), for the friction through the porous stratum was almost nothing. In the case of water moving in large openings, such as pipes, friction is an important factor. A somewhat similar example was observed by the author in Missouri, where the loss of head by flow in the Roubidoux sandstone was about 200 ft. in 75 miles. A theoretical means of comparison with the observed facts is to note the size of the openings in the rocks. All tubular openings less than 0.508 mm.[5] are capillary. Therefore, by geometrical proof, it can be shown that sandstones with uniform rounded grains of less than 2 mm. in diameter, would contain mainly capillary openings. Rocks with uniform rounded grains, regardless of the size of grain, contain about the same

[1] A paper read before the Geologic Conference of Oklahoma, January 7, 1916, at Norman, Oklahoma.

[2] Van Hise, *Monograph, U.S.G.S. 47*, p. 125.

[3] G. P. Merril, *Rocks, Rock-Weathering and Soils*, p. 198.

[4] *Monograph, U.S.G.S. 47*, p. 587.

[5] Alfred Daniell, *Text Book of Physics*, p. 315.

amount of pore space, and this is greater than in rocks which have varying-sized and angular grains. Most rocks are made up of particles irregular in shape and less than 2 mm. in diameter, consequently the movement of underground water must be greatly affected by capillary action, *and evidently the forces of static capillarity must be overbalanced before movement can take place.* For that reason a discussion of Poiseuille's law of flow in capillary tubes has been omitted, and the conditions of static capillarity are thought to be of *first importance.*

The phenomenon of capillarity—that of a column of liquid rising or being depressed by a small opening—is due to two causes: (1) the surface tension of the liquid, and (2) the fact that the material of which the tube is composed has a greater or less adhesion for the liquid than the cohesion of the liquid itself.

Surface tension is the force at the surface of a liquid, which tends to make the liquid contract, and can be expressed by the following formula:

a) $$T=\frac{\pi r^2 hqg}{2\pi r \cos a},$$

where r equals the radius of the tube; h, the height of liquid standing in the tube; q, the density of the liquid; g, the acceleration of gravity; and a, the angle of contact between the liquid and the tube.

Surface tension is a linear function of the absolute temperature,[1] and that for water can be expressed by:

b) $$T=0.21(370-t)\ ^{2}$$

where t equals the temperature Centigrade.

Pressure causes some change in surface tension, but presumably small. "For changes in the properties of water induced by pressure of, say, 1,000 atmospheres are usually similar in magnitude and direction to those observed when a relatively small quantity of a salt is dissolved in it; and the surface tension of such dilute (0.5 N or less) solutions differs by only a small percentage from that of pure water."[3]

[1] Knipp, *Physical Review*, XI, 151.

[2] Johnston and Adams, *Journal of Geology*, XXII, 9.

[3] *Ibid.*

Different substances have different surface tensions, which can be calculated by means of formula *a*) with the necessary observed factors. For instance, crude oil at 20° C. has an average surface tension of about 25 dynes per cm.;[1] water at 18° C. about 75 dynes; and mercury at 20° C. about 540 dynes.[2]

Surface tension also varies with the nature of materials in surfacial contact. For instance, the surface tension of mercury when in contact with water is different from when in contact with air. Unfortunately, a number of such different values are not recorded, so that this discussion is limited to liquids in contact with air.

It is necessary that the adhesion of the material in the tube be either greater or less than the cohesion of the liquid, otherwise there would be no chance for surface tension to display itself. When adhesion is less than cohesion, depression in the liquid results, as in the case of mercury and glass; when adhesion is greater than cohesion, there is a rise in the capillary tube. If adhesion greatly overbalances surface tension, the liquid surface may break and the liquid mount up the sides of the vessel, as in the case of some light oils in a low porcelain cup. Consequently, before one liquid will replace another in capillary openings the replacing liquid must not only have a greater surface tension but also a greater adhesive power for the material of which the tube is composed.

Capillary force according to equation *a*) is a function of surface tension, contact angle, diameter of pore space, density of liquid and acceleration of gravity. In the case of water-air surface the contact angle is 0, therefore (cos *a*) equals 1; the density of water is 1; so the equation resolves itself into:

$$h=kT/r,$$

where k equals 0.00204.

Starting with a temperature of 15° C., at a depth of 100 m., the capillary pressures shown on p. 801 are computed from the above formula. Pressures are recorded in kilograms per square centimeter.

The following calculations show, first, that capillary pressures decrease with depth on account of the increase in temperature;

[1] Washburn, *A.I.M.E.*, L, 831.

[2] Tait, *Properties of Matter*, p. 264.

secondly, that above 750 m. capillary pressure in openings of 0.01 micron is greater than the combined rock and hydrostatic pressures; therefore capillarity is most important in the upper 3,000 ft. of the earth's crust; and thirdly, that above 5,000 ft. one liquid of greater surface tension and adhesion for the tube material should readily replace a weaker liquid in small openings; or in other words, the liquid of less surface tension should be concentrated in the larger openings.

CAPILLARY PRESSURES UNDER VARYING CONDITIONS*

Depth Meters†	Hydrostatic Pressure	Capillary Pressure for Pore Diameter of		Rock Pressure	Hydrostatic and Capillary Pressures
		100Mc	0.01Mc		
100	10	.03	306	27	316
500	50	.03	294	135	344
1,000	100	.027	278	270	378
2,000	200	.025	250	540	450

* Johnston and Adams, *op. cit.*, XXII, 13.
† An increase of temperature of 1° for every 30 m. was used to obtain these results.

Capillary phenomena can take place in openings of 0.01 micron, as shown by Bakker,[1] where he concludes that the minimum size of capillary openings is a few times the diameter of the molecule. According to Whitney,[2] mud contains more than 10,000,000,000 particles per gram. If these were perfectly round particles, so that the pore space could be a maximum, the diameter of the individual would be about 3 microns. Therefore the maximum openings would be about 0.5 micron. Clay used in the following experiments was made up of particles which varied from 1 to 5 microns in diameter, as measured by a microscope. The openings then at a maximum would be a fraction of a micron. Now, since the openings in mud are evidently less than 1 micron by both of the above methods of approach, it has been assumed for the following hypothetical problem, that in compressed shales where the particles are not round nor of equal size the openings are diminished to 0.01 micron.

[1] *Zeitschrift für physikalische Chemie*, LXXX, No. 2, 129.

[2] *U.S. Dept. Ag., Weather Bureau, Bull. 4*, p. 73.

Capillary pressure of 300 atmospheres means that water will enter the pore spaces above static water level until the pressure in the pore tubes, due to the weight of the column of liquid above or otherwise, is equivalent to 300 atmospheres pressure; or that, if the water is held back by a gas or liquid of less surface tension, it will accumulate a pressure in the said gas or liquid proportional to the difference in capillary pressures for that temperature and size of opening.

The following assumptions have been made for a hypothetical problem: (1) there exists a cavity or series of connected openings, larger than 0.5 mm., under a strip of rock 10,000 ft. wide and 1,000 ft. thick. The openings in the rock above are as small as 0.01 micron, and filled with water; (2) the material below the cavity is an oil shale in which the openings are 0.01 micron, and that water is in the lower part of this shale under sufficient head to make it rise to the level of the bottom of the cavity.

The water will drive the oil into the open cavity with a pressure equal to the difference in the capillary pressures of oil and water for that size of opening. This amount for the given temperature of 15° C. and openings of 0.01 micron is approximately 200 atmospheres, or about 400,000 lb. per sq. ft. The weight of the rock column above is approximately 150,000 lb. per sq. ft.; and that of the full water column would be less than 62,000 lb., because the column cannot possibly act upon a full square foot, but only upon the area of pore space, for convenience say 50,000 lb. Now the resultant pressure upon the rock above the cavity is 400,000 minus (150,000 plus 50,000), or 200,000 lb. per sq. ft.

