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PART III—GENERAL GEOLOGY, ORE AND PHOSPHATE DEPOSITS, PHILIPPINES

CONTENTS.

THE NEWARK SYSTEM

OF THE

POMPERAUG VALLEY, CONNECTICUT

BY

WILLIAM HERBERT HOBBS

CONTENTS.

ILLUSTRATIONS.

OUTLINE OF REPORT.

In view of the several important monographs which have very recently appeared dealing with other areas of Newark rocks, the introductory chapter of this report is devoted to a summary of our knowledge of the Newark system. After considering the work of others on the Newark of the Pomperaug Valley, the subject-matter of the report is treated in four chapters devoted respectively to deposition, petrography, deformation, and degradation.

Under the head of Deposition the characters of the several members of the series are given consideration. The associated igneous rocks of the system are shown to be contemporaneous extrusions of lava. The unconformable relation of the system to its basement floor of crystalline rocks is determined, and the essentially conformable contacts of the several members of the series with their neighbors are examined in detail. The probable source of the Newark sediments is found in a large pegmatitized area to the northeast of the valley.

Under the head of Petrography the macroscopic and microscopic characteristics of each member of the system are treated in detail. The sediments are shown to be composed almost throughout of the débris of pegmatite and granite. A specimen of intraformational shale conglomerate from the lowest member of the system is believed to show that portions of this formation were for a longer or shorter period above the sea level during its period of deposition. The baking of the conglomerate at its contact with the overlying sheet of basalt has produced secondary enlargement of the quartz grains. In the vesicular upper surface of the same basalt sheet shale has been deposited, a fact which, taken in connection with the induration at the lower contact, shows clearly the extrusive character of the sheet. This section of the report closes with a review of the chemical and petrographical relationships of the basalts within the several Newark areas.

Under the section devoted to Deformation the geological structure of the area is considered in great detail. It is found that vertical or nearly vertical joint planes have developed in great numbers within the area of the basin, and on the basis of the observations an attempt is made to determine the properties of the individual faults along these joints, their relationships to one another in the fault system, and the manner in which the area as a whole has been deformed through the depression of the orographic blocks which the joints have conditioned.

It is found that throughout the greater part of the basin four series of parallel faults prevail, a fifth series being occasionally developed. Of the four prevailing series, two are nearly normal to each other, but the depression of the area has taken place mainly along planes belonging to one of these perpendicular series and to one of the remaining prevalent series. It is found that the individual fault planes of each series are spaced with remarkable uniformity, but that their throw has been distributed over zones of near-lying fault planes, the throws of the same order of magnitude being also separated from one another by somewhat uniform space intervals. Along some of the closely spaced planes of dislocation in a fault series the throws have in some cases been so small that the faults pass into a system of joints.

The orographic blocks produced by the jointing are, like the throws along the fault planes, of several orders of magnitude, the smallest quadrangular blocks that can be properly measured being designated the "unit" blocks. Measurements under particularly favorable conditions of "unit" blocks bounded by faults of two of the prevailing series disclose an important relation between their shape and the directions of the four prevailing fault series.

The larger orographic blocks of the basin, which, because made up of unit blocks, are designated composite blocks of different orders, are found to correspond in shape with the unit blocks themselves. The southern portion of the valley, in which series of faults have been discovered different from those which prevail throughout the valley as a whole, reveals the presence of large composite blocks bounded by faults of two of the general prevailing series, of which blocks the exceptional faults correspond approximately both as regards their direction and their position with the diagonals. It is an observation of much interest that the ratios of the sides of these composite blocks are remarkably simple.

The striking resemblance of the intersecting system of parallel fault series with a system of compression joints, and, in fact, its local gradation into such joints, has suggested the theory which has been adopted to explain the origin of the faulting. Compression of the area in a nearly east-west direction is believed to have found relief in the prevailing dislocations of the area as a whole. The depression of the area is supposed to have taken place along certain of these planes of dislocation, but in composite blocks the shape and size of which has been controlled primarily by the outlines of the area in which upward pressure subsequent to dislocation was inadequate to support the load. The exceptional fault members of the southern portion of the area, being coincident with the diagonals of the depressed composite blocks, are believed to owe their formation to the downthrow of these blocks, and not to the original relief of the area from compression.

Under the section headed Degradation the drainage system of the area is considered, and it is found that the streams within the valley, and also in the area surrounding it, have been directed in their courses to correspond with the direction of the prevailing fault series. Their canal-like channels and their peculiar zigzag courses both find explanation in their adherence to the direction of the preexistent channels formed by downthrown orographic blocks. The peculiar topographic relief forms of the valley confirm this conclusion. The Pomperaug River itself indicates several important revolutions in its history, one of which was marked by complete reversal of its upper drainage. In the closing chapter of the report the work of the ice within the area of the basin is briefly considered.

THE NEWARK SYSTEM OF THE POMPERAUG VALLEY, CONNECTICUT.

By William Herbert Hobbs.

CHAPTER I.

GENERAL INTRODUCTION.

SECTION I.—THE NEWARK SYSTEM OF THE ATLANTIC SLOPE IN THE LIGHT OF RECENT STUDIES.

Distribution.—The Newark system of the Atlantic slope is represented by a series of elongated areas extending with a somewhat sinuous trend S. 45° W. from the Minas Basin, on the Bay of Fundy, to the northern boundary of South Carolina, and comprising, according to Russell's estimates, about 10,000 square miles. The arrangement of the several areas, whose longer axes are for the most part approximately parallel to the principal extension of the province, varies only moderately from that of an interrupted rectilinear belt, double in its southern portion, and to the north interrupted by the arm of the sea separating the Massachusetts and the Acadian peninsulas. (See Pl. II.) The several areas in this belt have been designated by Russell, beginning with the northeasternmost, Acadian, Connecticut Valley, Southbury,[1] New York-Virginia, Barboursville, Scottsville, Danville, Dan River, Taylorsville, Richmond, Farmville, Deep River, and Wadesboro, besides which there are a number of smaller isolated outliers.

Excepting the distance separating the Deep River and Dan River areas and that separating the New York-Virginia and Southbury areas (each about 45 miles), the continuity of the belt from Massachusetts to South Carolina is nowhere interrupted for more than about 30 miles. From the Connecticut Valley area to where the belt is interrupted by the arm of the sea at Boston is a distance of 70 to 90 miles. The belt as a whole is 1,200 miles long, and always less than 100 miles wide.

[1] Here called Pomperaug Valley. See page 30, footnote 5.

The knowledge of the system acquired previous to 1892 has been summarized by Russell in a report[1] characterized as much by sound judgment in correlating as by thoroughness and accuracy in collecting and transcribing data. Since the publication of this correlation paper several important reports on the Newark system have appeared. These treat of the Connecticut Valley area,[2] the New Jersey portion of the New York-Virginia area,[3] the New York extension of the same area,[4] the Richmond area,[5] and the Catoctin belt of Maryland and Virginia.[6] The papers of Emerson and Davis are final reports and include much of the matter which had appeared in reports by the same authors dealing with special features of the areas concerned.

Rock material.—The rocks of the Newark system comprise a conformable series of conglomerate, breccia, arkose, sandstone, shale, slate, and limestone, with which beds of coal are associated in the southern areas. The coarser deposits characterize especially the borders of the areas, thus indicating that they are, in part at least, a basal conglomerate. In the Connecticut Valley area the coarse conglomerate is found along both the eastern[7] and the western[8] borders, while in the New York-Virginia area and in the smaller areas to the south it is found chiefly on the western border. In the Deep River area, however, which belongs in the eastern division of the belt, a bed is found occupying the eastern border. Russell[9] states that in all cases, as far as can be judged, the coarse deposits are of local origin or are derived from neighboring shores. The rocks which have supplied the material are chiefly adjacent crystalline rocks. Kümmel,[10] however, in his recent monograph has shown that along the western border of the New Jersey area the material of the Newark beds was not derived from the older beds which immediately adjoin them, for although quartzite adjoins the Newark beds for a distance of only a fraction of a mile, quartzite conglomerate is developed along the border for over 19 miles, and gneiss conglomerate is developed for a distance of only 4 miles, although gneisses and granites are found for 50 miles along the border, or for

[1] The Newark system, by Israel Cook Russell: Bull. U. S. Geol. Survey No. 85, 1892.

[2] Geology of old Hampshire County, Massachusetts, comprising Franklin, Hampshire, and Hampden counties, by Benjamin Kendall Emerson: Mon. U. S. Geol. Survey, Vol. XXIX, 1898, pp. 351-501

The Triassic formation of Connecticut, by William Morris Davis: Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1898, pp. 1-192.

[3] The Newark system or red sandstone belt [in New Jersey], by Henry B. Kümmel: Ann. Rept. State Geologist New Jersey for 1897, Trenton, 1898, pp. 25-159.

[4] The extension of the Newark system of rocks [in New York], by Henry B. Kümmel: ibid for 1898; Trenton, 1899, pp. 45-57.

[5] Geology of the Richmond Basin, Virginia, by N. S. Shaler and J. B. Woodworth: Nineteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1899, pp. 385-519.

[6] Geology of the Catoctin belt, by Arthur Keith: Fourteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1894, pp. 345-358.

[7] Russell, op. cit., p. 33.

[8] Emerson, op. cit., p. 355. Also, Davis, op. cit., p. 20.

[9] Op. cit., p. 34.

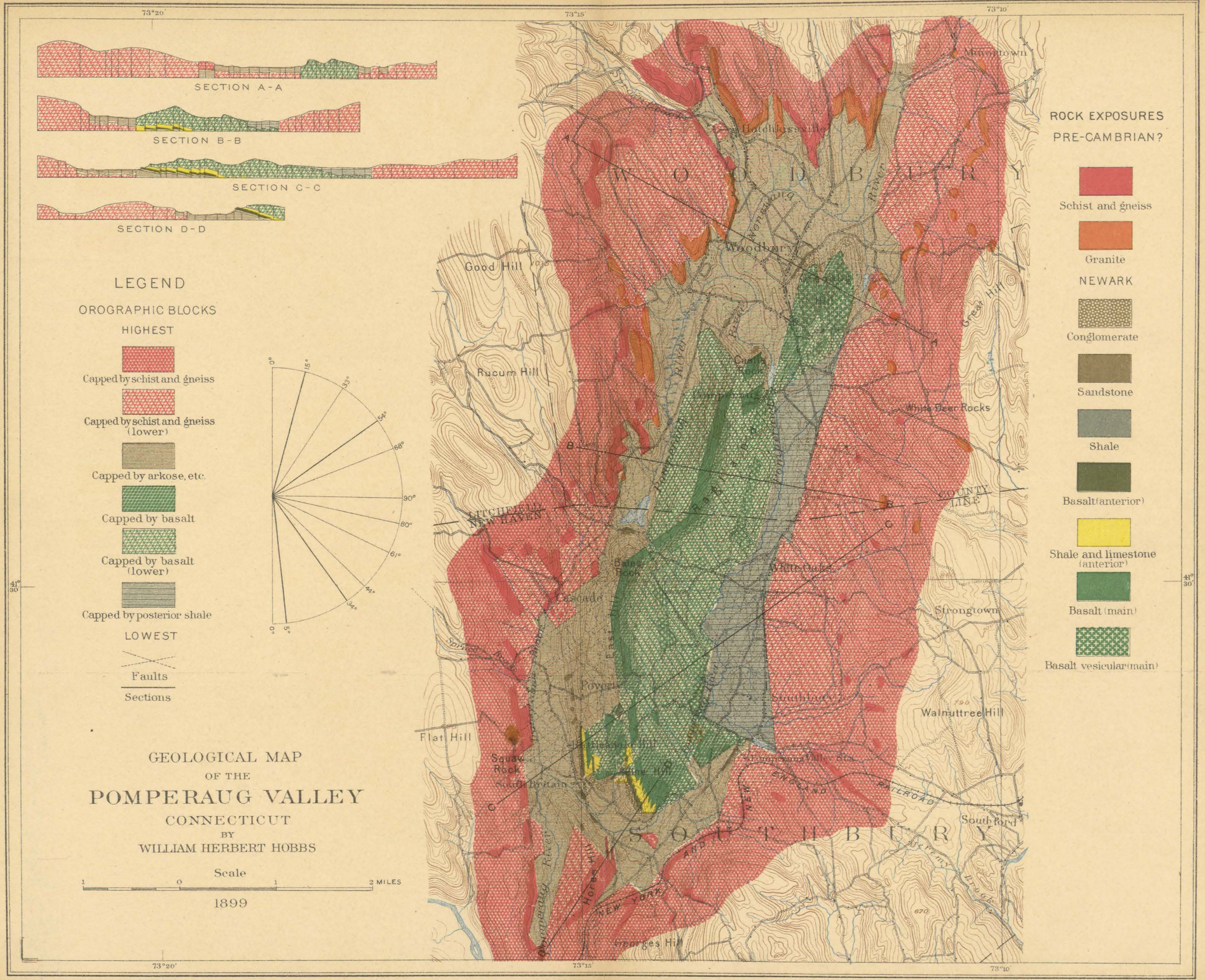
[10] Op. cit., p. 55 et seq.

PLATE I.

PLATE I.

GEOLOGICAL MAP OF THE POMPERAUG VALLEY, CONNECTICUT.

The region represented by this map is one of a great number of dislocations whose planes stand nearly vertical, and so far as known the boundaries of formations in this region have been determined by fault planes. The inferred position of planes of dislocation and their extensions, based upon observations in the field, are indicated by the dotted lines of the maps. The color scheme of this map is peculiar in that the deepest shade of each color is used to show the position of the outcrops of a particular formation. Lighter tints of the same color are employed to show the inferred extensions of the formation beneath the surface of the ground. When more than one tint of any color is used in addition to the one reserved for outcrops, the depth of the tint indicates the supposed altitude of the orographic block compared with other blocks which are capped by the same formation. These inferences are based on both geological and topographical peculiarities, but in the parts of the map showing the central area of Pine Hill and central Ragland the location of boundaries of blocks has been made with much less accuracy than in other portions of the map.



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three-fourths of the entire distance. Emerson also states that in the Massachusetts area the material has not been altogether of local derivation. He says:[1]

> On Fox Brook, south of the road from West Mountain, in Bernardston, the very coarse arkose can be seen almost in contact with the schists, showing that almost from the beginning the strong northward tidal currents carried their granitic material even into this far northern portion of the basin.

In the Richmond Basin Shaler and Woodworth find evidences of the movement of sediments northward and westward.[2]

Keith finds that the Newark sediments of the Catoctin belt were derived from several near-lying foci, and that the currents which carried them moved from north to south.[3]

The greater portion of the clastic rocks of the Newark have been described as sandstones and shales, characterized almost throughout by a reddish-brown color due to the oxidation of iron. It is likewise characteristic of them that their constituents are mainly quartz, feldspar, and mica. They are composed of the débris of granite and gneiss, and are hence properly to be described as arkoses. The prevalence of angular fragments and the evidence of oxidation everywhere observed have been taken to indicate that this débris was formed by subaërial decay of the crystallines on which the Newark was laid down. If the hypothesis of Russell is correct,[4] this condition argues for a warm and humid climate at the time of the disintegration of the material and for the incrustation of the grains by ferric oxide during the subaërial decay of the rock from which they were derived—a process now found in operation over large portions of the earth's surface where a warm and humid climate obtains.

In the southern areas of the Newark belt important seams of bituminous coal occur. In the New York–Virginia and more northern areas such beds are altogether wanting, although thin layers of rich bituminous shales are found. In place of the coal beds is found limestone in thin layers, particularly in the Connecticut Valley and Pomperaug Valley areas. A limestone conglomerate occurs also in the Catoctin belt.

Life remains.—The Newark rocks have furnished evidence of the existence of life during the Newark period, the most abundant fossil remains being the coal plants in the southern areas and the ganoid fishes in the northern. The few bones discovered and the great number of footprints observed in the areas north of Maryland argue for an abundant batrachian and reptilian fauna in these areas. Two mammals, *Dromatherium* and *Microconodon*, and a few imperfectly preserved mollusks, crustaceans, and insects have also been observed.

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[1] Op. cit., p. 355. [2] Op. cit.. pp. 439–440. [3] Op. cit., p. 352.

[4] Subaërial decay of rocks and origin of the red color of certain formations, by I. C. Russell: Bull. U. S. Geol. Survey No. 52, 1889, pp. 1–65.

Associated igneous rocks.—Associated with nearly all of the areas of the Newark rocks are found dikes and sheets of basic rock, usually called simply "trap," but better designated diabase or basalt, since throughout the extent of the Newark belt, as well as in the similar dikes which traverse the surrounding territory, the "trap" has a nearly uniform basaltic composition and structure. The dikes trend generally northeast and southwest, being narrower in the crystalline rocks than they are in the Newark beds. They frequently show finer-grained marginal zones or columnar structure normal to the inclosing walls. The latter they have frequently altered, by hardening them, by changing their color, and by the intrusion of mineral material into them. The trap sheets which are interstratified with the Newark beds have been shown to be in part extrusive surficial flows buried beneath later deposits, and in part intrusive sills injected into the already formed Newark beds. The Nova Scotian trap has been shown by Marsters[1] to be extrusive in origin. In the Connecticut Valley area and the New Jersey area, where these rocks have been most carefully studied, the evidence for the extrusive origin of most of the sheets of basalt is so overwhelming as to be beyond reasonable controversy. The heavy sheet of intrusive basalt in the Connecticut Valley area extends along the western margin (West Rock, Gaylord Mountain, Barndoor Hills), and in the New Jersey area along the eastern margin (the Palisades Range on the Hudson River). Less careful study has been given to the areas farther to the south, but throughout the Richmond Basin and the Catoctin belt the associated igneous rocks are intrusive in their origin and generally dikes.[2] The absence of large sheets of extrusive basalt from the southern areas of Newark rocks may perhaps be explained by supposing that the subsequent degradation was here greater, or it may be that basalt was never extruded in those areas.

Deformation.—The surface of the terrane in the several areas of the Newark is generally (an exception is the Danville area[3]) below the surface of the surrounding rocks. Throughout the series no marked foldings, but only gentle archings of the strata have been observed, although notable and sudden changes in dip have been recorded. These observed changes in dip have been brought about by dislocation of the strata along faults of steep hade. In all areas which have been carefully studied these faults have been found to be very numerous, and the observers, with scarcely an exception, have expressed their belief that many other faults exist within the areas, which it has been found impracticable to locate definitely.

[1] Triassic diabase of Nova Scotia, etc., by V. F. Marsters: Am. Geologist, Vol. V, 1890, pp. 140–145.
[2] Shaler and Woodworth, op. cit., p. 495; Keith, op. cit., p. 354.
[3] Cf. Russell, op. cit., p. 86.

Emerson says of the Massachusetts section of the Connecticut Valley area:[1]

More favorable exposures and more detailed mapping have revealed many faults, and I feel sure that many more remain concealed.

Davis says of the Connecticut section of the same area:[2]

Close and continuous observation of outcrops being impossible, the faults as drawn upon the map are probably too few and too simple.

Kümmel says of the New Jersey area:[3]

I am strongly inclined to believe, therefore, that there are many undiscovered faults, particularly in the Stockton and Brunswick beds, with throw equal to those in the trap areas.

In the Catoctin belt a lack of persistent and distinctive strata renders it impossible to determine faults, but Keith[4] assumes that they exist there, basing his assumption on the great thickness of strata and on the great differences of apparent thickness.

Shaler and Woodworth say of the Richmond Basin:[5]

While the interior of the area shows at the surface little evidence of faulting and folding as compared with the highly tilted attitudes of the strata about the margin of the area, faults, folds, and flexures can be made out, and their relation to the marginal basal sections of the rocks is such as to lead to the supposition that, could we examine the base of the Newark rocks in the middle of the area, we should find there a repetition of the disturbances which are so pronounced a feature of the existing margins.

Russell, in his summary of the structure within the Newark areas, says:[6]

Some of the faults observed are of sufficient magnitude to bring to the surface the crystalline or Paleozoic rocks upon which the system rests. Others expose the basal conglomerate, but the greater number are small, and owing to the similarity of the strata affected by them are difficult and many times impossible to trace.

While faults are numerous, pronounced folds are absent. * * *

An examination of the entire system shows that faulting is as important an element in the structure of the Atlantic coast plain as it is in the Great Basin. * * *

It is to be supposed that the faults traversing the Newark rocks are but a portion of a great system which affects a large part, and perhaps the entire region of metamorphic rocks, in the midst of which remnants of the Newark system have been preserved.

Marginal faults.—The margins of Newark areas, where carefully studied, are generally found to be formed by faults or probable faults. Russell[7] has brought forward cogent arguments for supposing that the areas which have been but little studied are likewise bordered by faults for the most part, and that the areas throughout owe their preservation to their having been depressed below the base-level of

[1] Op. cit., p. 376.
[2] Op. cit., p. 136.
[3] Op. cit., p. 136.
[4] Op. cit., p. 355.
[5] Op. cit., p. 493.
[6] Op. cit., pp. 97–98.
[7] Op. cit., pp. 78–98.

erosion. As argued by Davis[1] for the Connecticut Valley area and by Russell for the other Newark areas, it is clear that the faults of the Newark system must extend downward into the basement floor of crystalline rocks, and hence it would be absurd to assume that the faulting exists only within the area now occupied by the Newark rocks. The statement of Kümmel[2] that a portion of the boundary of the New Jersey area where the Newark beds rest upon the eroded edges of the older rocks is not bounded by faults may possibly be no exception to the general rule, for faults may still exist in the crystallines at or near these boundaries; and if so, they would probably elude discovery.

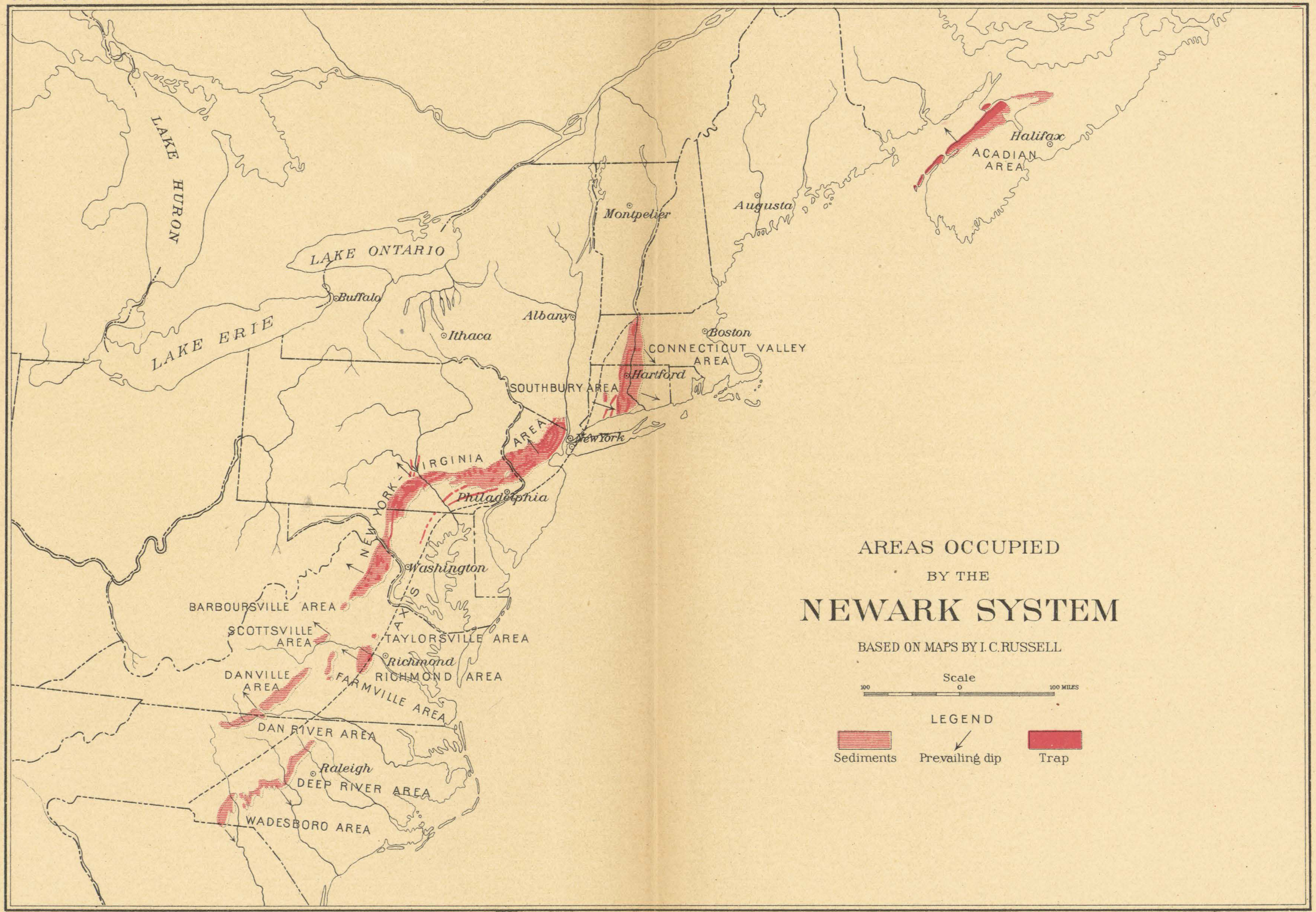
To summarize, then: The structure of the several Newark areas is that of much faulted monoclines of low inclination—a deformation which may be presumed to exist also in the Paleozoic and pre-Paleozoic rocks which surround them.

It is a fact of much interest that the prevailing dips of the beds in the New York-Virginia area and its continuation to the south in the Barboursville, Scottsville, Farmville, Danville, and Deep River areas are uniformly to the west or northwest, the westerly dipping, faulted monocline thus bringing to the surface higher and higher beds in going west. This dip is also characteristic of the beds of the Acadian area to the north. On the other hand, in the Deep River and Wadesboro areas, which form an eastern belt in the southern part of the province, the prevailing dips are to the southeast, and easterly dips characterize also the Pomeraug Valley area in Connecticut and the Connecticut Valley area as far north as Northampton, in Massachusetts. To this point the Connecticut Valley area clearly corresponds in its position with the continuation of the eastern belt in North Carolina, for the trend of the beds, which in the southern areas has been generally northeasterly, veers to the north in the latitude of New York and keeps this direction to the latitude of Northampton, where, as shown by the Holyoke Range, it turns sharply to the east. The narrow tongue of the Newark which extends northward from Northampton is characterized by variable directions of dip, but the Deerfield sheet of trap indicates another bending of the strata to the eastward.

It should be noted that the trend of the Newark belt within the United States is characterized by somewhat regular variations from the general trend of the province, producing an undulatory variation from a rectilinear belt. This is indicated by the principal extension of the individual areas and by the strike of the beds, and conforms closely with the main axis of the Appalachian folding. (See Pl. II, where the axis of the belt is indicated.)

[1] The Triassic formation of the Connecticut Valley, by W. M. Davis: Seventh Ann. Rept. U. S. Geol. Survey, p. 484.

[2] Op. cit., p. 115.



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The Richmond area, which has usually been regarded as a syncline, has recently been shown[1] to be rather a faulted monocline with low westerly dipping beds "extending from the eastern margin westward to a zone of faulted and folded structure, the dip of which is mainly eastward."

Arrangement of areas in an extended fault graben.—The above facts indicate that the Newark belt of rocks as a whole is really a double belt, the structural characteristics of which are not unlike those of an extended fault graben, the bottom of which is so arched as to bring the oldest beds to the surface in the central portion of the belt. This structure is emphasized by the close similarity of the sections of the eastern and western divisions of the belt in its northern portion. In the Connecticut Valley area there is found on the extreme western margin, with only a thin bed of clastic rocks underlying it, a heavy intrusive sheet—the traps of West Rock, Gaylord Mountain, and Barndoor Hills. Corresponding with this we find on the extreme eastern margin of the New Jersey area the thick intrusive sheet of the Palisades Range, with a small thickness of Newark clastics exposed beneath. In positions above the intrusive sheet we find in the Connecticut Valley area the extrusive beds of the anterior, main, and posterior flows, and in the New Jersey area the extrusive sheets of Watchung Mountain, which show many analogies with the Connecticut Valley series.[2]

Thickness of the system.—In the Connecticut section of the Connecticut Valley area Davis makes out the following series, which aggregates over 10,000 feet in thickness:

Thickness of Newark system in Connecticut Valley area.

Division.	Deposits.	Feet.
Upper	Sandstone, shales, and conglomerates	3,500
Middle	Posterior trap sheet (extrusive), 100 to 150 feet Posterior shales, ±1,200 feet Main trap sheet (extrusive), 400 to 500 feet Anterior shales, shaly sandstones, and impure limestones, 300 to 1,000 feet. Anterior trap sheet (extrusive), ±250 feet	2,250-3,100
Lower	Coarse sandstones, conglomerates, and shales, 4,300 to 5,600 feet Intrusive trap sheet, 500 to 600 feet Conglomerates and coarse sandstones, 200 to 300 feet	5,000-6,000

Emerson, in his Massachusetts section of the same area, has not attempted a chronological differentiation of beds, believing his series to represent synchronous phases of the same formation, but has given

[1] Shaler and Woodworth, op. cit., pp. 452, 467.

[2] Cf. On the physical history of the Triassic formation in New Jersey and the Connecticut Valley, by I. C. Russell: Annals New York Acad. Sci., Vol. I, 1879, pp. 225, 230. Also, The structure of the Triassic formation of the Connecticut Valley, by W. M. Davis: Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 483-484.

a different set of names to rocks which at the boundary of the State join those described by Davis. The upper sandstone of Davis is there continued in the entire clastic series of Emerson.

Emerson's series of synchronous facies is as follows:

1. Sugar Loaf arkose (west shore deposits).
2. Mount Toby conglomerate (east shore deposits).
3. Longmeadow brownstone. } (Off-shore central beds.)
4. Chicopee shale. }
5. Granby tuff (fragmental diabase).
6. Holyoke and Deerfield diabase beds (interbedded diabase).
7. Black rock volcanic necks and posterior diabase beds.

Emerson has wisely refrained from ascribing a thickness to the system based on width of exposure. A well boring at Northampton 3,700 feet deep failed to pierce the system, and he estimates that its maximum thickness must have exceeded a mile.

In the New Jersey section of the New York–Virginia area the clastic series has been given the following differentiation by Kümmel, the thicknesses entered in the list being the revised ones contained in his last report upon that region.[1]

Thickness of Newark system in New Jersey area.

	Feet.
Brunswick series	6,000 to 8,000
Lockatong series	3,500 to 3,600
Stockton series	2,300 to 3,100
Total	11,800 to 14,700

If the trap sheets had been included these figures would be increased by about 2,500 feet, so as to make a total thickness of 14,000 to over 17,000 feet. To me it seems that these estimates, as well as those of Davis, which are based on width of outcrops, are, in view of the great probability of undetermined faults, hardly more than guesses. The most reliable data, slight as they are, are furnished by three deep well borings, one of 3,700 feet at Northampton, Massachusetts; another, of 2,500 feet, near Midlothian, Virginia,[2] neither of which pierces the system; and a third at Southbury, Connecticut, which, starting at the top of the main basalt sheet, enters the crystallines at a depth of 1,235 feet.

Conditions of sedimentation.—The absence of characteristic marine or fresh-water fossils in the rocks of the Newark system, the rapid alternations of sediments, the cross bedding, the numerous footprints, and the raindrop impressions are generally taken to indicate that the Newark deposits were laid down in broad and shallow landlocked arms of the sea, in which expanses of mud were exposed during low water. The ripple marks and mud cracks, as well as the tracks preserved in

[1] Ann. Rept. State Geologist New Jersey, 1897.
[2] Shaler and Woodworth, op. cit., p. 443.

the deposits, indicate that the areas on which they were forming were undergoing subsidence, and that the tidal land wash constantly formed new sheets to receive new marks. The southern areas were above sea level, and were at times coal marshes. Russell has suggested that there may have been but one great sound, stretching from Nova Scotia to North Carolina, in which the tides flowed and ebbed, the southern end being swampy and marshy.

Probably the greater number of observers, however, argue that the Newark deposits have been laid down in local basins. Emerson, who favors this view, assumes that the depression of a great block south of an east-west line north of Long Island admitted the sea into the "deep fjord-like bay of the Connecticut River Trias." Regarding the formation of this fjord he says:[1]

The development of the fault system which borders this bay and has produced it may have been an attendant upon the larger movement, but it is quite clear that the depression of the bottom of the basin was, in part at least, synchronous with the accumulation of the Trias sands, and in part of later date.

He assumes, therefore, a "narrow fault-bounded and sunken block," which the water entered during a general Newark transgression of the sea upon the land. The bottom of the trough is supposed to have been occupied by débris of the crystalline rocks, owing to the deep secular disintegration, and this débris was transported by very powerful tidal currents, which moved northward along the western wall and returned southward along the eastern wall. The evidence for this tidal transportation has been derived from a comparison of the fragments in the arkose and conglomerate with the material now forming the walls of the trough.

Davis prefers to regard the Newark beds as "continental" deposits, as defined by Penck. He says:

In contrast to marine deposits, Penck has suggested the name "continental" for deposits formed on land areas, whether in lakes, by rivers, by winds, under the creeping action of waste slopes, or under all these conditions combined. This term seems more applicable than any other to the Triassic deposits of Connecticut. * * * The bedding planes of the strata, revealed only in scanty exposures in which the Triassic strata are generally worn across their edges, must in imagination be transformed into broad floors of washed sands and pebbles, derived from a land area on the west or east, and gradually drifted from the margin toward the middle of the trough, where they accumulated. * * * The sands were not washed directly to their place of settlement and there at once deposited; they were gradually moved along the water floor. The finest silts may have been actually carried in muddy lacustrine or estuarine waters, but they must have been many times laid down and taken up before finding a final resting place.[2]

The trough could not have been depressed to its full depth before the deposits began and then gradually filled to the surface. On the contrary, the depression of its floor must have gone on at about equal rate with the accumulation of sediment. * * * From the more permanent inclosing lands, whence the waste was persistently

[1] Op. cit., p. 373.

[2] Davis, op. cit., p. 33.

shed, the slopes should be pictured as descending into a shallow trough occupied by broad washes of sand and gravel, crossed by wandering streams. Shallow lakes may have now and then overflowed a middle strip or a greater part of the trough, and there finer sediments would gather.[1]

Assuming as he does a pre-Triassic plain of erosion in which the Newark deposits were laid down, Davis is compelled to explain the formation of the trough by differential elevation of inclosing walls as the basin of the trough was depressed. This, he assumes, may have been brought about either by warping, with the formation of a trough, or through graben faulting.[2]

Shaler and Woodworth, while admitting the possibility of the several Newark areas having been once connected, still favor the local basin hypothesis. In their view the Richmond region at the beginning of the Newark period was one of low relief and the seat of more or less considerable and broad river valleys, and with the margin of the land much farther east than it is at present. They look upon the deposits as having been formed in the rivers, or in lakes temporarily formed in the river valleys, and brought in about the lowlands by torrents from the highlands along slopes which represented a fall of 50 to 100 feet in the mile.[3]

Keith says of the conditions of deposition within the Catoctin belt:

The subsidence preceding deposition reduced the height of the land and slackened erosion. The waters were usually shoal, and currents ran from north to south. At one later period at least elevation took place, causing emergence and rapid erosion of most of the pre-Newark formations and some of the Newark deposit.[4]

Thus it seems that Russell is the only one among recent writers upon the subject who has strongly urged the broad terrane as against the local basin hypothesis for the formation of the Newark deposits. I shall revert to this problem in Chapter V, after the Pomperaug region has been described.

SECTION 2.—PREVIOUS WORK ON THE NEWARK ROCKS OF THE POMPERAUG VALLEY.[5]

Early works.—In the first volume of the American Journal of Science an editorial article[6] mentions the occurrence of prehnite, stilbite, agate, etc., at Woodbury, Connecticut, "in a little basin of secondary

[1] Davis, op. cit., p. 35. [2] Op. cit., p. 38. [3] Op. cit., pp. 405–407. [4] Op. cit., p. 352.