This pressure acts as upon a beam fixed at both ends. The capillary water above prevents the rising of the oil into the rock, but in turn affords no downward pressure on the oil in the opening, other than the weight of the hydrostatic column, as has been accounted for in the above assumptions.

The deflection for a beam fixed at both ends with a uniform load may be expressed by the following formula:

$$d = \frac{wl^4}{384EI},$$

where d is the deflection; w, the uniform load; 1, length of beam; E, the modulus of elasticity; and I, the moment of inertia.

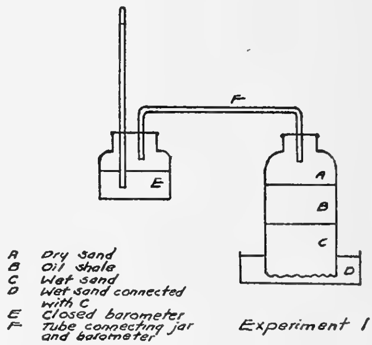
Substituting the values for a beam of rock 10,000 ft. wide, 1,000 ft. deep, 1 ft. broad, with E equal to 6,000,000 lb. per sq. in. (the value of granite), and I equal to $bh3/12$ or $(1{,}000)3/12$, the equation resolves itself into the following:

$$\frac{200{,}000 \times 10{,}000 \times 10{,}000 \times 10{,}000 \times 10{,}000 \times 12}{384 \times 6{,}000{,}000 \times 144 \times 1{,}000 \times 1{,}000 \times 1{,}000}$$

or approximately 72 ft. This means an anticline with a dip each way from the crest of about 1 degree.

Experiment 1

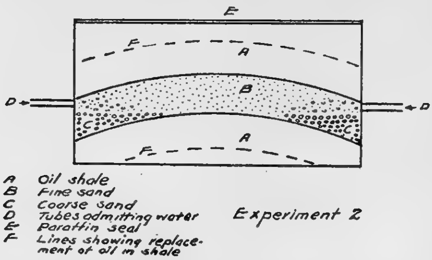
Statement.—An open glass cylinder (3 in. in diameter, and 8 in. in length) was placed in a pan of wet sand, so that the sand filled the lower one-third of the cylinder. The water had free access from the sand in the pan to the sand in the cylinder. Then a layer of oil-saturated mud was placed in the cylinder upon the wet sand; this mud occupied about one-third of the cylinder and was above the level of the water in the pan. The cylinder was then filled with dry sand, and the top sealed with a tube attachment to a closed barometer. Readings of the mercury were taken before sealing and compared with a standard barometer in the same room.



Results.—The water migrated upward about 1 cm. into the mud and the oil moved about the same amount into the dry sand. The mercury had risen within 24 hours, about $2\frac{1}{2}$ cm. over the atmospheric pressure as compared with the barometer; it then remained stationary. The oil also migrated down into the wet sand and collected in some of the larger openings.

Experiment 2

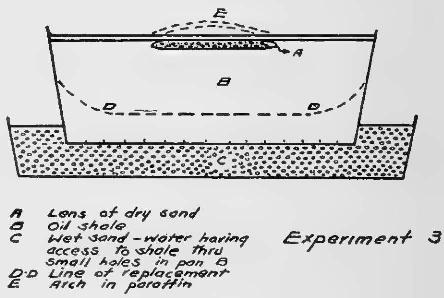
Statement.—A ($\frac{3}{4}$-in.) layer of wet sand was placed between two layers of oil in a (8 in.×4 in.×4 in.) rectangular glass box. The sand layer was arranged in an arched manner so that the artificial anticline dipped about 30 degrees to either side. The sand grains in the top of the curve were small (all passing a 40-mesh sieve), while those in the troughs were comparatively coarse (none passing a 10-mesh sieve). The top was sealed with paraffin and water was allowed to enter the box through openings at the lowest horizon of the sand. This water level was never as high as the top of the curve in the sand.



Results.—The water entered the mud in both directions from the sand layer and replaced about an inch strip of the oil in the mud. The oil moved into the coarser grains of sand and within 24 hours there was an oil pool in both synclines on either side of a water-filled anticline. Later, the oil began to move out of the openings which admitted water from the outside, and collected upon the surface of the water.

Experiment 3

Statement.—A (3-in.) layer of oil mud was placed in a (round 14-in. diameter) pan, which had a number of small holes in the bottom. A circular lens of dry sand (3 in. in diameter and ½ in. thick) was fitted down in the center at the top of the mud. The surface was leveled as carefully as possible and covered with a ¼-in. layer of paraffin. This pan was then set in a pan of wet sand, so that the water level stood about 1 in. below the top of the mud in the first pan.



Results.—After two weeks the paraffin had arched up over the dry sand, with a maximum rise of ⅜-in. The paraffin was punctured at this point, and within 24 hours the oil began to seep out and slowly run down the side of the dome. Several days later, seeps began to come out at various places, where the oil had dissolved its way through the paraffin. The oil also passed down out of the holes in the bottom of the pan through the sand, and collected upon the surface of the free water over the sand. Upon examination, the water had replaced about 1½ in. of the oil in the bottom of the pan.

In the foregoing experiments, the mud was made from a mixture of dried clays, the particles of which measured from 0.005 to 0.001 mm., and Oklahoma crude oil (38 Baumé). Enough oil was used to make the mud pack well.

CONCLUSIONS

At the time of this reading only the results of the elementary experiments can be given. This paper does not attempt to say that capillary forces have ever caused anticlines in nature, but merely points out that possibility. At least one thing is borne out by the above experiments: that the segregation of oil and water in openings of the ordinary oil rocks is not according to the general hydrostatic idea, but that the water forces the oil into the larger openings regardless of elevation or structure. This does not do away with the general anticlinal theory of accumulation. On the contrary, it substantiates this theory, as the larger openings are more often in the crest of the anticline, regardless as to whether the oil caused the fold or whether the oil migrated there after the fold had been made.

A PECULIAR PROCESS OF SULPHUR DEPOSITION

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The sulphur deposits of Japan have four different modes of origin: sublimation, impregnation, flow, and deposition in lakes. They are all doubtless of solfataric origin. The first two types are common everywhere around volcanic craters, but flows of sulphur are found, so far as the writer knows, only at Rausu, Hokkaido, and Tsurugisan, Rikuchu.

The lake type is very peculiar and unusual. Most of the productive sulphur mines of Japan are operated in deposits which are nearly circular in outline. Some of them which are stratified attain a thickness of 30 meters, and are overlaid by fine brown clayey or tufaceous substances which were derived partly from the surrounding rocks and partly from the sulphur itself.

The characteristic topography of the majority of these Japanese sulphur beds clearly shows that they were formed by deposition from crater lakes. The method of formation, however, appears to have been entirely different from that which produced the "gypsum" type of Sicily, Louisiana, and other places, for some were undoubtedly produced by a method similar to that which is now producing sulphur in a crater on Kunashiri, the southwestern of the Kurile Islands, nearest Hokkaido.

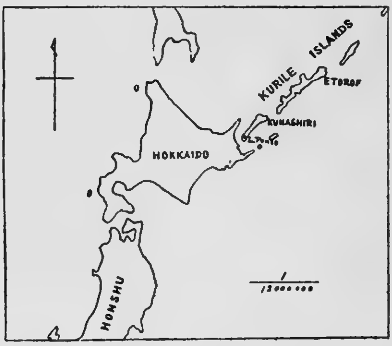

FIG. 1.—Sketch map of Hokkaido and the southern part of the Kurile Islands.

In the southwestern part of Kunashiri is Lake Ichibishinai, a crater lake 1 kilometer in diameter and 150 meters above the level of the sea. South of this lake, and 7 meters higher in elevation, there is a small circular lake called Ponto. This small lake is 210 meters in diameter and occupies an explosion crater. When this is quiescent, the depth of the lake is from 30 to 35 meters in the center, but during periods of activity it is 30 meters deeper. Toward the margins the lake becomes abruptly shallower, as shown in Fig. 2.

The water of the lake is strongly acidic, and has a temperature of 40° C. Around the margins, through innumerable small fissures, sulphur is deposited, and the country rock is strongly impregnated with it. That the fissures extend beneath the surface of the water is clearly shown by the bubbles of gas which rise to the surface of the lake in various places. The amount of gas emitted is ordinarily not very great, but during periods of low barometric pressure enormous quantities escape. Not only do the fissures emit gas, but the conduit of the crater itself is active, and during the months of February, June, July, and August, when the barometer is low in this vicinity, periodic eruptions of hot water and gas take place.

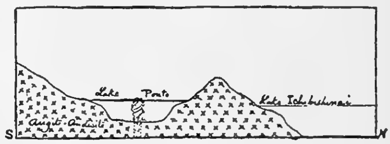

FIG. 2.—Profile of Lake Ponto and Lake Ichibishinai.

During the writer's visit to this locality in August, 1912, paroxysmal eruptions of gas and water were noticed near the center of the lake at intervals of from one to three hours, and whenever the bubbling began workmen rowed to the spot. By means of a pulley attached to a framework resting upon two boats, the men lowered a cylindrical iron bucket, with a capacity of about 140 liters, in the center of the bubbling area to the bottom of the lake. When the bucket was withdrawn, it was practically filled with sulphur grains which were formed by the union of the gases with the water in the lower part of the conduit. Being specifically heavier than water, the sulphur grains, forced upward by the ebullition, sank toward the bottom and into the bucket. In this manner, while the crater is active, a hundred buckets of sulphur are easily brought up in a day.

The greater part of the sulphur is dark gray in color, but some is yellow. The grains are hemispherical, oval, kidney-, fig-, or spindle-shaped (Fig. 3), and they are usually about 0.2 to 3.0 mm. in diameter. The grains are not solid, but hollow, and the cell walls, which are usually rough on the outside on account of a coating of impurities and of very minute sulphur particles, are so thin that they are very easily broken. In fact, many of the larger grains are broken by mutual impact in the water. In the flat side of many of the hemispherical forms or at one end of those that are round there is a small hole, which was made by the exit of the gases which remained within it after it was formed. Most of the grains are brought up as distinct individuals, but in some cases they are united in large botyroidal masses. On account of their thin shells, they cannot keep their original forms if even slight pressure is applied, and the sunshine also destroys them.

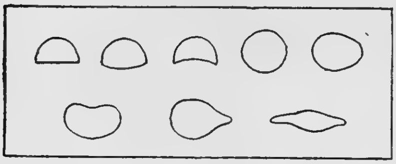

FIG. 3.—Forms of sulphur grains

Two modes of origin of the sulphur in solfataras have been suggested by geologists and chemists: first, the oxidation of hydrogen sulphide, probably according to the equation

$$2H_2S+O_2=2H_2O+2S,$$

secondly, the mutual reaction of hydrogen sulphide and sulphur dioxide, according to the equation

$$2H_2S+SO_2=3S+2H_2O.$$

The hydrogen sulphide and sulphur dioxide, emanating from the conduit, form numberless bubbles in the lake, and where they are in contact with the water the sulphur is deposited. Thus, layer after layer of sulphur may accumulate in a lake and bedded deposits be formed.

Similar oölitic sulphur grains are being formed at the present time in the crater lakes of Shirane[1] and Noboribetsu, but they are not being worked.

[1] H. Kawasaki, *Jour. Tokyo Geol. Society*, No. 122.

Studies for Students

CONTRIBUTIONS TO THE STUDY OF RIPPLE MARKS

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The two interesting papers on ripple marks by E. M. Kindle and J. A. Udden, published in the *Journal of Geology* for October-November, 1914, and February-March, 1916, respectively, suggest that readers of the *Journal* might be interested in a brief review of certain previous contributions to the subject, particularly since most of the questions raised by these two writers have occupied the attention of earlier investigators. In connection with a study of wave action, I have recently had occasion to consult a number of reports on ripple marks, and offer in the following paragraphs a synopsis of some essays not mentioned by Kindle or Udden. No attempt has been made to compile a complete bibliography of the subject, but reference is made to most of the more important papers which have come to the writer's attention.

The accumulation of sand and finer débris in parallel ridges and troughs somewhat resembling water waves in form, though not at all in origin or in method of formation, was long ago recognized as a normal product of wave and current action. Under various names, such as "current mark," "wave mark," "ripple drift," "current drift," and "friction markings," the phenomenon now generally known as ripple mark has repeatedly been described. Although not infrequently found on sandy beaches, ripple marks are perhaps better developed on tidal flats and over the broad bottoms of shallow estuaries, lakes, and ponds. They are not unknown on the deeper sea floor of the off-shore zone, where their occurrence to a depth of over 600 feet has been demonstrated. Ripple marks which are exposed by the falling tide may be delicately dissected by rill marks, an example of this phenomenon having been described by Dodge.[1]

Among the earlier accounts of ripple marks, one of the most interesting is based on the little-known work of an ingenious French engineer named Siau.[2] In 1841 he published a brief note entitled "De l'action des vagues à de grandes profondeurs," based on observations of ripple marks in deep water, made with the aid of an ordinary sounding apparatus. While examining ripple marks, visible during quiet water, on the bed of a channel off the west coast of the Isle of Bourbon, Siau noted that the heavier particles of the sand tended to accumulate in the troughs between the ridges, while lighter material was concentrated along the ridge crests. Profiting by this discovery, he coated a sounding lead with tallow and lowered it to the sea floor where the depth was too great for direct visual observation. When brought to the surface the tallow sometimes retained, adhering to it, only heavy particles of sand, in which case the surface of the tallow had a convex form, showing that it had been pressed down into the trough between two ripples. In other cases the tallow was coated with lighter particles only, and had a concave form, as a result of having been pressed down upon a ripple crest. At great depths, where the ripples were more closely spaced, two parallel bands of materials differing in specific gravity would be impressed upon the tallow at the same time, the heavier material coating a convex ridge, and the lighter a concave depression in the tallow. By this ingenious device Siau was able to prove the existence of ripple marks at a depth of 617 feet.

The ripples described by Siau were believed by him to be due to the back-and-forth currents which are produced on a sea bottom by oscillatory waves. Such ripple marks are called "oscillation ripples," and are characterized by symmetry of crests, neither slope being steeper than the other, since the ridges are built up by currents which operate from both sides with approximately equal

[1] R. E. Dodge, "Continental Phenomena Illustrated by Ripple Marks," *Science*, XXIII (1894), 38–39.

[2] Siau "De l'action des vagues à de grandes profondeurs," *Comptes rendus de l'academie des sciences*, XII (1841), 774, and *Annales de chimie et de physique*, 3e Sér. (1841), 118.

force. The crests are sharp and narrow as compared with the more broadly rounded intervening troughs. De la Beche, in his *Geological Observer* describes another type of ripple mark, produced by the action of a current flowing steadily in one direction over a bed of sand.[1] These "current ripples" have a long, gentle slope toward the direction from which the current comes, and a shorter, steeper slope on the lee side. Sand grains removed from the gentle slope are carried to the crest and dropped down the steeper slope, causing the ripples to migrate slowly with the current, much as sand dunes migrate with the wind.