[5] This area of Newark rocks has been referred to by Russell as the Southbury area. By Davis it has been called the Southbury-Woodbury area. As a matter of fact, the only localities where the series of rocks representing the Newark system can be made out within the area is near the village of South Britain. The basin includes, besides South Britain, the villages of Woodbury, Southbury, Pomperaug, and Hotchkissville, all of which have a single railway station—Pomperaug Valley. The name of the station has been well chosen, for the five villages occupy positions near the bed of the Pomperaug River. The basin of Newark rocks is practically coextensive with the valley of this river, only the distant headwaters of which lie outside it and within the area of the crystallines. Percival described the Newark in this area under the title of the "smaller secondary formation" of Connecticut, and W. C. Redfield referred to it as the "basin on the Pomperaug River near Southbury, Connecticut." (Proc. Am. Assoc. Adv. Sci., Vol. X, Pt. II, p. 183.) The location of this area is shown in fig. 1.

[6] New localities of agate, chalcedony, chabasie, stilbite, analcime, titanium, prehnite, etc., by B. Silliman: Am. Jour. Sci., 1st series, Vol. I, 1818, p. 135.

greenstone which exists there." In a more extended paper[1] in the succeeding volume of that journal this basin is briefly described and the

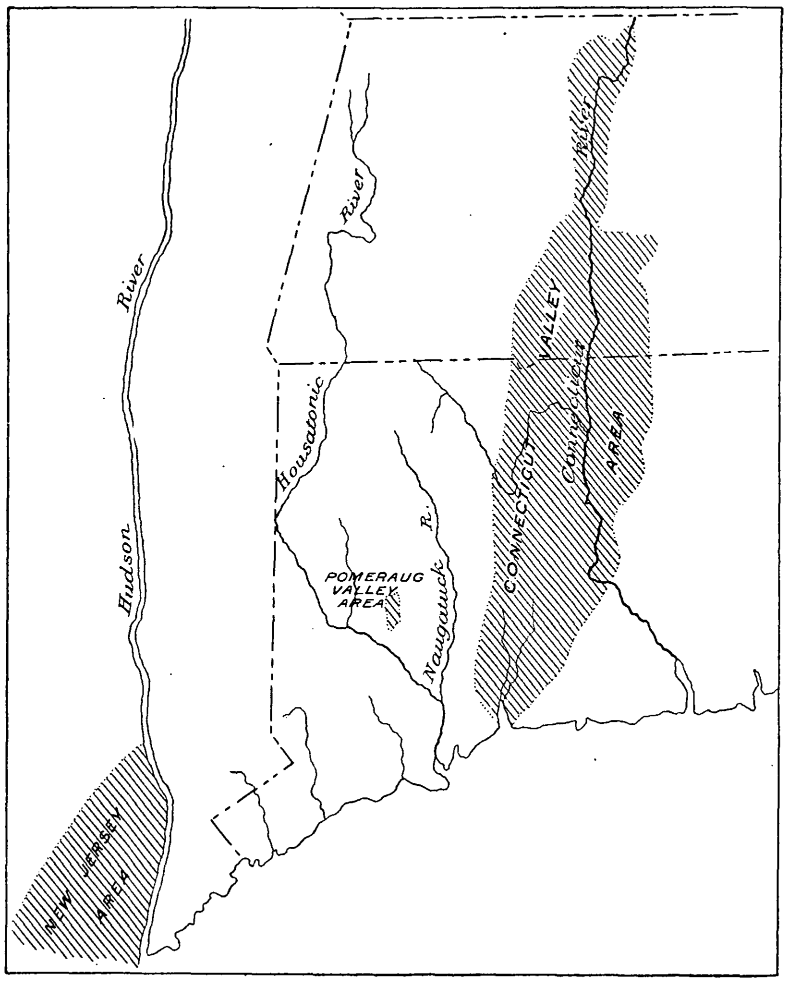

FIG. 1. Map of the Newark areas of southern New England and adjacent territory, compiled from maps by Emerson, Davis, and Darton. Scale, one inch equals 27 miles.

topography so well depicted that I can not refrain from quoting a few passages:

While descending the last hill the geological traveler is forcibly struck with the new physiognomy of the valley in which Woodbury lies. Its features are totally different from those of the country on which he still is and from those of the remoter regions all around.

Abrupt fronts of dark colored naked rock rise perpendicularly from flat and, apparently, alluvial plains. They have mural precipices and sharp ragged ridges,

[1] Sketches of a tour in the counties of New Haven and Litchfield in Connecticut, with notices of the geology, mineralogy, and scenery, etc., by B. Silliman. Am. Jour. Sci., 1st series, Vol. II, 1820, pp. 230-233.

fringed with wood, and are marked by a great accumulation of ruins of the rock sloping from the foot half or two-thirds of the way up the rock; on the opposite side of the hills the descent is gradual, without precipices, and comparatively easy.

No one who with habits of observation has traveled from New Haven to Hartford and so on to Northampton and Deerfield—no one, in short, who has ever been conversant with a trap country—can fail almost at first glance to refer this to that class of rocks. * * * From our being now within 24 miles of New Haven it might be imagined that this tract is merely a branch of the great secondary trap formation which commences at that town, but it will appear that it is not; on the contrary it is perfectly distinct—it is strictly a basin; an island (if I may say so) of secondary trap in the midst of an ocean of gneiss. * * *

I know of nothing in this country similar to this basin, except the coal basin of Richmond, which, although small, is much larger than this.

Silliman made the mistake of supposing that the red sandstone which he found was the Old Red sandstone of Werner, as in fact it had already been represented on Maclure's geological map of the United States. In 1822 Dr. Thomas Cooper makes mention[1] of the fact that he possesses specimens of "floetz trap" from Woodbury, such as had been found by Professor Silliman "as covering the red sandstone through Connecticut;" and argues for its volcanic origin, a view apparently not held by Professor Silliman.

Prof. Edward Hitchcock, in a narrative account of a mineralogical trip across Massachusetts and Connecticut,[2] emphasizes the similarity of the sandstone and greenstone of Woodbury and Southbury with the rocks of the same name in the Connecticut Valley. On the basis of the discovery of shale and bituminous limestone in the basin of the Pomperaug Valley, he declares that this basin is a real coal formation, a statement which is perhaps responsible for the many disastrous attempts which have been made to exploit coal mines in that vicinity. Of real scientific value, however, was the recording (on the authority of Dr. Smith of Southbury) of the fact that "an impression of scales, probably those of a fish, had been found in the bituminous limestone," and the further statement that "a siliceous petrifaction of the trunk of a tree, 8 or 10 inches in diameter, had been found in Southbury."[3] In the final report on the geology of Massachusetts,[4] as well as in earlier volumes of Massachusetts reports, Hitchcock makes brief mention of the area of Newark rocks in the Pomperaug Valley.

W. C. Redfield, in 1841, mentions[5] the occurrence in the red sand-

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[1] On volcanoes and volcanic substances, with a particular reference to the origin of the rocks of the floetz trap formation, by Thomas Cooper, M. D.: Am. Jour. Sci., 1st series, Vol. IV, 1822, p. 239.

[2] Miscellaneous notices of mineral localities, with geological remarks, by Edward Hitchcock: Am. Jour. Sci., 1st series, Vol. XIV, 1828, pp. 227-228.

[3] Description of several species of fossil plants from the New Red sandstone formation of Connecticut and Massachusetts, by E. Hitchcock: Rept. Assoc. Am. Geol. Nat., 1843, pp. 294-296, Pls. XII and XIII.

[4] Report on the geology, mineralogy, and botany of Massachusetts, by E. Hitchcock, Amherst, 1835, pp. 220, 513.

Also final report on the geology of Massachusetts, by E. Hitchcock. Northampton, 1841, pp. 446, 456-458.

[5] Short notices of American fossil fishes, by W. C. Redfield: Am. Jour. Sci., 1st series, Vol. XLI, 1841, p. 27. See, also, Proc. Am. Assoc. Adv. Sci., Vol. X, 1857, Pt. II, pp. 180-188.

stone of Southbury of the remains of the ganoid fishes, *Catopterus gracilis* and *Palæoniscus*.

Shepard, in his report on the geological survey of Connecticut,[1] adds nothing to our knowledge of the formation, although he mentions a chalybeate spring at Woodbury and some occurrences of minerals.

Percival.—The first comprehensive study of the Newark rocks of the Pomperaug Valley was made by that eminent geologist, Dr. James G. Percival,[2] whose work on the geology of Connecticut was undertaken under such trying conditions and when methods of study were primitive as compared with those now employed. His results were never adequately published, but his recorded observations were nevertheless so thorough and so accurate that subsequent studies have in the main supplemented rather than altered them. The results of his studies may best be stated in his own words, which are sufficiently brief, the sketch from his map (fig. 2) serving to make clear this statement:

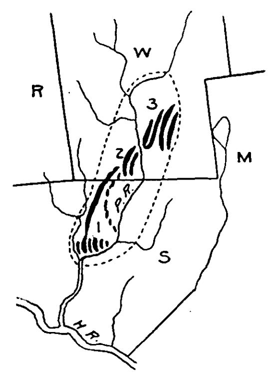

FIG. 2.—Basalt ridges of the Pomperaug Valley (after Percival). W, township of Woodbury; M, township of Middlebury; S, township of Southbury; R, township of Roxbury; *H. R.*, Housatonic River; *P. R.*, Pomperaug River; 1, Southern area; 2, Middle area; 3, Northern area. The dotted line is the margin of the Newark area ("smaller secondary basin.")

The trap in this formation forms only a single range, presenting, in its whole extent, a well-marked curvature, and divided by cross valleys into three distinct sections, succeeding each other in receding order. Of these, the southern (1) extends from the southeastern point of the range to a pass crossing the latter at the road from Southbury to Roxbury; the middle (2) extends from that pass to the Pomperaug, south of Woodbury village; while the northern (3) includes all the remaining portion of the range. The curve of this range is apparently formed, throughout a great part of its extent, by a series of parallel ridges, overlapping each other in a greater or less degree and arranged, toward the opposite extremities, in reverse order, namely, in advancing order towards the southern, and in receding order towards the northern extremity. This arrangement is most remarkable at the two extremities of the range, its middle portion, for some distance, presenting only a single line of elevations, nearly in continued order.

The main trap range, in its southern section (1) and the southern part of its middle section (2), is bordered, on the east, by an apparently distinct range of a very porous chloritic and decomposable amygdaloid, forming a series of low rounded swells, generally covered with the rock in small fragments. This latter range is accompanied, at least towards its southeastern point, by bituminous shale and limestone, recently excavated for coal. Similar excavations have been made in the bands of shale at the southwestern extremity of the main range.

* * * * * * *

The Secondary rocks of the two basins consist of sandstones or conglomerates and shales, generally red, but occasionally of different colors. The sandstones vary

[1] Report on the Geological Survey of Connecticut, by Chas. Upham Shepard, New Haven, 1837, p. 188.
[2] Report on the geology of the State of Connecticut, by James G. Percival, New Haven, 1842, pp. 410–412, 429–430, 450–452.

from the finest grain, passing into the shales, to the coarsest conglomerates; the latter sometimes containing even small bowlders embedded. * * * The sandstones of both these formations are obviously formed of fragments of Primary rocks, similar to those of the adjoining Primary formations, and in most instances the larger fragments, particularly in the coarser conglomerate along the eastern border of the larger Secondary formation, can be distinctly traced to different varieties in the adjoining Primary, frequently in the immediate vicinity. These facts satisfactorily indicate that these Secondary formations were formed from the débris of the Primary rocks, part of which, at least, might have occupied the site of these Secondary formations.

The sandstones and shales of the different Secondary basins have an obvious connection with the trap of those basins, both in their distribution and in the arrangement of their elevations. These rocks are not distributed in regular parallel superimposed ranges, but their limits are distinctly controlled by the arrangement of the trap systems.

* * * * * * *

The sandstone of the smaller Secondary formation is chiefly confined to a narrow underlying range, anterior to the trap range of that formation, apparently most developed at the southwestern and northeastern points of that range. At one point, in the former direction, south of the Pomperaug (South Britain), a mass of sandstone reposes on the Primary (mica slate, GS. 3α), dipping northeast from the latter, and toward the south front of the trap range, at a large angle; but generally the sandstone appears as an outwork to the trap, separated from the Primary by a valley of greater or less width. The sandstone of this anterior range is either coarser grained, lighter red, and more granitic, or finer grained, darker red, and more argillaceous; the latter sometimes forming a valuable freestone. Both varieties, particularly the latter, are characterized by pores, usually small, lined with a black or purple ferruginous coating, forming quite a distinctive peculiarity. The shale of this formation occupies the space included between the main trap range and its anterior amygdaloidal range, and apparently between the main range and its posterior range, although the latter interval is chiefly covered with diluvium. The shale is, however, scarcely developed, except in connection with the southern section of the trap range, at its southwestern extremity. * * * The shale of this formation is usually very soft, argillaceous, and friable, chiefly light red, with beds of brown and dark bituminous shale, including thin beds of dark and light gray bituminous limestone. Impressions of fish are found in these beds, particularly in the limestone.[1]

Davis.—Prof. William M. Davis, whose studies of the Newark rocks of Connecticut have now extended over nearly a score of years, developed his well-known theory of block faulting in the Newark from a study of the Pomperaug Valley, which he therefore describes as having furnished the key to the Triassic structure. These studies were published in 1888.[2]

The sequence of the deposits determined in the vicinity of South Britain was as follows:

Sequence of deposits near South Britain, Connecticut.

(5) Indication of higher members buried in drift.
(4) Heavy sheet of trap.

[1] Op. cit., pp. 410, 411, 427, 428, 429, 450–451.
[2] The Triassic formation of the Connecticut Valley, by William Morris Davis: Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 468–474, 486–490.

(3) Shales containing fish scales and calcareous beds, 200 feet or more.
(2) Thin amygdaloidal trap.
(1) Sandstones and conglomerates at base, several hundred feet thick.

Special study was made of geological structure in the areas northeast of South Britain and east of Woodbury, and sketch maps and sections were prepared (see figs. 3-5) for each of these areas. The peculiarities of the structure are considered to be brought about by faults, which are classified as oblique faults and strike faults. Concerning these the author says:

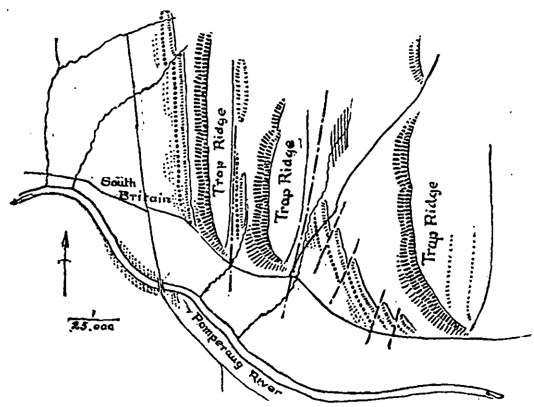

FIG. 3.—Sketch map of the trap ridges near South Britain in the Pomperaug Valley. The outcropping faces of trap ridges are marked with dark hachure lines; the amygdaloid is shown by short faint hachures; the conglomerate, sandstone, and shale are indicated by large dots, small dots, and lines. Four oblique faults dislocate the amygdaloid and conglomerate outcrops between the middle and eastern trap ridges. Larger faults separate the ridges themselves. (After W. M. Davis.)

Oblique faults.—The first locality that threw light on the systematic arrangement of the faults was near South Britain, in the Pomperaug Valley, within the small western Triassic area illustrated in fig. 97.[1] Here the paired outcrops of a conglomerate overlain by the thin amygdaloidal trap appear five times in a third of a mile, every pair being distinctly out of line with its neighbors and the displacements always involving a moderate upthrow on the east of a fracture running obliquely to the strike of the beds. The actual fractures are, as usual, nowhere to be seen, as the outcrops have but little prominence on a grassy slope, but there can be no question whatever of their occurrence (p. 469).

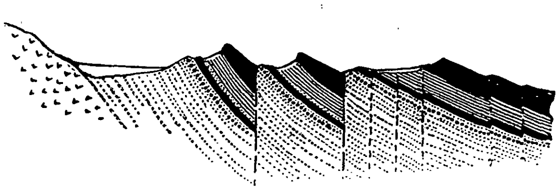

FIG. 4.—Inferred structure of the district shown in fig. 3. The two faults of larger throw, by which a single sheet of trap is represented in three ridges, are proved by the threefold repetition of series of beds comprising sandstone, conglomerate, and amygdaloidal trap, shale, and heavy trap. (After Davis.)

Strike faults.—All the examples thus far described are of tolerably easy recognition, because the dislocation is not great and corresponding members of the formation may be seen not far out of line on the two sides of the fracture. In all such cases the fault line makes a considerable angle with the strike of the faulted beds, but in the examples yet to be considered the fault line is essentially parallel to the strike, and therefore causes repetition of strata in a series of parallel outcrops; and at first sight the corresponding members in such cases are entirely independent and unrelated. The first clear evidence of this structure found by the writer was again close to South Britain in the Pomperaug Valley, which may therefore be said to

[1] See fig. 3.

have furnished the key to the Triassic structure. Although far separated from the Connecticut Valley, the topography and the implied structure of the two areas are so closely alike that it seems legitimate to carry evidence from one to the other. In this interesting locality a single series of beds, consisting of the conglomerate, amygdaloid, shales, and heavy trap already mentioned, is faulted so as to present three successive outcrops, with upthrow always on the east, as shown in fig. 98.[1] The beds in each block vary somewhat in dip, but in other respects are closely similar. If the trap sheets had been sedimentary rocks, the repetition by faulting must have long since been discovered. A short and low ledge of trap in the northern part of the valley that follows the westernmost fault line is the only obscure member of the series, and this may be regarded as a small mass of trap standing between branches of the fault.