Sorby gave a very good description of current ripples in *The Geologist* for 1859, but failed to recognize the existence of wave-formed oscillation ripples, although he noted, and even pressed too closely, the analogy between true waves and ripples.[2] For many years current-formed ripples were the only type recognized in most textbooks. In 1882, in opposition to the general view, Hunt claimed that as a rule ripple marks are the product of oscillatory wave action, and supported his claim with observations based on the artificial production of ripple marks, as well as with numerous observations of naturally formed ripples.[3] He was evidently unaware of the fact that Siau had supported the same theory some forty years earlier, and in a later paper he erroneously credited Forel with priority in the recognition of oscillation ripples.[4] Hunt incidentally describes oscillation ripples in his paper "On the Action of Waves on Sea-Beaches and Sea-Bottoms."[5] He also discusses the nomenclature of ripple marks at much length in a paper published in 1904,[6] and elsewhere quotes Lieutenant Damant, R.N.,

[1] H. T. De la Beche, *The Geological Observer* (Philadelphia, 1851), p. 506.

[2] H. C. Sorby, "On the Structures Produced by the Currents Present during the Deposition of Stratified Rocks," *Geologist*, April, 1859, p. 141.

[3] A. R. Hunt, "On the Formation of Ripple-Mark," *Proc. Roy. Soc. London*, XXXIV (1882), 2, 18.

[4] A. R. Hunt, "The Descriptive Nomenclature of Ripple-Mark," *Geol. Mag.*, N.S., I (1904), 411.

[5] A. R. Hunt, "On the Action of Waves on Sea-Beaches and Sea-Bottoms," *Proc. Roy. Dublin Soc.*, N.S., IV (1884), 261–62.

[6] A. R. Hunt, "The Descriptive Nomenclature of Ripple-Mark," *Geol. Mag.* N.S., I (1904), 410–18.

as having observed ripple marks while diving at depths of 60 and 70 feet.[1]

In 1883, the year following the publication of Hunt's earliest paper cited above, there appeared three important essays on ripple marks: one by De Candolle on "Rides formées á la surface du sable déposé au fond de l'eau et autres phénomènes analogues"; another by Forel on "Les rides de fond étudiées dans le lac Léman"; and a third by Darwin "On the Formation of Ripple-Mark in Sand." De Candolle produced ripple marks artificially by experimenting, not only with sand and various substances in powdered form covered by water, but also with liquids of varying viscosity, covered with water and other liquids.[2] Regarding sand or powder mixed with water as a viscous substance, he concluded from his experiments that "when viscous material in contact with a fluid less viscous than itself is subjected to oscillatory or intermittent friction, resulting either from a movement of the covering fluid or from a movement of the viscous mass itself with respect to the covering fluid, (1) the surface of the viscous substance is ridged perpendicularly to the direction of friction, and (2) the interval between the ridges is directly proportional to the amplitude of the friction-producing movement." That ripple marks depend on simple friction alone, and not on any change of level in the covering liquid, such as occurs during wave action, De Candolle proved by an experiment with a rotating disk submerged in a tank of water. After submerging the disk and mixing an insoluble powder in the water, the apparatus was left until the powder settled on the disk and floor of the tank as an even film, and the water came to rest. An oscillatory rotary movement then applied to the disk caused radiating ripples to form upon it, while no ripples formed on the stationary bottom, and the surface of the water remained quiescent. The author concludes that the formation of ripples in sand, whether under currents of air or under water currents, is identical in origin with the formation of water ripples under moving air. If the cur-

[1] A. R. Hunt, "Facts Observed by Lieut. Damant, R.N., at the Sea-Bottom," *Geol. Mag.*, N.S., V (1908), 31–33.

[2] C. de Candolle, "Rides formées à la surface du sable déposé au fond de l'eau et autres phénomènes analogues," *Archives des sciences physiques et naturelles*, 3e Sér., IX (1883), 241–78.

rent moves always in one direction we have intermittent friction due to varying velocities. Otherwise we have oscillatory friction due to alternating change of direction. Current ripples result from the first type of friction, oscillation ripples from the second.

Forel in his excellent essay on "Les rides de fond étudiées dans le lac Léman"[1] sets forth the mature results of studies which had been briefly mentioned by him in three communications of earlier date.[2] Abandoning his first theory, that the formation of ripple marks is dependent in part upon the vertical pressure of water waves upon the bottom,[3] Forel reached the following important conclusions as the result of many careful observations and experiments: (1) Current ripples are asymmetrical and migrate with the current like ordinary sand dunes, whereas oscillation ripples are stationary and symmetrical. (2) Each oscillation ripple is really a composite of two current ripples, resulting from the action of two currents moving alternately in opposite directions, each current attempting to form the ridge into a current ripple migrating with it, but being defeated when the return current tries with equal force to shape the ridge into a current ripple directed in the opposite sense. (3) The length of the water body has no direct effect on the spacing of the ripples. (4) Other things being equal, the ripples are more closely spaced with increasing depth. (5) At a given depth, and with other conditions uniform, the ripples are more widely spaced with increase in coarseness of sand grains. (6) Ripples once formed do not experience a change in spacing as a result of diminishing amplitude of oscillation of the water, although the original spacing does depend upon the amplitude of oscillation, as pointed out by De Candolle. (7) For any given coarseness of sand grains there is a certain mean velocity of the oscillating currents which will produce ripples; lower velocities

[1] F. A. Forel, "Les rides de fond étudiées dans le lac Léman," *Archives des sciences physiques et naturelles*, 3e Sér, X (1883), 39–72.

[2] F. A. Forel, "La formation des rides du Léman," *Bulletin de la Société Vaudoise des sciences naturelles*, X (1870), 518; "Les rides de fond," *ibid.*, XV (1878), P.V. 66–68; "Les rides de fond dans le golfe de Morgues," *ibid.*, 76–77.

[3] F. A. Forel, "La formation des rides du Léman," *Bulletin de la Société Vaudois des sciences naturelles*, X (1870), 518; "Les rides de fond étudiées dans le lac Léman," *Archives des sciences physiques et naturelles*, 3e Sér., X (1883), 40.

will fail to move the sand grains, and hence cannot build ripples, while higher velocities agitate the whole mass of sand so violently that no ripples can form. (8) The formation of ripples is initiated by some obstacle or inequality on the surface of the sand, behind which sand grains accumulate in the eddy caused by its presence; this leaves a furrow on either side of the initial ridge, due to the abstraction of sand accumulated in the ridge; and these furrows in their turn cause additional ridges to develop on their outer margins, and so on. (9) In a given locality, ripple marks almost always form with the same spacing, regardless of the varying intensity of winds and waves affecting the water body; this is in consequence of laws 7 and 6 stated above. (10) The depth at which ripple marks may form is limited by the depth to which wave action may extend with sufficient energy to move the bottom sands; hence it depends on the size of the waves, and therefore in part indirectly on the size of the water body; in the Rhone, the limiting depth is a few decimeters; in Lake Geneva, some ten meters; and in the ocean, from 20 to 188 meters, according to Lyell and Siau. Forel revised De Candolle's law regarding the relation of ripple spacing to the amplitude of the friction-producing movement to read: "The breadth of the ripples, or the distance from one crest to another, is the length of the path followed during a single oscillation by a grain of sand freely transported by the water." The length of this path varies directly as the horizontal amplitude of the oscillatory movement of the water, directly as the velocity of that movement, inversely as the density of the sand, and inversely as the size of the sand grains.

Darwin's paper "On the Formation of Ripple-Mark in Sand" is especially noteworthy for its careful analysis of the vortices which are so important a factor in the construction of the ripples.[1] When symmetrical oscillation ripples were subjected to the action of a steady current, Darwin noticed that not only did sand grains migrate up the weather slope of each ripple with the current, but that they also ascended the lee slopes, apparently *against* the current. This proved conclusively the existence of vortices. Darwin

[1] G. H. Darwin, "On the Formation of Ripple-Mark in Sand," *Proc. Roy. Soc. London*, XXXVI (1883), 18–43.

then proceeded to study the vortices by watching the movements of a drop of ink released from the end of a fine glass tube at that point in the water where the action was to be observed. In this manner the vortices associated with the alternating currents which produce oscillation ripples were analyzed with a high degree of precision, and much light was thrown upon the method of ripple growth. Darwin concluded that "the formation of irregular ripple marks or dunes [current ripples] by a current is due to the vortex which exists on the lee side of any superficial inequality of the bottom; the direct current carries the sand up the weather slope and the vortex up the lee slope. Thus any existing inequalities are increased, and the surface of sand becomes mottled over with irregular dunes." The intermittent friction which De Candolle adduced is not essential in this explanation of current ripples. Oscillation ripples of regular pattern are changed by a continuous current into regularly spaced current ripples; but a uniform current cannot of itself initiate regularly spaced ripple marks. "Regular ripple mark [oscillation ripples] is formed by water which oscillates relatively to the bottom. A pair of vortices, or in some cases four vortices, are established in the water; each set of vortices corresponds to a single ripple crest." Forel's conception of an oscillation ripple as a composite of two current ripples formed alternately by oscillating currents is regarded as correct; but his law for the relation of ripple spacing to amplitude of oscillation is believed to require some modification.

Further studies of ripple-forming vortices were made by Mrs. Hertha Ayrton, the results of which were not published until 1910.[1] With the aid of well-soaked grains of ground black pepper, or of particles of potassium permanganate dissolving and coloring the water while the latter was in oscillation, she observed the formation of vortices and endeavored to explain the mechanics of their growth. Although she expressed disagreement with the conclusions of Darwin and others on certain points, most of her results afford essential confirmation of their main contentions. Some doubt must attach to certain of her deductions, such as

[1] H. Ayrton, "The Origin and Growth of Ripple-mark," *Proc. Roy. Soc. London*, Ser. A., LXXXIV (1910), 285–310.

one to the effect that no ripple-forming vortex occurs in the lee of an obstacle over which a steady current is passing, and that hence "a steady current is unable either to generate or to maintain ripple mark."

The British Association Reports for the years 1889, 1890, and 1891 contain three papers by Reynolds on the action of waves and currents in model estuaries, in which are some valuable observations regarding what may well be termed giant tidal ripples.[1] While experimenting with artificial tidal currents, Reynolds discovered that current ripples were formed in the model estuaries. By making due allowance for the difference in size between the model estuaries and those in nature, he concluded that real tidal currents ought to produce very large current ripples, possibly 7 or 8 feet in height and 80 to 100 feet apart.[2] Some years later Vaughan Cornish discovered natural tidal ripples of the same type as those produced artificially by Reynolds, having a height of 2 feet and an average distance of more than 37 feet from crest to crest.[3] In two later papers Cornish described giant tidal ripples more fully, and illustrated their essential features with a large series of beautiful photographs.[4] Some of these ripples have a height of nearly 3 feet above the intervening troughs, and a distance between crests of from 66 to 88 feet in extreme cases. The giant ripples are often covered with ordinary ripple mark, and while Cornish recognized that the larger forms were produced by the continuous steady flow of tidal currents, he was at first inclined to invoke pulsatory currents in order to explain the smaller ripple mark.[5]

[1] Osborne Reynolds, "Report of the Committee Appointed to Investigate the Action of Waves and Currents on the Beds and Foreshores of Estuaries by Means of Working Models," *Rept. British Assoc.* (1889), pp. 327–43; *ibid.* (1890), pp. 512–34; *ibid.* (1891), pp. 386–404.

[2] *Ibid.* (1889), p. 343.

[3] Vaughan Cornish, "On Tidal Sand Ripples above Low-Water Mark," *Rept. British Assoc.* (1900), pp. 733–34.

[4] Vaughan Cornish, "Sand Waves in Tidal Currents," *Geogr. Jour.*, XVIII (1901), 170–202; "On the Formation of Wave Surfaces in Sand," *Scottish Geogr. Mag.*, XVII (1901), 1–11.

[5] Vaughan Cornish, "On Tidal Sand-Ripples above Low-water Mark," *Rept. British Assoc.* (1900), p. 733; "Sand Waves in Tidal Currents," *Geogr. Jour.*, XVIII (1901), 197–98; "On the Formation of Wave Surfaces in Sand," *Scottish Geogr. Mag.*, XVII (1901), 8.

This theory seems to be a survival of De Candolle's erroneous idea that "intermittent friction" is essential to the production of current ripples, and is practically abandoned by Cornish in his more recently published book on *Waves of Sand and Snow*.[1] Gilmore described tidal ripples on the Goodwin Sands having a height of "two or three feet."[2]

It should be noted that all of the giant ripples referred to above belong to the asymmetrical type; they are true current ripples. So far as I am aware no giant oscillation ripples have ever been observed along modern shores. It may be doubted whether tidal currents could form symmetrical ripples, notwithstanding Reynold's suggestion to the contrary.[3] The flow and ebb of the tide constitute an oscillating current, it is true; but the currents are often of unequal force. Where equally strong, each current persists long enough to remodel the ridges formed by the preceding current, giving them an asymmetrical form appropriate to the current operating last. On the other hand, Gilbert has described structures in the Medina sandstone formation of New York which he believed to be giant ripples of the symmetrical type, formed by oscillating currents due to wave action.[4] In dimensions these ridges were similar to the average examples of tidal ripples described by Cornish, having a height of from 6 inches to 3 feet, and a distance from crest to crest of from 10 to 30 feet; but their nearly symmetrical form did not suggest a similar origin. Gilbert reached the tentative conclusion that they were formed by waves 60 feet high in deep water of a broad ocean. This conclusion was criticized by Fairchild, who advanced convincing arguments in support of the opinion that the forms in question were beach structures, possibly successive beach ridges built on the strand.[5] Branner

[1] Vaughan Cornish, *Waves of Sand and Snow* (London, 1914), pp. 289–90.

[2] John Gilmore, *Storm Warriors, or Lifeboat Work on the Goodwin Sands* (London, 1874), pp. 108–9.

[3] Osborne Reynolds, "Report of the Committee Appointed to Investigate the Action of Waves and Currents on the Beds and Foreshores of Estuaries by Means of Working Models," *Rept. British Assoc.* (1889), p. 343.

[4] G. K. Gilbert, "Ripple-Marks and Cross-Bedding," *Bull. Geol. Soc. Amer.*, X (1899), 135–40.

[5] H. L. Fairchild, "Beach Structure in the Medina Sandstone," *Amer. Geologist*, XXVIII (1901), 9–14.

suggested that they might represent fossil beach cusps seen in cross-section.[1]

In 1911 A. P. Brown published a paper entitled "The Formation of Ripple-Marks, Tracks, and Trails," in which he endeavored to show that asymmetrical ripples (current ripples) are formed by deposition, whereas symmetrical ripples (oscillation ripples) result from the erosion of a formerly smooth botton, consequent upon the rippling of overlying water by wind action.[2] His conclusions do not appear to be supported by a sufficient body of convincing evidence, and are opposed by theoretical considerations and by the great body of experimental data already referred to. In presenting his theory this author makes no reference to the many previous investigations of ripple marks of all kinds, the important results of which have been summarized above.