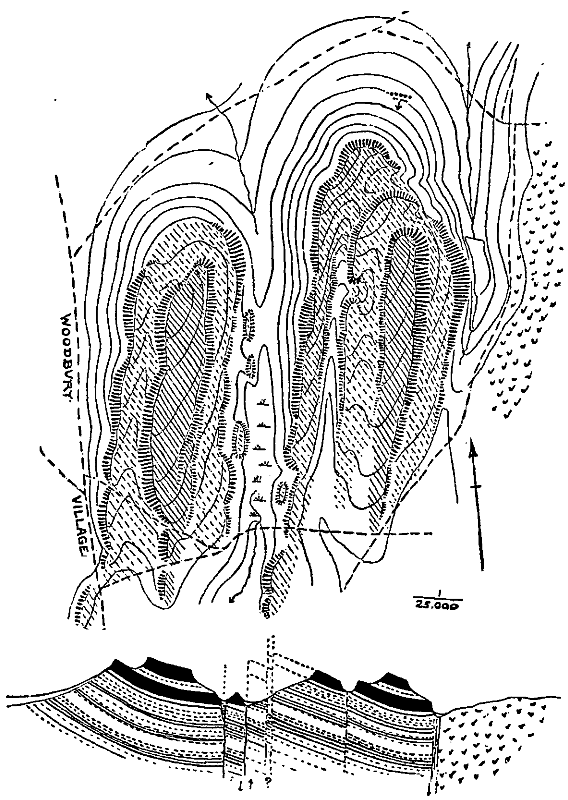

FIG. 5.—Map and section of trap ridges near Woodbury. The topography is indicated by sketched contours, with hachures for trap bluffs. The lower sandstone slopes are all covered, and the northern bluff of the western group of ridges is quite buried in drift. The crystalline rocks appear on the east. The section suggests an interpretation of the surface forms. (After Davis.)

It will be remembered that no evidence could be given in the first section of this report as to the intrusive or overflow origin of the trap sheets in the Pomperaug district; but an argument based on the faults just described gives sufficient reason for supposing that, whatever their origin, the sheets had their present position in the stratified series before the tilting and faulting took place. There are only three suppositions to be considered: First, that they were overflows; second, that they were intrusions thrust in before the faulting; and, third, that they were intrusions thrust in during or after the faulting. In either the first or the second case they necessarily were tilted and faulted with the adjacent stratified beds. The third case may be excluded by the reductio ad absurdum, for it requires that six separate intrusions should arrange themselves independently in a determinate and systematic manner. The same line of argument may be applied to several other trap ridges of this district.

The ridges east of Woodbury (fig. 99[2]), in the same western Triassic area, offer another illustration of the same faulted structure, although the evidence for it might commonly be thought less conclusive, because it does not rest on a repetition of sedimentary strata; but a visit to the spot leaves little doubt as to the meaning of the

[1] See fig. 4.

[2] See fig 5.

structure. The ridge-making beds in two similar groups of hills east of the village consist of a lower and an upper sheet of compact trap, separated by an amygdaloidal layer; shales probably occur between these sheets, but they are nowhere to be seen. The similarity in the structure and topography of the two groups is so striking that one can not resist the belief that they are composed of the same set of trap sheets, repeated by a fault with upthrow of 500 or 600 feet on the east in the intermediate valley. The several low ledges of unevenly jointed trap on the western side of the valley may be fragments of the sheets caught in the fracture, as suggested in the figure.[1]

Since the Davis theory to explain the faults in the Newark beds was derived from a study of the Pomperaug Valley area, and from it extended to the Connecticut Valley area, it requires a careful consideration here. The conditions which call for explanation by this theory as understood by Davis are: First, that the strata have been disturbed from their original position; second, that this occurred after the completion of the deposition, thus involving the entire thickness of the system; third, that the disturbing forces acted from without after the entrance of the intrusive trap sheets; fourth, that this external force affected a greater mass than that of the Newark rocks, and fifth, that it was felt over a region so large as to embrace isolated Newark areas, thus suggesting that the stresses and strains were determined less by the Newark deposits themselves than by the underlying crystallines. A sixth probable condition was added, that the disturbing force was "a long-enduring and a slow-acting horizontal compression," exerted in an east-west or southeast-northwest direction. A seventh condition, and the most important one, is elsewhere stated (p. 481) to be that the entire system of Newark rocks shall be broken into a series of long, narrow, parallel-sided blocks by faults having upthrow almost always on the east, and a uniform tilt in the block to the eastward.[2] The ingenious theory offered by Davis to meet these conditions supposes that the underlying crystalline rocks have a generally uniform northeast-southwest strike and a steep easterly dip. Intense horizontal compression of the area in a direction normal to the strike of the crystalline beds is supposed to cause a tilting of the nearly vertical rock slabs, with differential accommodation of these beds upon one another, so that their basset edges, which before would in an east-west section have presented a continuous and only gently curving line, are so broken as to produce a series of serrations with steep western and gentle eastern slopes. This accommodation of the beds by faulting along their bedding planes is of necessity not confined to the crystallines, for the faults must pass upward through the overlying Newark deposits, and thus produce faults with upthrow always in the same limb.

When the structure of the Pomperaug Valley area has been con-

[1] Op. cit., pp. 471–473.

[2] Op. cit., pp. 481–490.

sidered, this question will be examined in more detail. In his latest paper,[1] Davis reaffirms his belief in the adequacy of this hypothesis, which has in the meantime been adopted[2] for other areas of the Newark system.

Russell.—Russell in his correlation paper on the Newark system, in reviewing Davis's studies in the Pomperaug Valley area, suggests that that area is "a local fault basin, and that its preservation is due to the depression by faulting of a small portion of the original Newark terrane below the present horizon of base-level erosion."[3]

Hovey has described[4] the well-boring for oil made in 1888–89 near Southbury, in the Pomperaug Valley. He reports that:

> The well intersects red and black shales, red sandstones, and conglomerates, and two trap sheets, and at about 1,235 feet passes from the fragmental Triassic rocks into the highly crystalline gneisses and mica-schists, so widely distributed throughout New England.

SECTION 3.—CONDITIONS OF THE PRESENT INVESTIGATION.

The present study was undertaken in connection with the preparation of the geological map of an area in southwestern New England. Field work was carried on during the months of August and September, 1899, during a portion of which time efficient assistance was rendered by Mr. Henry H. Robinson, of New Haven. For considerable local information and for specimens of fossil fishes and woods, as well as for other favors, I am under obligation to Rev. David F. Pierce and Mr. Henry M. Canfield, both of South Britain, Connecticut. For counsel regarding the theoretical considerations included in this report, I am indebted to Prof. Chas. S. Slichter, of the University of Wisconsin.

The area here studied extends about 10 miles north and south by about 5 miles east and west, the included area of Newark rocks being, however, considerably smaller and comprising less than 20 square miles. Its longer axis has a direction N. 15° E., and an extension of about 8 miles. The topography of the area is represented with exceptional fidelity upon the New Milford, Waterbury, Derby, and Danbury atlas sheets of the United States Geological Survey, the area being for the most part, however, included in the Waterbury and Derby sheets. A glance at these sheets is sufficient to show the marked depression of the area of Newark rocks below that of the surrounding crystalline schists, whose wall-like slopes meet the floor of the basin in peculiar finger-like dovetailings. From the floor of the basin the hard Newark traps rise in the central portion, the softer sandstones and shales having been carved away by the Pomperaug River, so as to produce cameo-like surfaces.

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[1] The Triassic formation of Connecticut, by William Morris Davis: Eighteenth Ann. Rept. U. S. Geol. Survey, 1898, Pt. II, p. 140.

[2] Emerson, op. cit., p. 377; Kümmel, op. cit., p. 146.

[3] Russell, Bull. No. 85, p. 82.

[4] The oil well at Southbury, Connecticut, by E. O. Hovey: Sci. Am., May 3, 1890, p. 275.

In the course of the field study it soon became evident that the geological structure of the area was so complicated that it could not be adequately represented upon the topographic atlas sheets, which are printed on a scale of one inch to the mile. Accordingly, for the areas about the villages of South Britain and Woodbury, where the Newark rocks are best represented, detailed maps were prepared on a scale of four inches to the mile, and on these maps for considerable areas nearly every outcrop was located by pacing from some near determined base. By this means relations were made out which must otherwise have escaped observation. The study is, therefore, particularly for the areas represented by these detailed maps, one of much detail.

The subject-matter of this report will be treated under the general heads: Deposition, Petrography, Deformation, and, lastly, Degradation.

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CHAPTER II.

DEPOSITION.

SECTION I.—MEMBERS OF THE NEWARK SYSTEM AND THEIR AREAL DISTRIBUTION.

The Newark system as represented in the Pomperaug Valley consists of, first, a coarse arkose conglomerate with included layers of red arkose sandstone and shale (the basal member), which may be designated the South Britain conglomerate; second, a thin sheet of amygdaloidal basalt, which, in conformity with the usage of Percival and Davis, may be designated the anterior basalt ("trap") sheet; third, a series of red shales, black bituminous shales, and gray bituminous limestone, which will be designated the anterior shales; fourth, a generally dense black basalt sheet, which, again in conformity with the established nomenclature, will be designated the main basalt ("trap") sheet; and, fifth, shale and sandstone probably belonging to the posterior sandstones as defined for the series of the Connecticut Valley area. This uppermost member of the series is somewhat problematical, inasmuch as it is found exposed at a single locality only, but the evidence from the Southbury oil-well boring, as well as that from the topographic development of the valley, is altogether in favor of its presence. The fact, too, that it would doubtless have been without any considerable amount of protection from overlying trap sheets is sufficient warrant that its beds would in any case be very largely removed through the action of both stream and ice erosion.

The series, then, is as follows, beginning with the base:

Series of Newark system in Pomperaug Valley.

(1) The South Britain conglomerate.
(2) The anterior basalt sheet.
(3) The anterior shales.
(4) The main basalt sheet.
(5) The posterior shales.

South Britain arkose conglomerate.—This basal member of the Newark system is found principally in the vicinity of the village of South Britain, the best exposures being on the shoulder of Pine Hill, east and southeast of D. M. Mitchell's place (see Pl. VIII). Other good sections are found in the bed of the Pomperaug River, extending north from the road bridge, and in the ridge one-half mile long northeast of the village and west of Rattlesnake Hill. Shales and sandstones doubtless belonging to the same formation are found in occasional exposures, chiefly in gullies, extending from the latter another half mile to the northward, beyond which is a large area of drift-covered slope. These shales are seen to best advantage in the Oliver Mitchell Brook section (fig. 6). At a single locality only (at the western base of the trap wall of East Hill) this formation has been found exposed between that point and Woodbury. The northern slope of Horse Hill, to the southwest of South Britain, is strewn with large blocks of this formation, although many have already been carried away and utilized as building stone. At several localities near the

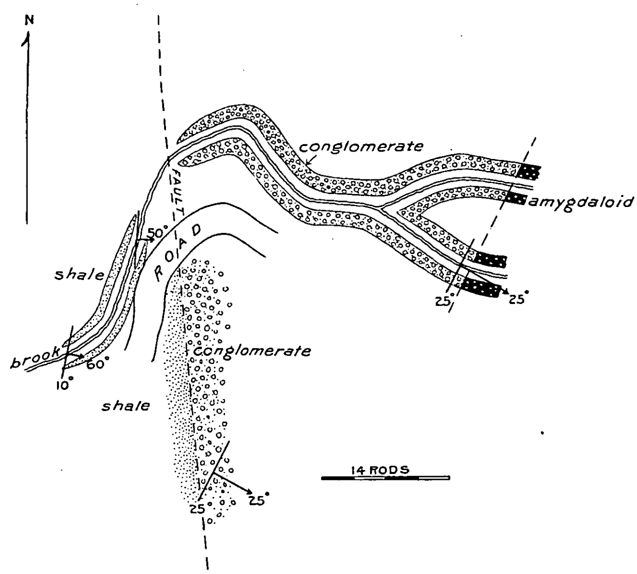


FIG. 6.—Geological sketch map of Oliver Mitchell Brook, near South Britain. The arkose conglomerate is indicated by small circles, the shale by stippling, and the amygdaloidal basalt by black areas spotted by white circles.

summit of the hill (on the land of Mr. Bradley) the conglomerate has been encountered in plowing, and it was found possible to examine it here over a considerable area by simply removing a few spadefuls of earth. In the northern portion of the basin the conglomerate is seen in two exposures only, one north of each of the twins of Orenaug Hill. There are other localities, however, where the peculiar red color of the soil over limited areas is taken to indicate that the rock would probably be encountered at the depth of only a few feet from the surface. Such localities may be seen near Pomperaug Valley Station and on the north flanks of Bates Hill, Ragland, and West Orenaug Hill.

While generally a coarse breccia or conglomerate composed of angular fragments, the South Britain conglomerate incloses, as already mentioned, beds of red sandstone and shale. The shales are best observed in the left (western) bank of the Pomperaug River below the South Britain bridge, and also below the amygdaloid in the Oliver Mitchell Brook section.

A very large proportion of the pebbles of the conglomerate are either cleavage fragments of a red orthoclase feldspar or rounded masses of vein quartz. With these are found feldspar inclosing quartzes in parallel orientation (pegmatite or "graphic granite"), both coarse and fine granite, with an occasional pebble of the common white gneiss of the region or of mica-schist. Sometimes quartz pebbles contain needles of black tourmaline, and an occasional pebble is composed of mica in large scales—apparently a micaceous phase of pegmatite. The great mass of the material—the feldspar, quartz, graphic granite, and muscovite—has clearly been derived from pegmatite, granitic material being the next in order of abundance.

In size the pebbles vary from microscopic dimensions to several inches in diameter. The feldspar is invariably in cleavage fragments, at most but slightly rounded on the edges and angles, although the quartz pebbles are subangular and the granite pebbles are frequently thoroughly abraded to the form of flat oblate spheroids or triaxial ellipsoids. One pebble having the form of a well-rounded ellipsoid, coated with a film of ferric oxide, on being broken in halves was found to be composed on the one side of coarse granite and on the other of finer granite. The latter was remarkably fresh, while the former showed considerable evidence of decomposition, and was throughout stained with a brown ferruginous oxidation product. The fact that the feldspar pebbles are found so generally in only moderately rounded cleavage fragments may indicate their transportation by violent currents, which would fracture them before reducing them to rounded forms.

One of the blocks of conglomerate collected on the northwest slope of Horse Hill is a coarse arkose sandstone containing very flat pebbles of red shale a half inch or more in diameter and an eighth of an inch or less in thickness. Although this rock has not been found in situ, it is clearly of local origin, and the shale is moreover identical with that which forms subordinate layers in the conglomerate itself. Such shale layers are found interbedded with the conglomerate in the bed of the Pomperaug River at South Britain and along the western shoulder of East Hill, north of Oliver Mitchell's. This shale conglomerate is therefore an intraformational conglomerate,[1] and is best

[1] Paleozoic intraformational conglomerates, by C. D. Walcott: Bull. Geol. Soc. Am., Vol. V, 1894, p. 192. Also, Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, p. 723.

explained, as it seems to me, by assuming that while the South Britain conglomerate was in process of deposition certain portions, partially consolidated, were locally elevated above the general water surface.

At or near the contact of this horizon with the overlying member—the sheet of amygdaloidal basalt—the conglomerate or arkose is more dense and firm than is normally the case. It rings under the blow of the hammer, and it is moreover usually paler in color. The rock occupying the bed of the river at the South Britain dam, though not now in the vicinity of basalt, has all the above characteristics, and, like the other occurrences of pale, dense arkose in the basin, it is believed to owe its peculiar properties to a baking process induced by heated igneous rock (see p. 89).

Anterior basalt sheet (*amygdaloid*).—This member of the system is found only near South Britain in the southwestern portion of the Pomperaug Basin. It consists of a belt of very vesicular and much weathered basalt, always less than 50 feet in thickness. Its vesicles are of only moderate size, but very numerous and partially filled either with hydrated oxide of iron or with the characteristic infiltrated minerals calcite, epidote, chlorite, etc. The groundmass of the rock has generally a greenish or brownish color dependent on the degree of alteration which it has suffered. Owing to the entrance of water into the half-filled vesicles, frost has been an active agent in disintegrating the rock, and has covered the surface of most outcroppings with a layer of small angular chips of a size averaging that of a hazelnut, beneath which the fresher rock is obtained only by digging. By this deposit of chips the horizon may be easily followed when no even moderately fresh rock is exposed at the surface. The extension of this sheet forms a broken belt, which, starting from the southwest foot of Pine Hill, trends north-northwest with interrupted but nearly continuous segments until it bends sharply to the southwest in the hill east of Oliver Mitchell's brook, in the latitude of the "Triangle" (see fig. 7). The thread is next taken up by an interrupted NNE.-SSW.

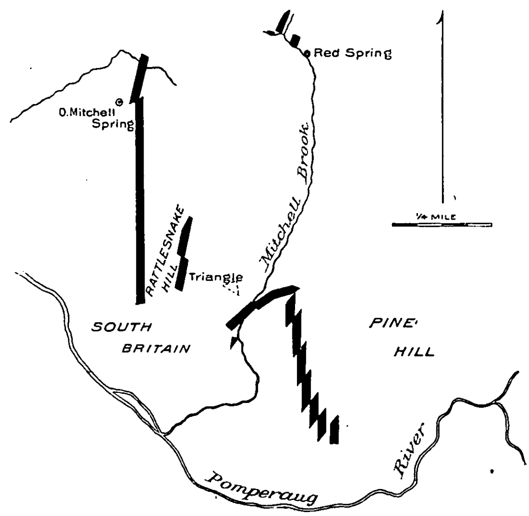


FIG. 7.—Map showing the areal development of the anterior sheet of basalt.

belt beginning in the "spring house section," southeast of Rattlesnake Hill. To the westward of the same hill a belt of the amygdaloid trends a little west of north from Sage's creamery a distance of over half a mile, to near Oliver Mitchell's spring, where it offsets slightly to the westward, its outcrops extending in a slightly different direction an eighth of a mile farther to Oliver Mitchell's brook. The only other occurrence of this sheet is found in a few small exposures near the Red Spring in the valley to the south of Poverty.