Ripple marks have repeatedly been discussed in connection with the interpretation of fossil ripples found in sedimentary rocks. We need mention but a few of these discussions in the present connection. As early as 1831 Scrope described fossil ripple marks found on slabs of marble, and explained them as due to the oscillatory movements of shallow water.[3] Darwin, starting from the very questionable assumption that a great ebb and flow of the tide is essential to the formation of numerous ripples, concluded that the presence of a large number of ripple marks in a geological formation indicates with a considerable degree of probability that the tides of early times rose higher than those of today.[4] Van Hise figured and described one type of oscillation ripples, and emphasized their value as criteria for determining the original altitude of steeply inclined strata.[5]

[1] J. C. Branner, editorial note, *Jour. Geol.*, IX (1901), 535–36.

[2] A. P. Brown, "The Formation of Ripple-Marks, Tracks, and Trails," *Proc. Assoc. Nat. Sci. Philadelphia*, LXIII (1911), 536–47.

[3] G. P. Scrope, "On the Rippled Markings of Many of the Forest Marble Beds North of Bath, and the Foot-Tracks of Certain Animals Occurring in Great Abundance on Their Surfaces," *Proc. Geol. Soc. London*, I (1831), 317–18.

[4] G. H. Darwin, "On the Geological Importance of the Tides," *Nature*, XXV (1882), 214.

[5] C. R. Van Hise, "Principles of North American Pre-Cambrian Geology," *Sixteenth Ann. Rept. U.S. G. S.*, Part I (1896), 719–21.

Spurr showed that where continuous deposition takes place from a current which constantly maintains asymmetrical ripples on the surface over which it flows, the forward movement of the ripples combines with the deposition of heavier and larger fragments in the troughs and lighter particles on the crests to give a peculiar type of false bedding in the resulting formation.[1] Jaggar criticized Spurr's conclusions on the ground that his own experiments and observations indicated that ripple marks could not be produced in heterogeneous material;[2] but Spurr met the criticism with a fuller discussion of the matter in which his original contention is well sustained.[3] A short time previously Sorby had described a somewhat similar phenomenon in a paper[4] printed almost exactly half a century after the publication of his first account of ripple marks, already cited. From an examination of the "ripple-drift" type of false bedding in rocks, Sorby believed that one could "ascertain with approximate accuracy, not only the direction of the current and its velocity in feet per second, but also the rate of deposition in fractions of an inch per minute."[5] Additional discussions of fossil ripple marks are cited by Kindle in his paper referred to at the beginning of this article, but need not be repeated here.

[1] J. E. Spurr, "False Bedding in Stratified Drift Deposits," *Amer. Geologist*, XIII (1894), 43–47.

[2] T. A. Jaggar, Jr., "Some Conditions of Ripple-Mark," *Amer. Geologist*, XIII (1894), 199–201.

[3] J. E. Spurr, "Oscillation and Single-Current Ripple Marks," *Amer. Geologist*, XIII (1894), 201–6.

[4] H. C. Sorby, "On the Application of Quantitative Methods to the Study of the Structure and History of Rocks," *Quart. Jour. Geol. Soc. London*, LXIV (1908), 180–85.

[5] *Ibid.*, pp. 181, 197–99.

Reviews

Geology of Saratoga Springs and Vicinity. By H. P. Cushing and R. Ruedemann. New York State Museum; Bull. No. 169, 1914. Pp. 177, pls. 20, figs. 17, maps 2.

Scientific interest regarding Saratoga Springs and vicinity centers about its mineral waters, and this report has been published in response to a demand for detailed information on local geological conditions.

Rocks of Pre-Cambrian, Cambrian, and Ordovician age outcrop in the area. The Paleozoic rocks are divided into deposits of eastern and western troughs, characterized by different sets of formations. The western trough was being eroded in Lower Cambrian times, but in the east the Georgian is the only Cambrian present. The rocks of the western division are horizontal or nearly so, but in the east the beds are intensely folded and crumpled. Two great normal faults with a number of branches cross the Saratoga quadrangle. These are known to be genetically connected with many of the mineral springs.

A unique feature is the Northumberland volcanic plug. It outcrops just north of Schuylerville as a knob of extrusive rock and is unlike any other igneous rock in the state. It has been connected with one theory for the origin of the mineral springs, but unfortunately the authors were unable to determine with certainty whether the rock is in place or not, and are in doubt in regard to calling it a volcanic neck or a fragment of a surface flow.

It was planned to have Professor Kemp write a chapter for this bulletin on the origin of the mineral waters but his results were published in an earlier report. The authors are not convinced that Kemp's conclusions are justified by the field evidence. Kemp holds that the mineral waters, in part at least, are of magmatic origin. He cites as proofs their local occurrence, the volcanic neck, the large amount of free CO_2, and the almost complete absence of sulphates. The authors believe that the absence of carbonated waters to the north is due to lack of shale covering and resulting dilution with surface waters. They hold that the volcanic knob furnishes no evidence of igneous activity of sufficient recency to justify connecting it with present-day juvenile waters. The abundant CO_2 may come from deeply buried impure limestones and shales. The absence of the SO_4 radicle does not dismiss the possibility of connate waters as a source of the mineral salts. The sulphates originally in the connate waters may have been lost as the waters moved along toward the surface by some such chemical reaction as the precipitation of gypsum by the action of sodium sulphate on calcium carbonate in the presence of free CO_2.

Thus the chief problem that this quadrangle offers is held in question still, but this is not due to lack of skill or painstaking effort on the part of the authors of this report. It is a worthy contribution to the geological literature of this state.

W. B. W.

Genesis of Pyrite Ores of St. Lawrence County. By C. H. SMITH, JR. New York State Museum, Bull. No. 158, 1912, pp. 143–82. Figs. 29.

Under the most favorable conditions, definite conclusions regarding the geneses of ore bodies cannot always be drawn, and when these are found in bodies of rock as highly metamorphosed as the Grenville series many complications arise.

In this area, pyrite is widely disseminated, but the ore bodies are associated only with "rusty gneisses thought to be metamorphosed impure sandstones and shales." The writer believes that the metallizing period was subsequent largely to the main period of metamorphism, and was brought about by magmatic emanations permeating the gneisses and replacing with pyrite certain minerals which are usually very stable. These emenations came from the abundant intrusions after active movement of the magmas had ceased. It is not stated that the pyrite all came from the magmas. In fact, to explain the association of the ore bodies with the gneisses alone, it is suggested that only the sulphur was of igneous origin, and that the iron was furnished by the metamorphosed sediments. To cover minor occurrences of pyrite three additional periods of formation are postulated, but are not considered to have been of importance in determining the ore bodies.

Additional points of interest are found in the lack of association of the ore bodies with gabbros, as some authors have stated in other areas, and possible genetic relations of pyrite with associated graphite.

The explanation of the ore bodies strikes one as quite involved, but the author assures us that it is in very small proportion to the complexity of field problems and conditions.

W. B. W.

Geological History of New York State. By WILLIAM J. MILLER. New York State Museum, Bull. No. 168, 1914. Pp. 130, pls. 52, figs. 40.