Anterior shale.—This horizon is only rarely found in outcrop. The best exposures for indicating its place in the series are located in the "spring house section," east of Sage's creamery at South Britain. There are but two other sets of exposures, one in Oliver Mitchell's brook, the other in the vicinity of the Red Spring south of Poverty. Although so little of this horizon is found exposed, its presence is nevertheless inferred in other localities with much probability from the topography, for wherever the anterior basalt is found along the southwest flank of the Newark area, a valley of nearly uniform width, generally devoid of outcroppings, separates it from a scarp of the main basalt sheet to the eastward. There is, moreover, nothing remarkable in the absence of the shale from the surface of its areas, for aside from its soft, yielding character, it has not been protected by harder beds except immediately below the main basalt cliff, where it would, of course, be buried in talus. An extension of the area of shale of the "spring house section" is probably indicated in a deposit of red and blue clay which was reported to have been found beneath the peat swamp north of Sherman Hill and east of Rattlesnake Hill. According to Henry M. Canfield, on whose property the peat bog is located, the red and blue clays were found when peat was taken from this swampy area during an especially dry season a good many years ago. From the occurrence of the northeasterly trending bands of conglomerate and amygdaloid to the northwest of this swampy area it should have been occupied by shale, provided the Newark series is not interrupted at the boundary of the amygdaloid.

The rocks of this member are of quite fine grain, but show considerable variation in color and in composition. Besides the soft gray and red shale, there is found a dark shale, which, on being broken, smells strongly of bitumen, and is in fact a bituminous shale. A gray or slate-colored impure limestone, frequently also rich in bitumen, is found in the vicinity of Red Spring and a little to the northward of it.

Almost or quite a century ago a deep shaft was opened in the gully below the "spring house" (South Britain) in the vain hope of discovering a coal mine. According to Mr. H. M. Canfield, this shaft penetrated shales, and gray and bituminous limestones as well, fragments of all of which were afterwards washed from the dumps down the gully. Near the main highway at the bottom of the gully these rocks are now to be found in considerable abundance.

Main basalt sheet.—The main basalt sheet, because of its great density and hardness and its great stability from a chemical point of view, has controlled the principal relief forms within the Pomperaug Basin. Although its thickness can not be accurately determined, it is probably several hundred feet. Its outcrops, generally bounded on the west and sometimes on other sides by steep scarps, occupy all the high points of the valley. As stated by Percival, they are arranged in two parallel belts whose general trend is with the valley, but for the southern portion of the basin this statement is true only in a general sense, for south of Poverty there are three prominent parallel ridges, with lower and less regular belts farther east. From the latitude of Poverty northward to Pomperaug the two parallel ridges are, however, very marked, the western and higher one being continuous, the lower and eastern one frequently interrupted, and in the southern portion its relief is low and the presence of the basalt is not always apparent without search (see fig. 8). The course of this double belt is not rectilinear, but zigzag—first it runs nearly a mile about due north, then with a sharp elbow it turns N. 54° E. for another mile, then it assumes a direction N. 15° E. for a mile and a half, the two ridges being everywhere distant from one another about one-third of a mile. Northward from Pomperaug the double ridge is less prominent, although the exposures of basalt clearly extend in a direction N. 54° E. for something less than a mile, from which point the double ridge is resumed with a trend of about N. 15° E. by the twin hill known as Orenaug Hill. The exposed area in each twin of Orenaug Hill is, however, rhombic in outline instead of being a narrow belt with parallel sides, as is generally the case between Poverty and this point.

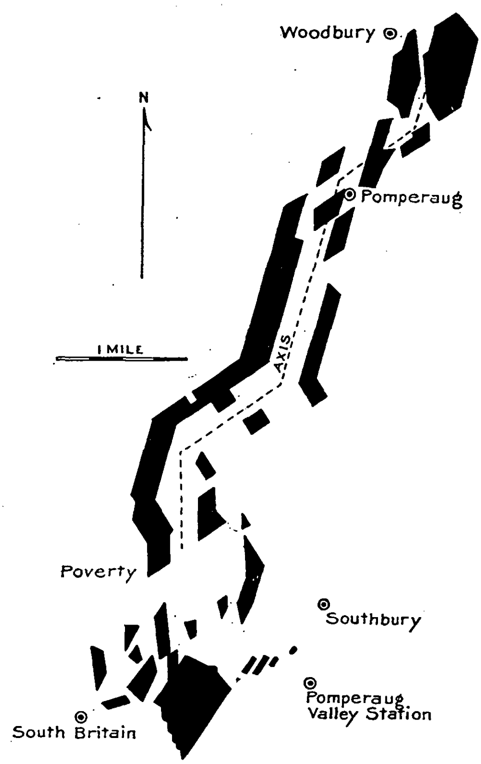


FIG. 8.—Map showing the areal development of the main basalt sheet.

The arrangement of the exposures in the vicinity of South Britain is much less simple than in the area to the northward, for a single section across the ridges would here in one direction intersect no fewer than six distinct belts. The most prominent of the basalt ridges in this vicinity are Rattlesnake Hill, the southern extension of East Hill, a parallel ridge between them, Sherman Hill (trending almost at right angles to those just mentioned), and Pine Hill, which is a complex of northerly trending ridges forming a southward extension of East Hill. A section across this ridge is shown in fig. 9. The series of ridges just enumerated are seen in profile in every view of the valley from its southern wall, but with special advantage from the railroad cut on the north flank of the hill designated on the topographic map Georges Hill (see Pl. V, *A*).

The rock of the main basalt sheet in the western East Hill–Ragland belt is a dense black basalt or diabase which rings under the hammer and offers the greatest resistance to its attacks, as well as to those of the decomposing and disintegrating forces of the atmosphere. Locally it shows nearly perfect prismatic or columnar jointing, as in the cliff

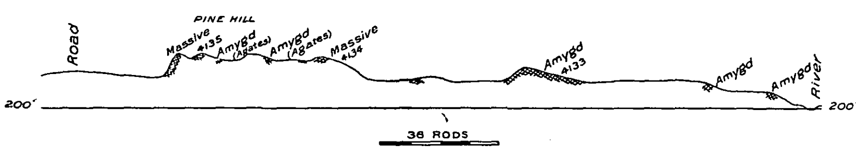
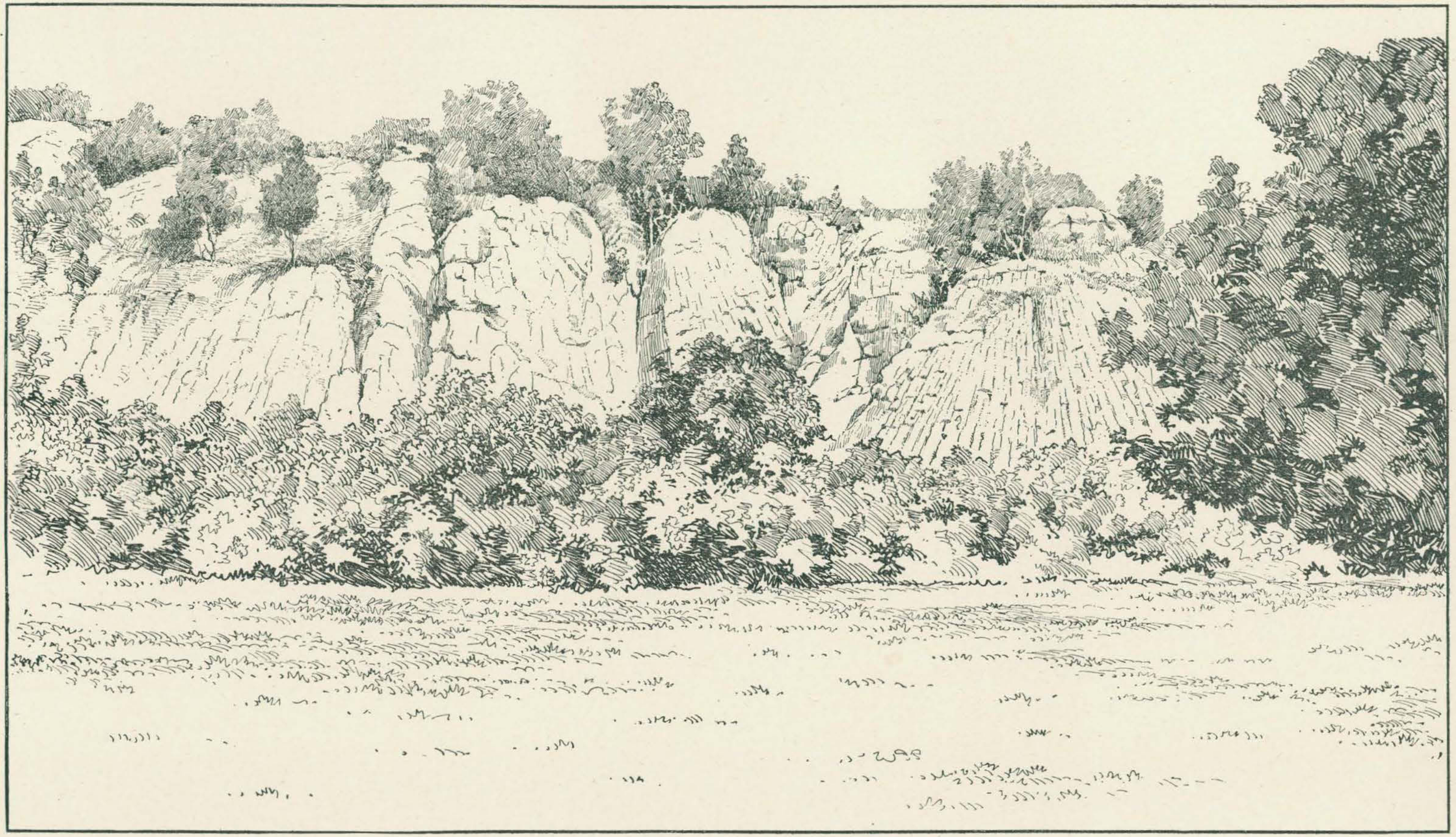


FIG. 9.—Profile of Pine Hill. The western ridges are of the more massive rock, but some of them contain evidences of vesicular texture in the presence of small, nearly spherical, agates. The eastern ridges are considerably more amygdaloidal in texture.

forming the western face of Sherman Hill, or, better, in the western cliff face of East Hill in the Poverty district. In the latter locality the structure is displayed in great perfection, the prisms radiating from centers in the almost perpendicular wall having been individually separated into segments by parting planes perpendicular to their main axes (see Pl. III). In the small "neck" shaped hill one-fourth of a mile northwest of Pomperaug Valley Station the upper surface of the exposure is crossed by thin silica veins to form a honeycomb-like network, suggesting that prismatic jointing cracks have here been subsequently healed by infiltration of silica.

It is not uncommon to find numerous minute elongated lenticular cavities in the basalt of this sheet, these vesicles being generally lined and partially filled with brown iron oxide.

In contrast with the western belt of the main basalt sheet, the eastern one is characterized by coarse vesicular structure, spheroidal parting, and, what is doubtless the natural consequence of these open structures, greater decomposition and disintegration. In comparison with the anterior basalt sheet, the vesicles of the main sheet are generally larger but less numerous, and it is generally, but not always,



COLUMNAR STRUCTURE IN THE BASALT OF THE MAIN SHEET, SOUTH END OF EAST HILL CLIFF, NEAR SOUTH BRITAIN, CONNECTICUT.

easy to distinguish specimens from the two sheets on this basis. The fresher appearance of the main basalt, however, aids in this determination. The same tendency to cover its slopes with chips of weathered rock which was noted in connection with the anterior sheet is also to be observed here.

The spheroidal parting is often very beautifully shown in exposures of this sheet—e. g., at the road corner northwest of the Oak Tree House at Southbury. It is best observed, however, on the right (western) bank of D. M. Mitchell's brook, just above the main bend and below the Stiles shale pits and due east of the "Triangle."

The cavities, which in the basalt of the southeastern areas vary from elongated lenticular vesicles filled with brown oxidation products to amygdules the size of a pea or larger filled with calcite, epidote, etc., in the northeastern area of Orenaug Hill become geodes the size of the fist or even considerably larger. These geodes are lined or even filled with very beautiful botryoidal masses of pale green prehnite, with which are associated calcite, barite, certain zeolite minerals, etc. In the area of amygdaloidal basalt located in the elbow of the eastern belt southeast of Bates Rock are found somewhat similar geodes filled with chalcedony to form agates, or lined sometimes with transparent colorless or with amethystine quartz crystals. The basalt[1] near the summit of Pine Hill, in the southwestern part of the area, contains elongated vesicles partially filled with limonite, and also almost perfect spheroidal ones a few millimeters in diameter filled sometimes with limonite, but at other times with a massive opalescent yellow to white substance which cuts glass and is doubtless either opal or chalcedony.

SECTION 2.—RELATIONS OF THE NEWARK SYSTEM TO THE BASEMENT FLOOR OF CRYSTALLINE ROCKS.

Percival states that the sandstone of the basin at one point south of the Pomperaug River (near South Britain) reposes upon the Primary (mica-slate), dipping northeastward from it toward the trap range. After diligent search at the locality I am led to believe that this statement was intended to convey the meaning that the sandstone or conglomerate beds at that point approach the crystallines, and by reason of their dipping away from them would by an assumed extension pass over them, for nowhere have I found an exposed contact of the two formations. That the Newark beds do repose upon the crystallines can hardly be doubted, since no rocks of intermediate age are exposed in the vicinity. Moreover, the attitude of the South Britain conglomerate on the northern slope of Horse Hill, correctly described by Percival as dipping away from the crystallines (toward

[1] Specimen 4135.

the trap), is presumptive evidence at least that the former arches over the latter in a great roof. The ledges of conglomerate encountered by plowing near the summit of the hill, and the great blocks of the same rock scattered over its northern slope, indicate that in all probability the uppermost bed over the entire northern summit and slope of the hill is conglomerate. That these loose blocks are of strictly local derivation seems probable from the fact that their distribution conforms somewhat closely to the topographic peculiarities believed to be characteristic of the softer rock. A probable outcrop of the conglomerate was actually found within a few rods of gneiss near the eastern foot of Horse Hill, about one-eighth of a mile south of the Curtiss place (see fig. 31, p. 92), but this locality furnishes nothing conclusive regarding the relations of the conglomerate to its floor. That a marked unconformity exists between the two systems here in question is of course to be expected from the accumulated knowledge derived from other Newark areas, and especially from the study of the Roaring Brook section at Southington, in the Connecticut Valley, by Davis.[1]

It seemed desirable, however, to uncover if possible the contact of the two systems in the Pomperaug Basin, and after several unsuccessful attempts had been made by digging, a trench was finally opened on the shoulder of Horse Hill about one-eighth of a mile south-southwest of the Curtiss place (A in fig. 31, p. 92). This trench was begun at the top of the steep slope, which below is occupied by exposures of gneiss. Above (west of) this initial point there is a sort of level plateau, strewn with pebbles of sandstone and conglomerate, and continuous without marked topographic interruption with the locality on the brow of the hill where the conglomerate has been exposed by the plow. To the eastward of the same initial point the steep slope descends a few rods to a narrow shelf, in the middle of which is a probable outcrop of the conglomerate. Below this shelf a second steep slope, with exposures of the gneiss, descends to a marsh on the level of the main highway. The probable conglomerate exposure is separated from the gneiss on both the west and east by 1 or 2 rods of difficult trenching, so that the table at the top of the section offered the best prospects of discovering a contact of the two formations. From the exposure of gneiss at the brow of the upper steep slope a trench was carried about 14 feet westward. The gneiss was uncovered at the depth of a few feet, its basset edges having been planed away to form a generally level surface, on which groovings and scratchings are still preserved—its surface was ice planed. Occupying two shallow trough-like depressions of this surface, each a few inches in width and extending to a depth of less than an inch, was found brown sandstone, which was easily scaled away with the ham-

[1] Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1898, pp. 19-26.

mer, exposing a rough gneiss bottom in each trough (c in fig. 10). From this observation it seems to be clear that the crystalline rocks (g) here form the basement on which the Newark beds were unconformably deposited, that this floor presents inequalities of surface, and that the ice of the Glacial period planed away most of the over-

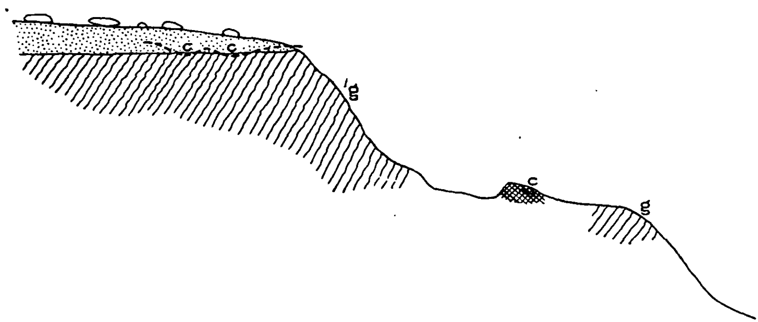


FIG. 10.—Section of the gneiss ridge of Horse Hill (locality A in fig. 31) on the Curtiss place, looking north, showing South Britain conglomerate in hollows of the glaciated gneiss surface. c, conglomerate; g, gneiss.

lying sandstone and conglomerate, leaving of it only such as was protected in the bottoms of those troughs, on the surface of the gneiss terrane, which were below the level of abrasion.

SECTION 3.—CONTACTS BETWEEN THE SEVERAL MEMBERS OF THE NEWARK SYSTEM.

A considerable number of contacts of the conglomerate with the anterior basalt have been found, and others can be uncovered by a little scratching with the hammer at a number of places. Elsewhere, for special objects, digging has been resorted to with success. In the case of the main sheet of basalt the problem has been more difficult, since the talus slopes at the foot of its cliffs and the yielding nature of the shales and limestones on either side of it would make the discovery of a contact with this member a very fortunate circumstance.

Contact of the South Britain conglomerate with the anterior basalt sheet.—The exposures of these members of the Newark system generally appear in close companionship, and in only one instance has an exposure of the amygdaloid been discovered without the observation of a distinct and parallel conglomerate ridge west of it. The bed of weathered chips, with which the basalt almost invariably covers its surface, in many cases obscures the contact of the two rocks, but a small amount of work with a spade will generally suffice to lay it bare, as has been done in a few instances. Contacts have been exposed in this manner at the following localities: First, at the point where the basalt belt makes its sharp turn to the southwest east of South Britain; second, near the hill road from D. M. Mitchell's to the oil well on the

Wheeler place; and, third, at a point a few hundred feet east of the Oliver Mitchell spring.

In D. M. Mitchell's brook, a few hundred feet above where it crosses the hill road and just below where a small rill enters from the east, the contact of the amygdaloid and conglomerate is exposed for about 10 feet in the western wall of the brook. A specimen broken from this contact showed that the fine conglomerate is to some extent incorporated in the basalt as irregular-shaped, brown, hornstone-like inclusions. (See fig. 11, representing specimen 4136). The surface of the contact, while in the exposure trending N. 45° E., or about parallel with the strike of the conglomerate, nevertheless cuts across its plane of bedding. Moreover, the surface is not a plane, but undulating, and it is apparently the original structure plane joining the two formations. (See fig. 12.) The conglomerate for a distance of several feet from the contact has been greatly indurated, so that it rings under the blows of the hammer, but it shows little evidence of bleaching.

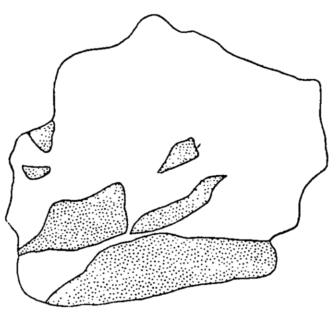


FIG. 11.—Fragments of baked arkose conglomerate in anterior basalt flow, near its under surface. D. M. Mitchell's brook section. (Spec. 4136, U. S. Geol. Survey.) Natural size.

A short distance north of this locality the bank bends sharply to the east, and in the steep left (southern) bank, only a few feet above the water surface, amygdaloid is again found in contact with the underlying conglomerate along an irregular plane which dips at an angle of about 25° SE. The conglomerate is indurated as though by baking. Near this spot is found an abundance of reibungsbreccia, but the slipping which has produced the breccia has not been along the contact of the two formations. (See p. 71.)

Just over the summit of the conglomerate bench which lies east of D. M. Mitchell's place a hard baked conglomerate is found within a few feet of the amygdaloid, but here it is bleached almost to whiteness. (Specimen 4113a.) Not far distant from this locality is a similar baked variety of the conglomerate, about 25 paces from the nearest exposure of the basalt, although, in view of the low dips of the series, this may represent but a few feet of actual distance from the former roof of basalt. The preservation of the conglomerate as a distinct ridge following the lower contact of the anterior basalt sheet with such persistence, though its beds are elsewhere only rarely exposed, is unquestionably connected with its induration by the basalt, which has thus not only prepared the conglomerate to resist the forces of disintegration, but by forming a trough has preserved its own substance as well.

As already mentioned, the conglomerate which occupies the bed of the Pomperaug River below the dam at South Britain has the same characters as the basalt-contact variety, and its origin is believed to be the same, movement along a dislocation having removed the basalt from view in a manner which will be subsequently explained (p. 89).

To summarize the observations of the contact of the conglomerate and the anterior basalt sheet, it may be stated that this surface of contact seems to be somewhat irregular for short distances at least, cutting across the bedding of the conglomerate, and, further, that irregular fragments of the conglomerate have been incorporated in the basalt, and that the former is abnormally hard and sometimes abnormally white in the vicinity of the latter.

Contact of the anterior basalt sheet with the anterior shales.—Of the four contacts of the anterior shales with the anterior basalt sheet which have been studied, three were already exposed, while the fourth was laid bare by a very little digging. Two of these are clearly fault contacts, but the other two appear to be the original structure planes joining the two formations.

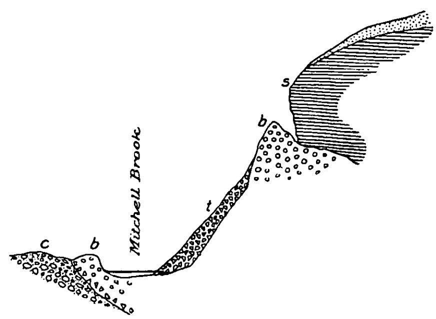


FIG. 12.—D. M. Mitchell Brook section. *c*, baked arkose conglomerate; *b*, anterior basalt; *s*, red anterior shale; *t*, talus of basalt. The parallel lines in the sediments indicate the dip of the bedding plane.

In D. M. Mitchell's brook, at the locality already referred to as the best-exposed contact of the amygdaloid with the underlying conglomerate, the basalt is in contact with the superjacent fine red shale only 25 feet (estimated) above the lower contact with the conglomerate. By a little digging this contact was exposed for 10 or 12 feet in the direction of the strike, and its surface found to be warped so that its inclination varies from 15° to as much as 60° SE. Its strike is N. ± 35° E., and the strike of the shale, which may be followed for from 30 to 50 feet, is likewise N. ± 35° E., with dip uniformly about 15° SE. The shale is everywhere soft and exactly like that observed at greater distances from the basalt. (See fig. 12.)

The other locality where a probable original contact of the amygdaloid with the shales is to be observed is 30 paces northeast of the junction in D. M. Mitchell's brook, a short distance northwest of Red Spring. (See *a*, fig. 13, for location, and fig. 14 for section.) At a depth of a few feet below the surface of the ground the upper surface of the amygdaloidal basalt was here exposed. This surface is somewhat irregular, but has an average dip of 55° E. Overlying it, after the manner of shingles on a roof, are the layers of a gray shaly limestone, which, like the red shale layers at the contact just described, appear not to have been sensibly disturbed by any local movement along the contact (see fig. 14).

The observations at the two localities agree, therefore, in indicating that the floor on which the shale and limestone were deposited was a slightly inclined one and, moreover, was possessed of notable irregularities of surface.

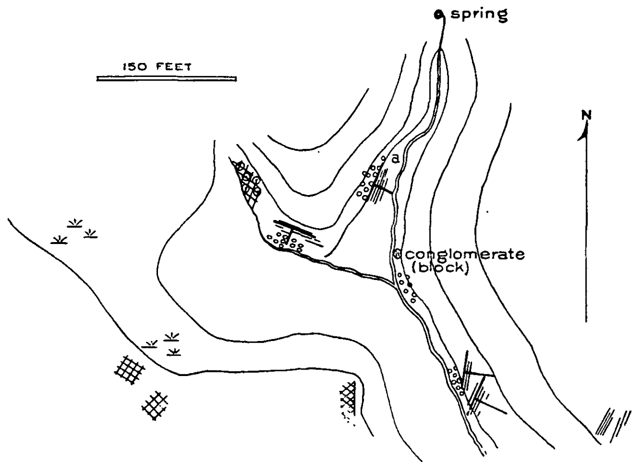


FIG. 13.—Sketch map of an area near Red Spring. a, Contact of anterior shale on anterior basalt, exposed by digging. The anterior basalt is indicated by small circles, the anterior shale by parallel rulings, and the main basalt by cross hachures. An outcrop of spheroidal basalt is indicated by the same design upon which is superimposed a set of circles.

The other exposed contacts of the amygdaloid and shale, which are located in the "spring house" section, near South Britain, are clearly fault contacts, and their consideration will be deferred until the deformation of the area is treated (see Chapter IV). One characteristic of the amygdaloid at this locality should, however, be mentioned here. By reference to the sketch map of the area (fig. 27, p. 86), it will be seen that the red shale here has outcrops in the shape of an acute triangle or wedge, the apex of which is exposed in the stream bed. The belt of amygdaloid, which is in contact with the shale upon the north, like that forming the cliff wall to the southeast, can be shown to be separated from the shale by a fault, as will be fully explained in the sequel (p. 86). The northern belt of basalt continues, however, to outcrop to the eastward in the stream bed, and it is specimens of this basalt which will

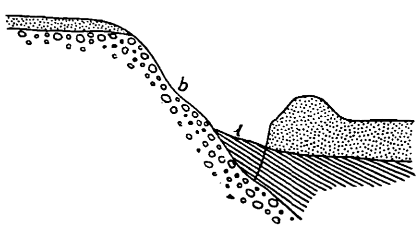


FIG. 14.—Section across the contact of anterior shale on the amygdaloidal basalt near Red Spring (locality *a*, fig. 13). *b*, basalt; *l*, shale; stippled area, cover.

now be considered. They were taken in the bed of the stream only a few feet above the apex of the wedge of shale. In them we find the usual characters of the anterior basalt sheet, there being numerous amygdules filled with calcite and chlorite, although the rock is less decomposed than the normal rock. The special feature which distinguishes these specimens from all others which I have observed is that near their upper surface (the uppermost inch or so of rock in the exposure) the coarse vesicles are filled not with infiltrated minerals, as is usual, but with the shale itself, which it would seem must have here been deposited or washed into them while in the state of fine sand or mud (see fig. 15). In the larger vesicles the shale may be seen to be made up of the same kind of particles as the shale exposed a few feet below in the stream. The shale inclosed in the vesicles of the basalt gives no evidence of any considerable induration, such as was observed at the lower contact of the amygdaloid, and the basalt in which it is inclosed is less compact than the normal portions of the rock, as shown in other parts of the same specimen, and it has, moreover, a more yellow-green color, due to the development of weathering products. It is, however, only in a thin layer, hardly more than an inch in depth, that the shale is found occupying the amygdules of the basalt. Beneath this apparently original surface layer the amygdules, although filled for the most part with calcite and the other characteristic minerals, are nevertheless, for a short distance, strongly stained by iron oxide, which has apparently been washed down from the shale above. It would seem, therefore, that this layer of basalt with intervesicular shale represents the original upper surface of the basalt sheet on which the shale was deposited, to be subsequently in large part removed by degradation so as to bring the original upper surface of the basalt at the present surface of the outcropping.

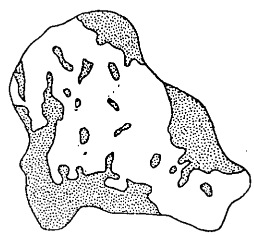


FIG. 15.—Shale deposited in vesicles of the anterior basalt near the original upper surface of the sheet. (Spec. 4139b, U. S. Geol. Survey.)

Contact of the main basalt sheet with the posterior shales.—No contact of the anterior shales with the main basalt sheet, and no actual contact of the main basalt with the overlying shales, has been observed, though shale is exposed on the west of the highway only a few feet east of the "oil well" on the Wheeler place, and the amygdaloidal upper surface of the main basalt is indicated at many places west of the well. All accounts of the rocks pierced by this boring agree in stating that, after first passing through shales, two layers of trap separated by shales or sandstones were encountered, but beyond these facts nothing is known regarding the contact of the main basalt with the shales overlying it.

SECTION 4.—SOURCE OF THE SEDIMENTS OF THE POMPERAUG VALLEY NEWARK.

In a former paragraph (p. 42) it has been pointed out that the pebbles of the South Britain arkose conglomerate are for the most part angular cleavage fragments of feldspar and subangular fragments of vein quartz, with occasional pebbles of graphic granite, muscovitic mica, and both coarse and fine granite. Pebbles of gneiss or mica-schist are present in comparatively small numbers. There can be no question that this material is largely the débris derived from the disintegration of pegmatite and granite, but principally the former, since the feldspar fragments are not infrequently of dimensions exceeding an inch, and their average size is far beyond that of feldspar crystals in a normal granite.

In the associated arkose and in the shaly beds feldspar fragments form with quartz the principal constituents, scattered among whose grains are a few glistening scales of muscovite. The material being essentially the same in the different layers of the conglomerate formation, it is assumed that all have a common origin, and that the differences in the size and in the relative proportions of the constituents are explained by the peculiar conditions of the assorting process which attended their deposition.

The crystalline rocks of the western upland of Connecticut contain large bosses of igneous granite, and pegmatization has occurred on a grand scale in some sections of the upland. An area which is in many ways remarkable because of the degree to which this process has been carried lies northeast of the Pomperaug Basin, and includes portions of the townships of Woodbury, Bethlehem, Watertown, Thomaston, Waterbury, and Middlebury. Within this area coarse pegmatites are common, and the stock granite, which with the pegmatite occupies almost the entire area, becomes in places so coarsely crystalline as in specimens to be easily confused with the true vein pegmatite.

South of this intensely pegmatized area and some distance east of the Pomperaug Basin heavy veins of pegmatite are only rarely seen, but the gneiss and granite, which are there the prevailing rocks, seem to have been thoroughly and intimately impregnated by extremely acid granitic material. Between this area and the Pomperaug Basin there intervenes a belt in which such evidences of acid injection are but rarely to be seen, and for a considerable distance west of the same area feldspathic pegmatites are not found in abundance, although the silica veins of Roxbury indicate that the region has not been exempt from acid injections. To the south of the basin also, for a considerable distance, pegmatization has not been developed to any such marked degree, although igneous bosses occur.

Unless, therefore, a very distant source is assumed, there is strong probability that the coarse feldspathic and other pegmatitic material incorporated in the South Britain conglomerate was derived from the intense pegmatized area lying to the northeast. This assumption requires that heavy rock débris shall have been transported a distance of 12 to 15 miles, but the rounded surfaces of the quartz and granite pebbles in the conglomerate indicate that they have been subjected to some wear. Either stream torrents or strong tidal currents might be competent to convey the material for this or even greater distances.

Both hypotheses require that there be, about the area of deposition, high walls possessed of considerable declivity. The hypothesis of transportation by torrents in particular assumes that the wall which supplied the torrents with their débris must have been comparatively near to the present Newark area.

SECTION 5.—FOSSILS IN THE NEWARK SEDIMENTS.

It has been known that the Newark rocks of the Pomperaug Valley contain the remains of both animal and vegetable life, the fish impressions in the shale having been incidentally mentioned by all persons who have written upon the area, yet except for the examination of a piece of fossil wood by Hitchcock[1] and the identification by Redfield[2] of *Catopterus gracilis* and *Paleoniscus* nothing is on record, so far as I am aware, concerning the fossils found in the basin. The undoubted equivalence in age of the rocks of this valley with those occupying the Connecticut Valley, where several localities have furnished abundant fossil remains, has minimized the importance of the Pomperaug Valley area in this respect. Considerable interest attaches, however, to the rather abundant remains of silicified wood which are strewn over the northern slope of Horse Hill and which have now become incorporated in the stone fences. The finest specimen that has been found, a section of tree trunk about 2 feet in diameter and over 2 feet in length, now stands on the lawn in front of the Curtiss place at the eastern foot of Horse Hill. A study of three specimens of wood collected on Horse Hill by Rev. D. F. Pierce, of South Britain, has been made by Prof. F. H. Knowlton, of the United States National Museum, and the results of his study appear in an appendix to this report. While found loose upon the land surface, the distribution of these fossil woods leaves no doubt that they have been derived from the South Britain conglomerate and probably from its lower layers. They are, so far as I know, the only fossil remains from that horizon.

The impressions of fossil fishes reported from the Pomperaug Basin have probably come either from the old coal pit (long since filled)

[1]Rept. Am. Assoc. Geol. Nat., 1843, pp. 294–296.

[2]Am. Jour. Sci., 1st series, Vol. XLI, 1841, p. 27; also, Proc. Am. Assoc. Adv. Sci., Vol, X, 1857, Pt. II, pp. 180–188.

in the gully below the "spring house" east of South Britain, or from the "Red Spring"[1] locality south of the Poverty district. Bright, glistening ganoid fish scales were found without difficulty by splitting open the gray limestone fragments at the latter locality, but no good specimens have, I understand, been found since the limestone was quarried and burned for water lime. According to Rev. D. F. Pierce, who has given considerable attention to the local geology and who has visited and collected from the Durham locality in Connecticut, several specimens belonging to two distinct species were found at that time. A specimen minus the head, but otherwise nearly perfect, and almost 6 inches in length, was found by him and sold to a mineralogist named Seymour. An even larger specimen was found by Dr. Crane, of Southbury. These and most other specimens found at the locality seem to have been lost. A fairly perfect specimen, alleged to have been found at the Red Spring locality, was, however, given me by Mr. Henry M. Canfield. This specimen has been examined by Dr. C. R. Eastman, who is inclined to regard it as an immature example of *Semionotus tenuiceps* Agassiz. This specimen is shown in Pl. IV, *A*. Another specimen has been sent me by Mr. Pierce, regarding which he says:

> I would not like to say certainly about this fish. It was found among some specimens I gave my son several years ago. The shale and the fish are like that I found here—evidently the same genus, from form of fin and scales. It is the only specimen I have or know of likely to be from this locality.

This specimen is somewhat less perfect than the one obtained from Mr. Canfield, but it is regarded by Dr. Eastman as probably *Semionotus fultus* Agassiz (Pl. IV, *B*).

While uncovering the contact of limestone with the underlying amygdaloid my assistant discovered a small specimen of a cycad which has been determined by Prof. F. H. Knowlton as *Pachyphyllum brevifolium* Newb.[2] I am not aware that any fossils have as yet been found in the shale superior to the main sheet of basalt.

SECTION 6.—ORIGIN OF THE BASALT SHEETS.

Both the anterior and the main sheets are, from their structure and composition, igneous rocks, which are believed to represent outflows of lava contemporaneous with the deposition of the Newark sediments; they are extrusive rather than intrusive in their origin. Whether poured out upon the sediments when above sea level or spread upon the bottom of the ocean shallows in which the Newark deposits were laid down it would be difficult to say, but it is not unlikely, from the inferred conditions of the Newark deposition, that these usually some-

[1] An ice-cold, constantly flowing spring which oozes out of a red mud formed from pulverized shale.

[2] This form has been described and figured by Newberry in Monograph XIV, U. S. Geological Survey, 1888, p. 89, Pl. XXII, fig. 3.

(A)

(B)

GANOID FISH REMAINS FROM THE ANTERIOR LIMESTONE OF THE RED SPRING.

(A) SEMIONOTUS TENUICEPS AG.

(B) SEMIONOTUS FULTUS AG.