This bulletin is a brief summary of the geological history of the state. It was the intention of the author to presuppose no scientific knowledge of geology on the part of his readers, and that the work should be in the nature of a textbook. A few pages in the introduction are devoted to geologic processes and throughout the context an effort is made to define technical terms. The reviewer does not believe the author succeeded in making the report sufficiently non-technical to be popular with laymen. It will serve better as a reference book for geologists who wish a brief statement of some of the larger phases of the region's history.

The report is illustrated with many excellent photographs of unconformities and other structural and physiographic features which abound in the state.

Unfortunately this report, in common with other New York reports, does not contain a table of contents and its value as a reference book is impaired thereby.

W. B. W.

Origin of Hard Rock Phosphates of Florida. By E. H. SELLARDS. Florida Geol. Survey, Fifth Annual Report, 1913, pp. 23–80, pls. 9, map 1.

The hard rock phosphates are found chiefly as bowlders and irregular fragments in a formation of Pliocene age that the author has named Dunnellson. The formation is rather heterogeneous but a phase of light-gray sands is the usual matrix in which the phosphate rocks are imbedded.

Theories generally advanced to explain these deposits have involved some form of guano alteration. The author believes the real source of the phosphate was from phosphoric acid derived from the disintegration, *in situ*, of overlying beds. The acid was borne downward by ground-water, and replaced limestone, or was chemically precipitated. No reactions are suggested for the latter process. The deposits are associated with clay lenses and other conditions that interfere with the free circulations of ground-waters. It is suggested that the presence of precipitating agents may be the important factor here rather than the retardation of ground-water circulation. The shattered and heterogeneous character of the formation is explained by the caving in of solution cavities and their subsequent refilling.

The theory presented seems to explain the larger features of the phosphate deposits, but the report should be considered a statement of progress of investigation, rather than the last word in explanation of the deposit.

W. B. W.

Water Supply of Eastern and Southern Florida. By E. H. SELLARDS. Florida Geol. Survey, Fifth Annual Report, 1913, pp. 113–288, pls. 5, figs. 17, map 1.

This report covers in detail an area of twenty-two counties in which, for the most part, the artesian waters may be tapped by flowing wells. This area includes the outer rim of counties along the eastern, southern, and southwestern borders of the state.

The principal aquifer is the Vicksburg limestone of Oligocene age. Underlying the whole state, this formation is exposed in the central part and dips beneath younger formations to the east and south. These younger beds have not been well differentiated and some wells may obtain water from them, but strong flows are from the Vicksburg. The structure includes a low anticline with its axis dipping gently to the east in the central part of the state. The water-bearing horizon is 100 feet below the surface along the coast, and near the crest of the anticline. In the northeast corner of the state the wells are from 300–400 feet deep and at the southern extremity from 900–1,000.

The gentle dip of the strata does not furnish strong pressure in any locality and a head of 25 feet is rather exceptional. Local topography affects the distribution of the flowing wells.

In some areas there has been great development of the artesian water supply. There are not less than 500 flowing wells in the city of Jacksonville. Statistics covering recent years show a progressive loss of flow from the wells in this city.

Much of the artesian water of the state is not potable on account of mineral salts, chiefly sodium chloride. This is notably true in the southern part. All the underground water of the state is very generally charged with hydrogen sulphide, but its use for domestic purposes is not prevented thereby.

A small area of flowing wells in the western part of the state is not treated in detail in this report.

W. B. W.

Geology of North Creek Quadrangle. By WILLIAM J. MILLER. New York State Museum, Bull. No. 170, 1914. Pp. 90, pls. 14, figs. 9, map 1.

This quadrangle lies wholly in Warren County, New York, in the southeastern Adirondacks. It is of geologic interest chiefly because of certain rock types and structures. At the present time no rocks of later age than Pre-Cambrian are present, but Paleozoic outliers just off the map seem to prove that late Cambrian and probably early Ordovician sediments have been removed. The Grenville series makes up the meta-sedimentary rocks, and the author believes the evidence favors their Archeozoic rather than Proterozoic age. This series has a limestone member of remarkable thickness, 10,000–12,000 feet, and below this is 3,000 feet of quite pure quartzite.

About 60 gabbro outcrops are shown on the map, usually with elliptical ground-plans. Their form is that of small stocks or bosses, rather than dikes. The author believes these gabbro occurrences furnish strong evidence in favor of Daly's magmatic stopping and assimilation hypothesis. The igneous masses were not intruded by pushing aside the country rock, but rather by a process of replacement. Marked primary variations in the gabbros and the presence of inclusions as xenoliths are cited in support of this theory and seem to make a strong case.

Garnets are present in the area in quantities of some economic importance. Some of the occurrences are attributed to the assimilation of Grenville sediments, and subsequent crystallization from "original magmas." This use of the term "original magma" for a magma that has assimilated considerable quantities of sediments is questionable.

W. B. W.

The Waverlian Formations of East Central Kentucky. By W. C. MORSE and A. F. FOERSTE. Kentucky Geol. Survey, Bull. No. 16. Pp. 76, figs. 5.

Stratigraphic relations of the Mississippian beds in Kentucky are of interest for economic reasons. In Ohio and West Virginia formations in the Waverly series are oil- and gas-producers and their extension into Kentucky is a fact of considerable importance.

This report covers twelve counties in the east-central part of the state. The beds were traced southward from known sections in Ohio, making the correlations fairly certain. The sections show that toward the south the sandstones of the oil horizons of Ohio rapidly grade into shales. Even the shales of the Bedford and Berea formations become very thin although they do not disappear. These changes are unfavorable for oil-bearing sands in the southern part of the state.

A number of changes in correlations in formations of the Waverlian are made from those given in earlier Kentucky reports and in the Richmond Folio. The latter part of the bulletin treats of the possibilities of these beds in producing building stones and clays. If a map of the area covered by the report had been given it would have made part of the discussion more intelligible.

W. B. W.

The Geology of the Rolla Quadrangle. By WALLACE LEE. Missouri Bureau of Geology and Mines, XII. Pp. 117, pls. 12, figs. 17, maps 2.

The area covered by this report is in the central Ozark region of Missouri and includes Phelps and Dent counties. The strata described include the Gasconade, Roubidoux, and Jefferson City formations. The general horizon is of interest because it includes part of the Ozarkian and the Canadian of Dr. Ubrich's classification. The author follows the usual classification, placing these beds in the Upper Cambrian. A few erosion remnants of Carboniferous age are found in the northeastern part of the area.

An interesting structural feature is found in a number of sink areas. The author believes it was developed from the caving and subsequent filling of solution cavities.

The economic products of this quadrangle are negligible and the chief value of the report lies in its contribution to the general stratigraphy of the region.

W. B. W.

Glass Sands of Oklahoma. By FRANK BUTTRAM. Oklahoma Geol. Survey, Bull. No. 10, 1913. Pp. 91, pls. 8, figs. 3.

Approximately one-half of this report is taken up with a general description of the glass industry. As the author is a chemist he has treated chemical processes in glass production rather fully.

Notable glass sand deposits of the state are limited to three areas: the Arbuckle Mountains, southeastern Oklahoma, and near Tahlequah, in the northeastern part of the state. The greatest deposits are in the Arbuckle Mountains, in the Simpson formation of Ordovician age. This formation is from 1,200 to 2,000 feet thick, and the sands outcrop at four horizons. Five sections give an average thickness for the glass sands of 248 feet. The supply of raw materials seems almost inexhaustible but transportation facilities are lacking in most localities. In southeastern Oklahoma the Trinity sandstone at the base of the Cretaceous carries commercial quantities of good glass sand, and several localities are readily accessible. In the northeast the Burgen sandstone, which has been correlated with the St. Peters, carries a 50-foot bed of high-grade glass sand, but is too remote from railroads for present development.