THE HELIOTYPE PRINTING CO. BOSTON.

what distinct phenomena were here merged in each other, the Newark sea bottom for considerable areas at least being periodically laid bare during low water, although covered at high water.

There are several reasons for assuming that the basalt sheets are surface flows rather than sills, and these may be summarized for each sheet individually, since some additional data are available in the one case which are not present in the other.

Anterior basalt sheet.—Observations which indicate that this sheet was extrusive in its origin are: (1) The prevalence in it of coarsely vesicular structures; (2) the absence of metamorphism at its upper contact, although this is a marked feature of its lower contact; (3) the deposition of fine sandstone within the vesicles of its (presumably) uppermost layer; (4) the greater abundance of vesicles near its upper surface, as indicated at the only locality where both upper and lower contacts are exposed near each other (D. M. Mitchell brook, near road crossing); (5) the irregularities of its upper surface, which seem to be best explained as the natural irregular surface of lava on which the later sediments were laid down, it being observed that intrusive rocks generally follow either a preexistent fissure plane or the structure plane of a formation.

Main basalt sheet.—For this sheet, as well as the anterior one, the almost perfect parallelism with the associated sediments indicates that, if intrusive, it must be a sill, and not a dike. This parallelism is in the present instance shown by its areal distribution, combined with its topography, as will be apparent to anyone who studies the general map of the vicinity of South Britain (Pl. VIII), noting the dips of the conglomerate, in comparison with Pl. V, *A*, which shows the profiles of the trap ridges as observed from the southern wall of the basin.

The observations which indicate an extrusive origin for this sheet are: (1) The large size and the abundance of the vesicles in its upper zone, in contrast with the dense nonvesicular nature of its lower portions; (2) the development of columnar jointing in the lower portions,[1] and (3) the development of spheroidal parting in the upper portions of the sheet.

It should perhaps be noted that on the surface of the low ridge of basalt south of the "oil well," which apparently represents the upper portions of the basalt sheet, are strewn fragments of basalt, some of which are not unlike the projectiles or "bombs" which have been found in well-known and recent volcanic regions. In them an arrangement of elongated, balloon-shaped vesicles, radiating from a center and surrounded by more compact material, is at least suggestive of some such origin as this.

The determination of the extrusive origin of the trap sheets of the Pomperaug Valley adds one more to the list of Newark areas in which

[1] Cf. The columnar structure in the igneous rock on Orange Mountain, New Jersey, by J. P. Iddings: Am. Jour. Sci., 3d series, Vol. XXXI, 1886, p. 325.

such contemporaneous sheets have been studied. Emerson and Davis in the Connecticut Valley and Darton in the New Jersey area have clearly proved, as it seems to me, the existence of important extrusive sheets.

No evidence has been secured to locate the fissures out of which the molten material was poured to produce sheets which are now so marked a feature in the landscape. It may be that the lower contact of the amygdaloidal sheet in D. M. Mitchell's brook section is near such a feeder, for the contact plane there cuts rather sharply across the bedding of the conglomerate, as already remarked, and the rock is moreover unusually firm and dense for that bed.

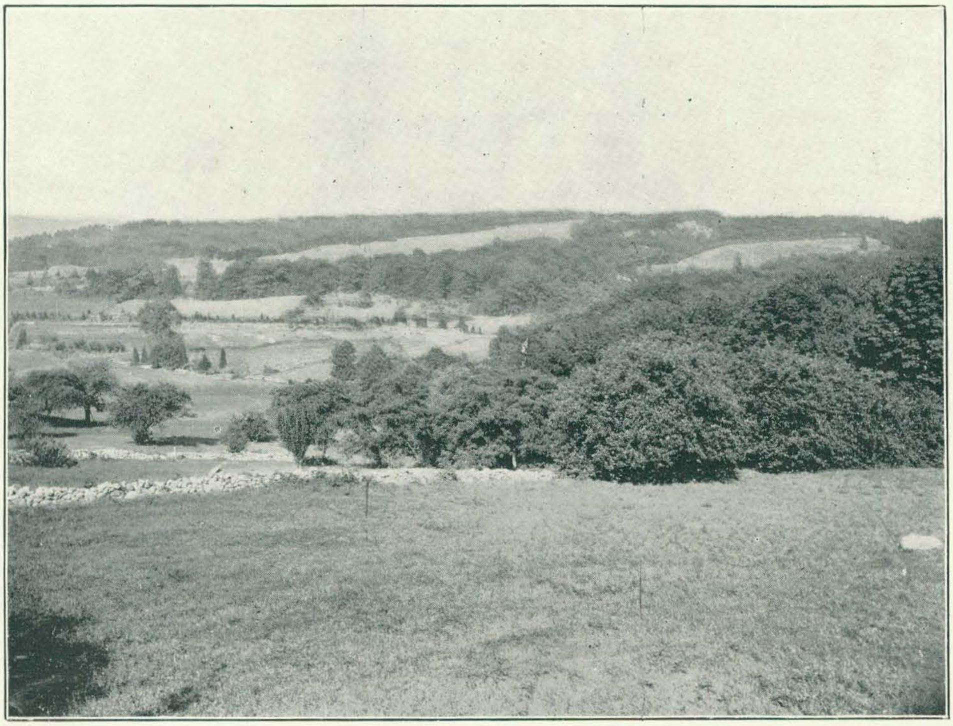
SECTION 7.—THICKNESS OF THE SERIES.

In view of the complex deformation to which the area has as a whole been subjected (see Chapter IV), any attempt to determine the thickness of the series on the basis of width of exposure and inclination of beds would yield untrustworthy results. So far as I am aware, the only basis for an estimate of the thickness of the series is afforded by the shaft of the oil well opened on the Truman Wheeler place, about 1 mile northwest of the railway station. This shaft was opened near the site of an ancient "coal pit," and was sunk by means of the plunger drill used in the Pennsylvania oil regions. For this reason no cores were obtained. The history of the enterprise, which was given up when a depth of 1,535 feet had been reached, has been given by Dr. E. O. Hovey,[1] who visited the locality shortly after the last work was done on the boring. According to his statements, black bituminous and red shales, red sandstones and conglomerates, and two trap sheets were penetrated, and at a depth of 1,235 feet the drill passed from the Newark beds into the crystalline gneisses and mica-schists. My own conversations with persons who were on the ground at the time the well was sunk, in the main confirm these statements of Dr. Hovey, who has informed me in a personal letter that he was shown the material from near the bottom of the shaft and identified it as belonging to the gneiss basement. As he states in the article quoted, "free-milling gold and silver ore was encountered in a zone near the 1,250-foot level." My own inquiries of persons living in the vicinity have elicited the information that the two basalt sheets mentioned by Dr. Hovey were encountered near the top of the shaft. It is probable, therefore, that they were the main and the anterior basalt sheets. As has already been pointed out, shale occurs as an outcrop within a few feet of the shaft, on the east, and amygdaloidal basalt (main sheet) a short distance to the west. The discovery in the dump of large specimens of reibungsbreccia composed entirely of

[1] The oil well at Southbury, Connecticut, by E. O. Hovey: Sci. Am., May 3, 1890, Vol. LXII, p. 275.

A. GENERAL VIEW OF THE BASALT RIDGES NEAR SOUTH BRITAIN, FROM THE SOUTHERN WALL OF THE POMPERAUG BASIN.

The serrated crests of the ridges mark the position of fault planes and the flattened summits indicate decapitation of the ridges by degradation. The fine river terrace at the base of the ridges is well brought out.



B. VIEW OF THE EASTERN TWIN OF ORENAUG HILL.

The view is taken from the foot of the eastern basin wall From the center of the picture a prominent scarp of the N. ± 34 ° W. series trends diagonally to the right into the distance. To the right of the scarp, in the middle of the picture, a similar but lower block is seen, which on the northeast is bounded by a parallel N. ± 34° W. scarp. This scarp is indicated particularly in the horizon line.

basalt and calcitic cement (doubtless from the ancient coal shaft) is in harmony with the observation that several faults intersect at or very near to the oil shaft (see map, Pl. VIII).

On the basis of these observations, it seems to me to be probable that the thickness of the Newark to the top of the main basalt sheet is here not far from 1,200 feet, the average dip being reckoned as 15°.

SECTION 8.—ECONOMIC RESOURCES.

In view of the fractured condition of the Newark rocks it is not to be expected that oil will ever be obtained from them. The attempts to sink shafts for coal—and there have been several—have ended in failure, and from what is known of the northern areas of Newark rocks there is not the slightest reason to believe that other attempts would be more successful.

In the vicinity of South Britain the sandstone and conglomerate have been utilized to a small extent for the foundations of houses, but the material used has been obtained largely from the loose blocks strewn over the surface of Horse Hill.

The most valuable material in the district would seem to be the dense basalt of the main sheet, which is adapted to the preparation of the very best grade of road metal. Within a half mile of the railroad station, and at numerous other localities, this material could be obtained in almost any amount desired. The sandy roads of the valley, over which the road scraper is annually dragged in a futile attempt at improvement, might, by a proper use of this material, and with an outlay but little greater in the end, be made to rank with the best in the State.

CHAPTER III.

PETROGRAPHY.

SECTION 1.—SOUTH BRITAIN ARKOSE CONGLOMERATE.

The conglomeratic phase of this formation is composed of pebbles of feldspar, quartz, graphic granite, both fine and coarse granite, gneiss, mica-schist, etc., in a matrix of finer fragments, all more or less reddened by iron and cemented by calcite. Sections prepared from the granite, gneiss, and schist pebbles indicate that they are not unlike the crystalline rocks of the surrounding upland. The finer-textured rocks of the formation, both red sandstones and red shales, are, in their normal condition, not suited for section cutting, and it is necessary to study them in sections prepared from the slightly indurated specimens. A specimen from the fault locality near the Oliver Mitchell spring (4140) indicates only a moderate amount of baking, the color being a pale brown, although indicating some variation in this respect. This rock is composed mainly of quartz and feldspar in angular fragments, the former, which is the more abundant, being often of a deep red-brown color.

Under the microscope the fragments of quartz and feldspar are seen to be very angular and to vary considerably in size. The quartz shows undulatory extinction and occasional banding. The feldspar is in part microcline and in part albite. The interstitial cementing material is very largely calcite, which is not twinned to any marked degree. An occasional fragment of fine crystalline limestone was observed in this section. Among the minerals present in less abundance are muscovite, greenish biotite, garnet, tourmaline, staurolite, and magnetite, all of which are apparently fragmental.

Intraformational shale conglomerate.—The intraformational conglomerate of Horse Hill is composed of much flattened, brown, angular pebbles of shale somewhat sparsely distributed through arkose beds of notably even grain. The pebbles have extreme dimensions of 2 cm. or more, and the base is finely speckled with white feldspar grains standing out sharply from the light brown of the mass, which in addition to this constituent shows quartz and mica. The examination of the slide reveals, further, that the feldspar is slightly more abundant than the quartz, and is in part microcline and orthoclase and in part acid plagioclase. The mica is both muscovite and a greenish biotite.

PLATE VI.

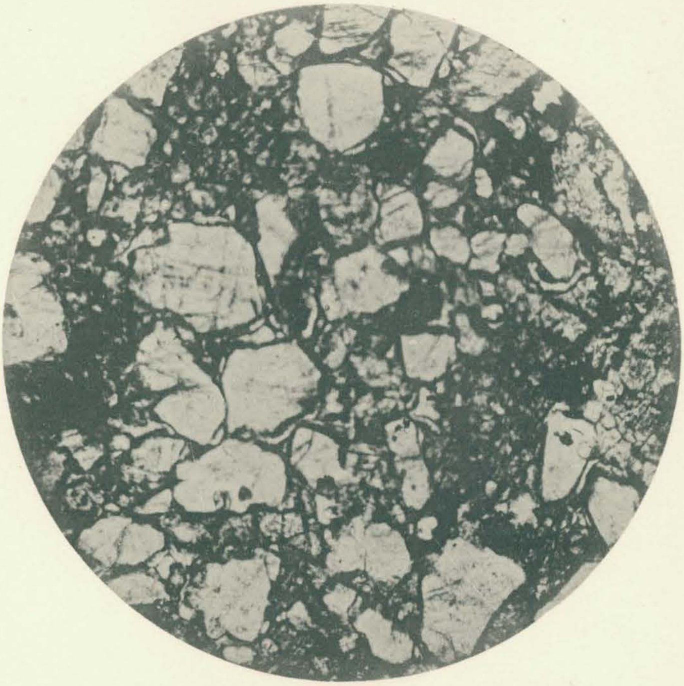
PLATE VI.

PHOTOMICROGRAPHS OF ROCK SECTIONS.

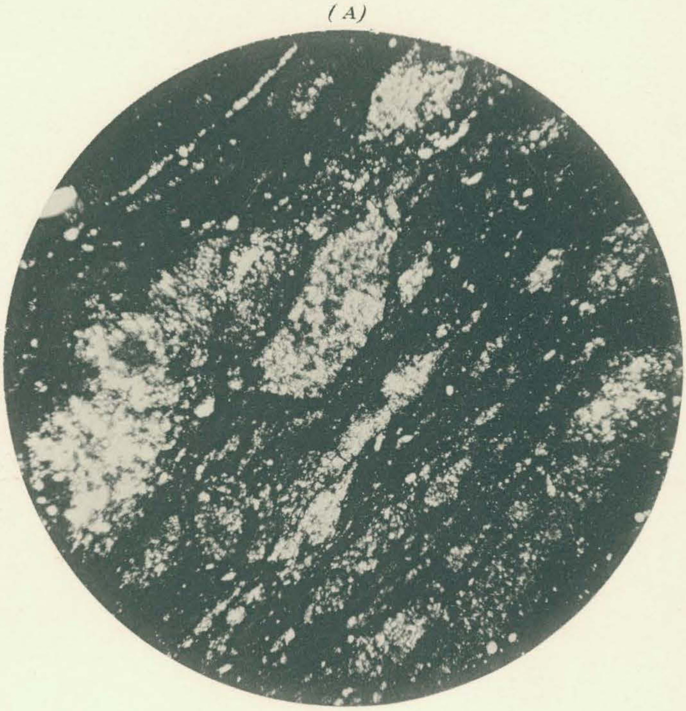
A.—Indurated arkose conglomerate from near contact with overlying sheet of anterior basalt. Southwestern shoulder of Pine Hill, South Britain. (No. 4113a.) Ordinary light. Magnified 25 diameters.

The most striking evidence of the induration is found in the enlargement of the quartz fragments.

B.—Fragmental bituminous limestone from Red Spring. Ordinary light. Magnified 25 diameters.



(A)



(B)

(A) INDURATED ARKOSE CONGLOMERATE.
(B) FRAGMENTAL BITUMINOUS LIMESTONE.

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Garnet and tourmaline are abundant, in generally broken crystals, except when they are entirely inclosed within quartz grains. The rock is notably free from cementing material, the grains interlocking together to produce in the hand specimen a somewhat miarolitic structure. By reason of their deep-brown color the shale pebbles are prominent features in the slide. Some are so fine in grain as to reveal little save their uniform brown color. In a few others which have a coarser texture angular fragments of quartz, feldspar, muscovite, and biotite are made out, showing that they are, as regards their composition, practically identical with the mass of the rock. As regards their shape, they are angular, showing no evidence of abrasion of edges and angles.

Contact effects in this formation.—While the arkose described from the fault near Oliver Mitchell's has clearly been hardened and to some extent whitened by the heat of the overlying sheet of basalt, it does not show the full effect of that indurating process. A specimen (4113a) from a point but a short distance north of the road southwest of Pine Hill, although taken from a point distant a number of feet from an actual exposure of basalt, was probably very near to the original contact plane. It is mainly composed of quartz and pink feldspar fragments, the latter alone imparting to the rock its pale salmon color, since the quartz grains are colorless. The lens reveals, in addition to the quartz and feldspar, scattered scales of muscovite and a few minute ones of biotite. The average grain of the rock is smaller than a pin head, but occasional feldspar fragments reach dimensions of one-eighth of an inch or more. The latter are angular, although the quartzes are found to be considerably rounded.

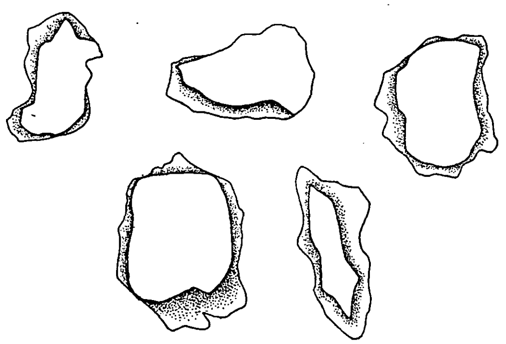


FIG. 16.—Secondarily enlarged quartz grains in the South Britain arkose conglomerate. Magnified about 50 diameters.

When this rock is examined under the microscope it is seen that the quartzes are almost uniformly enlarged by secondary accretions of silica, the newly formed quartz being orientated like the core on which it forms, the somewhat worn and weathered surface of the nucleal quartz grains being preserved only in a thick line of dark material. (See fig. 16 for form of individual grains, and Pl. VI, *A*, for general characters of the rock.) The quartzes generally contain some cloudy material as inclusions, and frequently also capillary needles of rutile. Feldspar is for the most part very fresh and finely twinned microcline, with occasional grains of acid plagioclase and untwinned feldspar. The cementing material is calcite, but in comparison with that of the less intensely metamorphosed rock it is present in smaller amount and is to a larger extent twinned polysynthetically. In addition to the accessory minerals observed in the specimens, the slide reveals a little uralitic hornblende, garnet, black tourmaline, sphene, zircon, and magnetite. In one instance sphene appeared to surround the garnet in a halo.

It is believed that the evidences of strong deformation which are found in the wavy extinction and in the banding of the quartz grains in all phases of this rock date from a period when these grains were constituents of the crystalline rocks of the region, and hence they are in no way to be connected with the metamorphism of the conglomerate.

SECTION 2.—ANTERIOR BASALT (OLIVINE-BASALT).