Analyses of these sands show that they compare very favorably with deposits now being worked in adjacent states. Having a marked advantage in the use of natural-gas fuel, Oklahoma sands should prove strong competitors for the glass market of the central Mississippi Valley.

W. B. W.

Inland Lakes of Wisconsin. By EDWARD BIRGE and CHANCY JUDAY. Wisconsin Geol. Survey, Bull. No. 27, 1914. Pp. 132, figs. 8, tables 4, maps 29.

A large portion of the data in this report has been published in various bulletins scattered through a dozen years. It seemed desirable to gather this material in a single volume, together with additional data not published hitherto.

No lakes occur in the southwest or driftless area, and all the lakes of the remaining three-quarters of the state are of glacial origin. In general the lake basins were formed in four different ways: by melting of blocks of ice imbedded in the glacial débris, by damming of preglacial valleys, by interlocking of terminal moraine deposits, and by inequalities in deposition of ground moraine.

The total number of lakes runs into the thousands, but only the larger ones are described. There are 21 hydrographic maps, and with each is a brief report on the geology and topography of adjacent regions and the origin of the lake basins.

Tables give data on the locations of the lakes, their size, and the depth and shape of their basins. Lake Winnebago with an area of 215 square miles is by far the largest in the state. Few of the lakes exceed one hundred feet in depth. The United States Geological Survey has estimated the total lake area of the state at 810 square miles. The authors believe that twice this amount is more nearly correct.

W. B. W.

Preliminary Report on Tertiary Paleontology of Western Washington. By CHARLES E. WEAVER. Washington Geol. Survey, Bull. No. 15, 1912. Pp. 80, pls. 15.

A Tertiary invertebrate marine fauna of 246 species is listed in this report. Eighty-four of these are new species and are described and figured for the first time. The fauna is very largely pelecypods and gastropods.

Lower Eocene rocks are absent. The Upper Eocene fauna totals 79 species. The Oligocene fauna is limited to 10 species. A detailed report will supplement this bulletin later and treat more fully of the stratigraphic and structural relations.

W. B. W.

Geology of East Central Oklahoma. By L. C. SNIDER. Okla. Geol. Survey, Bull. No. 17, 1914. Pp. 25, pls. 2, fig. 1.

The area treated in this report includes all of Haskell County and portions of five adjoining counties. It deals with structural features almost entirely and the stratigraphy given follows United States Geological Survey reports.

About twenty anticline and syncline axes are plotted. Well-drillers may locate the axes of anticlines roughly from this map and supplement it by detailed work in each locality. For the convenience of many who have not access to the annual reports of the United States Geological Survey, the report includes a map and descriptions of the principal folds in a region adjacent on the southwest. A number of wells are producing gas in these two areas, but oil wells of importance have not been reported.

W. B. W.

Ponca City Oil and Gas Field. By D. W. OHERN and R. E. GARRETT. Okla. Geol. Survey, Bull. No. 16, 1912. Pp. 30, pls. 2, fig. 1.

The Ponca oil and gas field is located in north-central Oklahoma near the Kansas line. It produced gas only until 1911 when the first oil well was brought in. Thirty producing oil wells were operating at the time this bulletin was written.

The report describes the formations of Lower Permian and Pennsylvanian age that outcrop in the Ponca City area, and also those underlying that outcrop to the east and west. The structure of the Ponca City anticline is shown by a contour map on the surface of the Herington limestone.

It is the opinion of the authors that many of the wells labeled "dry" are not deep enough to test their localities. Some holes do not go down 1,000 feet, and few below 1,600; but the approximate position of the lowest oil sand is much deeper, and the anticline will not be tested thoroughly until wells have reached the Tucker sands at a depth of nearly 3,500 feet.

W. B. W.

The Mineral Springs of Saratoga. By JAMES F. KEMP. New York State Education Department, Bull. No. 517, 1912. Pp. 79, figs. 8, tables 7.

There are few problems more difficult for geologists than those connected with the origin of mineral springs. The district centering at Saratoga Springs has long been famous for its mineral waters, and this report has been prepared in response to the very general interest regarding them. The report takes up briefly a historical sketch of the springs, the local geology, and a general description and classification of groundwaters.

The chemical composition of the water is known by analyses of three different periods, 1838, 1871, and 1905. These show a total of ten acid and twelve basic ions. The most abundant salt is sodium chloride followed by calcium, magnesium, and sodium bicarbonates. The waters carry an average of two or three volumes of CO_2 in solution. The sulphate ion is practically absent.

The author rejects any theory that attributes the springs to connate waters, the absence of sulphates being the strongest chemical evidence against such theories. The same geological section is faulted in many other places in the Hudson and Champlain valleys, yet even uncarbonated brine springs are lacking elsewhere. The author's conclusion is that many of the mineral constituents, as the haloids, sodium carbonate, and the carbonic acid gas, are from deep-seated sources. The tendency of dying volcanoes to give off abundant CO_2 and the occurrence within ten miles of the only purely volcanic rock in New York, Vermont, or western Massachusetts support this theory. The carbonated waters take on calcium and magnesium carbonates from the Little Falls dolomite on their upward journey. This conclusion accords with the marked tendency of economic geologists in the last decade to lay greater stress on the importance of magmatic emissions.

W. B. W.

Coal Resources of District No. I (Longwall). By Gilbert H. Cady. Illinois Coal Mining Investigations, Bulletin No. 10, Urbana, 1915. Pp. 149, pls. 9, figs. 27, tables 24.

The Longwall District, comprising Bureau, Putnam, Marshall, La Salle, and Grundy counties and the adjacent parts of Livingston, Kankakee, and Will counties, an area of about 1,700 square miles, contains nearly six billion tons of available coal and is one of the foremost districts of the state in economic importance. This bulletin is concerned with the stratigraphic and structural geology of the region, the economic geology of the coals and accompanying strata, and with the working data developed. The important beds are Nos. 2, 5, 6, and 7, of which No. 2 has been extensively mined. These coals have been studied in a large number of mines. The character of the coal beds and their general structure have been worked out in detail, and many sections through the productive coal measures have been tabulated. In addition to its value in connection with the coal resources, the bulletin is of general interest in that it contains an outline of the geology of the La Salle anticline, including Starved Rock, Deer Park, and the surrounding country.

A. D. B.

Coal Resources of District No. VII. By Fred H. Kay. Illinois Coal Mining Investigations, Bulletin No. 11, Urbana, 1915. Pp. 233, pls. 4, figs. 47.

District No. VII comprises Macoupin, Madison, St. Clair, Christian, Montgomery, Bond, Clinton, Washington, Perry, Moultrie, Shelby, Fayette, Marion, and parts of Sangamon, Macon, and Randolph counties, an area of about 7,000 square miles, containing coal estimated at more than forty-five billion tons in bed No. 6 alone. The stratigraphy of the coal measures has been carefully studied, and numerous sections have been measured and tabulated. Some interesting structures in the coal beds have been noted, and illustrated by a number of diagrams. The rocks of the area are confined to the Pennsylvanian, with comparatively simple structure. No. 6 is the only coal bed producing important quantities of coal.

A. D. B.

Notes on Geology of the Gulf of St. Lawrence. By J. M. CLARK. New York State Museum, Bull. No. 158, pp. 111–20.

The author treats briefly of the geology of Entry Island. Of chief interest is his description of a type of topography which he calls "demoiselle." The relief is due to numerous mammiform hills rounded into softly contoured domes of striking symmetry. These domes are caused by the erosion of small laccoliths.

W. B. W.

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