This rock has not been found in perfectly fresh condition, its open vesicular texture and the small thickness of the horizon making it easy to explain its generally decomposed condition. The body of the rock in the fresher specimens is dull gray, with a purplish or greenish tone, in which are recognized, in many instances at least, fine red specks similar to those characteristic of the navite type of diabases. The vesicles are sometimes roughly spherical and a half inch or more in diameter, but more generally they are extended and may be even vermiform. In a majority of instances they are filled with calcite, less frequently, however, with a green chloritic mineral, which is doubtless identical with the diabantite described by Hawes from the basalt of the Connecticut Valley.[1]

In the slide the long laths of feldspar piercing the other constituents and entirely lacking in any uniformity of orientation produce the typical ophitic or diabasic texture. With a length averaging perhaps ten times their thickness, these feldspar laths are twinned according to the albite law, so as to produce a few wide stripes only in each lath. Carlsbad twins are rare, while pericline twins were not observed. Measurements of extinction angles against the twinning line indicate that there is probably but a single feldspar present, and this is either a basic oligoclase or an acid andesine. In the fresher specimens the feldspars have been but little altered, but in others a pale-pink staining and a lack of definiteness in the twinning bands indicate incipient alteration.

The principal nonfeldspathic constituent of this basalt is a secondary mineral aggregate distributed in little areas which the feldspar laths penetrate and from which they project. These areas have a faint

[1] On diabantite, a chlorite occurring in the trap of the Connecticut Valley, by Geo. W. Hawes: Am. Jour. Sci., 3d series, Vol. IX, 1875, p. 454.

pleochroism in lighter and darker tones of chlorophyl green. Examined between crossed nicols, this material is seen to be made up largely of fine fibers and to have interference colors as high as red of the first spectrum. The extinction is inclined, the angles sometimes being as high as 15°. The fibers are positive, the longer axes corresponding with the lesser axis of elasticity. These properties are those of a uralitic hornblende, which is believed to be present in association with some chloritic material. That this material has been derived from pyroxene there can be little doubt, since the shape of the areas is often strikingly like that of pyroxene grains in basalts, and, further, the texture of the rock and its relationships to other basalts of the Newark system raise this probability almost to a certainty. Scattered patches of a darker, and in the slide nearly opaque, material are made out to be in large part composed of feather-like growth-forms of magnetite, such as are common in the basalts (fig. 17). The base in which the arborescent magnetite growths are embedded is in part uralite and in part calcite, but in places it seems to be a nearly isotropic substance colored by ferrite. It is not unlikely that these patches represent devitrified rock glass, into which the calcite and uralite were subsequently introduced.

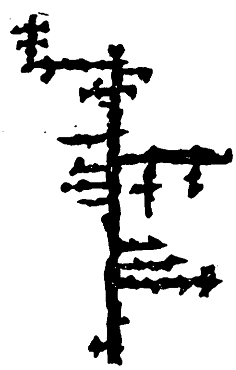


FIG. 17.—Arborescent forms of magnetite in basalt (magnified).

In addition to the patches just described there are large and small areas of a more finely fibrous green alteration product of low double refraction. Stains of iron cross these areas irregularly in some sections and probably correspond to the red specks which are noted when the rock is examined under the lens. This material is probably serpentine stained by iron, and both its irregular mesh texture and the outlines of some of its larger areas favor the view that it is derived from the serpentinization of idiomorphic grains of olivine. There is much calcite in the slides, and the amygdules are also filled chiefly with this mineral, though prehnite is also recognized in some of the latter. In some of the amygdules filled with calcite the central portions are stained brown, leaving a white rim of nearly uniform width.

A specimen taken from this basalt sheet southwest of Pine Hill has been analyzed by Dr. W. F. Hillebrand, with the following results:

Analysis of specimen from anterior basalt sheet near Pine Hill, Connecticut.

		Per cent.			Per cent.	
SiO_2		47.52	.792	BaO	Tr.	
TiO_2		1.19		MgO	6.84	.171
Al_2O_3		13.91	.136	K_2O	.77	.001
Fe_2O_3	7.06 (.004)	} a 10.82		Na_2O	3.06	.005
FeO	3.76 (.005)			Li_2O	Str. tr.	
NiO		Tr.		H_2O (below 105°)	1.75	
MnO		.18		H_2O (above 105°)	4.55	
CaO		5.71	.102	P_2O_5	.15	
SrO		None.		CO_2	3.68	
				Total	100.13	

The above analysis indicates large amounts of water and carbon dioxide, which have been introduced in the process of weathering. A

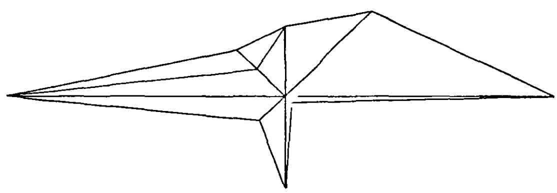


FIG. 18.—Brögger diagram to show the composition of the anterior basalt.

better idea of the unaltered rock will be obtained if the analysis is recalculated neglecting the water and carbon dioxide, as has been done in Table II, column 1, on p. 78. The analyses of two weathered varieties of the Connecticut Valley basalt from the main flow are placed in

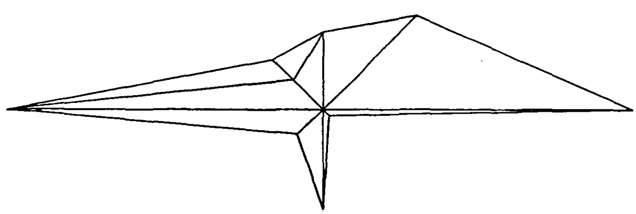


FIG. 19.—Brögger diagram to show the composition of the anterior basalt. Corrected for weathering.

column 2 of Table I (on p. 77), beside the South Britain rock. Recalculated, neglecting the water and carbon dioxide, they are printed in column 2, Table II, beside the recalculated analysis of the South Britan rock. Lévy-Brögger diagrams made from the corrected and

a Not corrected for pyrrhotite nor for V_2O_3, if present.

PLATE VII.

PLATE VII.

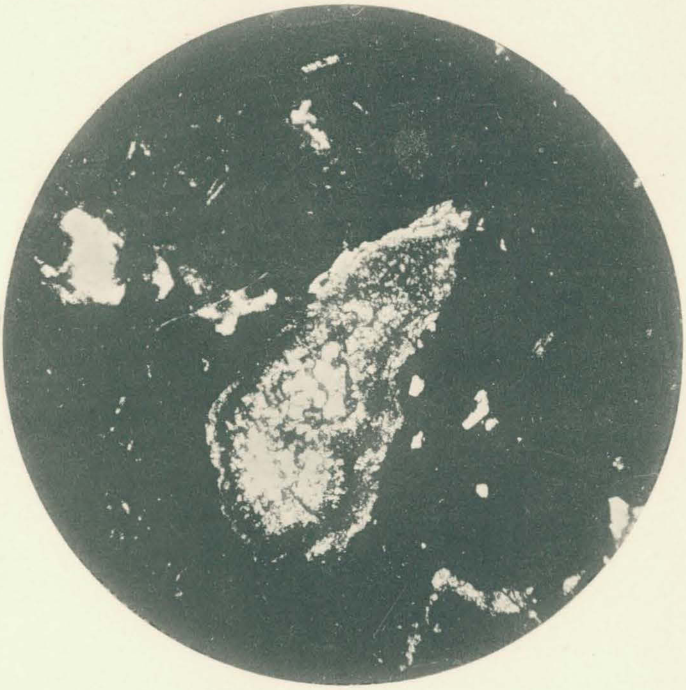
PHOTOMICROGRAPHS OF ROCK SECTIONS.

A. Upper surface of anterior sheet of basalt, showing amygdaloidal cavities filled in part with brown arkose and shale and in part with calcite, the latter filling the spaces left by the former. Bed of brook in the "spring house" section, South Britain. (No. 4139b.) Ordinary light. Magnified 25 diameters.

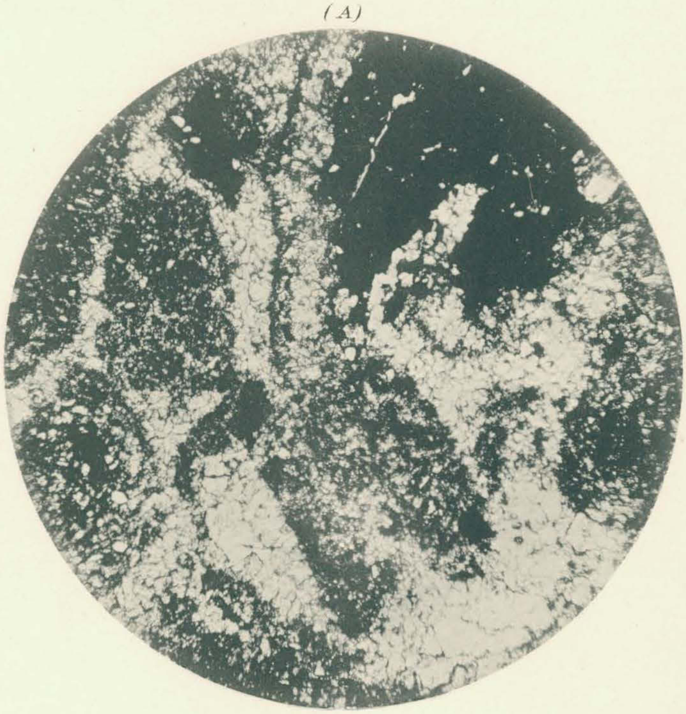
The arkose and shale is but poorly outlined from the surrounding altered basalt of the somewhat thick section. The calcite has a somewhat fibrous outer zone, but is granular within.

B. Fault rock (reibungsbreccia) near contact of anterior basalt and arkose conglomerate, D. M. Mitchell's brook, above bend, South Britain. (No. 4137b.) Ordinary light. Magnified 25 diameters.

The fragments of the breccia are of arkose conglomerate, anterior basalt, and anterior shale and limestone, cemented by calcite.



(A)



(B)

(A) UPPER SURFACE OF ANTERIOR SHEET OF BASALT.

(B) FAULT ROCK NEAR CONTACT OF ANTERIOR BASALT AND ARKOSE CONGLOMERATE.

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uncorrected analyses of the South Britain rock are shown in figs. 18 and 19, the second being from the recalculated analysis.

The surface layer of the basalt sheet.—Reasons have been given (p. 53) for supposing that specimens collected from the bed of the brook in the "spring house" section represent the original upper layer of the basalt sheet. These specimens on their upper side have exceptionally large vesicles (an inch or more in length) filled with sandstone, whereas lower down the rock is fresher, the vesicles are smaller, more nearly spherical, and filled with calcite, in part stained with iron.

In the section of this rock the feldspar is in laths so fine and so numerous as to produce a felty texture, although some tendency is noticed for the feldspars to group themselves in sheaves. Uralite occupies a few large scattered areas, sometimes having the outline of basal sections of pyroxene. A large amount of disseminated gray material, probably leucoxene, renders the feldspar laths and the rock section as a whole very difficult to study. The magnetite fronds which were observed in the normal rock are here unusually fine, and the texture of the rock throughout is finer than in the normal specimens and the decomposition is noticeably greater.

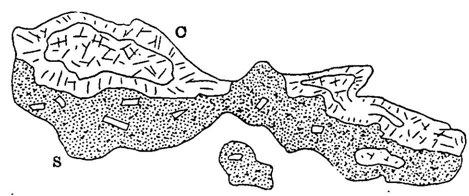


FIG. 20.—Arkose, shale (S), and calcite (C) together filling vesicular cavities in the upper surface of the anterior basalt (magnified). The calcite is bladed in a zone lining that portion of the cavity not already filled by the arkose, but within this zone the bladed character is wanting.

The slide shows amygdules partially occupied by sandstone, with calcite filling the remaining portion of the cavity, and possessing a structure which indicates that it formed after the sandstone was deposited (See fig. 20; also Pl. VII, *A*). The sandstone shows no evidence that it has been baked, but is brown and nearly opaque, except for the fragments of feldspar which it contains. One very large vesicle in the section contains fragments of the rock itself, as well as grains of the sandstone, all in a cement of calcite.

SECTION 3.—ANTERIOR SHALES AND LIMESTONES.

The shales of the anterior horizon are red, friable masses generally but poorly cemented. The material of which they are composed is finely comminuted, and under the lens it is possible to make out only the fine pink fragments of feldspar and thin white scales of muscovite. In specimens from the spring-house section, near the contact with the amygdaloid, the shaly structure is less marked than is usually the case, and irregular greenish sandy patches appear in the rock. A slickensided surface forms one side of the specimen, and these unusual characteristics are doubtless to be ascribed to the fracturing of the rock and slipping along a fault plane, as will be fully explained later.

The limestones of this formation are either gray or black, according as they contain little or much bituminous matter. The gray specimens in sections are seen to be composed almost entirely of calcite grains, among which are disseminated a few grains of quartz.

The bituminous limestone from near Red Spring is an almost black shaly limestone in which is found an occasional well-preserved ganoid scale. On the weathered edge of the specimen siliceous layers project with almost knife-edge sharpness. The rock can be split with some difficulty along the plane of bedding, giving off a strong bituminous odor as it is being broken. It is attacked with vigor and in great part dissolved by cold hydrochloric acid.

Under the microscope the coarser layers of the rock are seen to be composed of angular fragments of limestone with an occasional grain of quartz, all surrounded by the dark-brown seams of bitumen. The thinner layers contain much larger proportions of silica and the fragments of limestone are smaller. Irregular cracks traverse the rock in a direction transverse to its bedding, and these are filled by the dark bituminous matter. In general the limestone fragments which compose the mass of the rock may be described as subangular to angular, and it is probable that organic matter was deposited among them, in part fragments of coal plants and in part fish remains, and when the overlying sheet of basalt was poured out upon the shales and limestone the organic matter thus imprisoned between sheets of basalt was distilled by the heat communicated and the bituminous product resulting permeated all the interstitial portions of the rock. In the southern areas of the Newark system coal plants have been locally distilled, with the production of coke residues, by the heat communicated by intruded basalt.[1]

The granular texture of this limestone, which would hardly have been detected but for the bitumen present, is full of suggestion regarding the origin of this structure. There are at least four hypotheses which might be advanced to account for it: First, it might be assumed that the structure is secondary to the formation of the rock, or, in other words, it is a cataclastic effect of dynamometamorphic action; second, the limestone may have been formed in the same manner as the shales and sandstones in association with it, with the single exception that its material has been derived from the crystalline limestones instead of from the gneisses and acid intrusives; third, the material out of which the rock was formed may have been derived from some area of limestones belonging to a higher horizon than the Cambro-Silurian, a view requiring the assumption of a wide area of deposition for the Newark system of rocks; and, fourth, it may be assumed that the material was derived from a reef or reefs.

---

[1] Cf. Shaler and Woodworth, op. cit.

The first hypothesis may, I think, be safely dismissed from consideration, inasmuch as the deformation of the area has not been of the kind to produce schistosity. This is clearly shown by the tectonic structure of the area (to be presently discussed), as well as by the intimate texture of the associated beds in the comformable series. The second hypothesis is a simple and natural one, although the more extensive areas of limestone in the crystalline uplands are somewhat distant from the present basin. Against this hypothesis is the observation that the fragments of limestone in the rock do not have the coarse crystalline texture of the crystalline limestones of the uplands. The third hypothesis, which assumes that the source of the material is a later bed of limestone, is one that seems to the writer to have much in its favor. It assumes a large area of deposition for the Newark rocks, but, as will be shown later, there are other facts which point in this direction. The freedom of this limestone bed from any considerable admixture of arkose material may be explained by such a wide extension of the anterior basalt flow as to cover all the nearlying areas of crystallines. As regards the fourth hypothesis, it is hardly reasonable to assume the formation of local reefs, since the conditions of Newark deposition, as inferred from the associated sediments and from remnants of life forms, are not the ones suited to the formation of coral reefs. If the material was supplied from reefs, it must be assumed that it was brought into the areas of deposition through the agency of tidal currents.

SECTION 4.—REIBUNGSBRECCIAS.

Specimens of reibungsbreccia have been collected at four localities, viz: In the south wall of D. M. Mitchell's brook at the principal bend above the road bridge; on the hill slope to the northeastward of this locality; near Oliver Mitchell's spring (discovered by digging); and at the oil well on the Wheeler place, where the specimens were collected from material removed from the shaft. All specimens, save the one last mentioned, were found between walls of anterior basalt, South Britain arkose conglomerate, or anterior shale. Specimens from the oil well show one wall of amygdaloidal basalt which with much probability is from the upper portion of the main sheet. This is assumed not alone from the petrographical characteristics of the rock but from its occurrence in the immediate vicinity of the wall. From the size of the fragments found it is evident that they came from near the surface of the shaft, before the main drill hole was begun. The fragments in this breccia are all of the wall rock itself.

At the locality in the wall of D. M. Mitchell's brook, the southern wall of the fault in which the reibungsbreccia was formed shows a contact of conglomerate with overlying amygdaloid, and it is therefore not surprising that some of the specimens of the breccia have a wall of conglomerate and some a wall of basalt. The angular rock fragments in the breccia are of these two rocks (the former apparently in all cases baked) and, perhaps in greater abundance than either, the overlying shale. This latter rock, from its friable nature, was easily detached during the dislocation and dropped down in the fissure. The fragments of all these rocks are cemented by a zone of bladed or almost fibrous calcite, and calcite of a more granular texture fills in most of the remaining space so as to heal the fissures. When not completely healed, the calcite projects into the cavity in dog-tooth crystals ($21\bar{3}1$), some of which are modified by the one-half rhombohedron ($01\bar{1}2$). These crystals are sometimes three-fourths of an inch or more in length. Occasional crystals of white fluorite are found projecting into the cavity, and are easily recognized by their cubic form and their perfect octahedral cleavage. The largest crystals I have found here are about one-fourth-inch cubes, but Mr. Canfield reports finding inch cubes in the bed of the brook. Tabular pink or white crystals of barite are present in some cavities, but only in subordinate quantity. In one specimen a deep-purple fluorite was found. In a breccia specimen from near the Oliver Mitchell spring calcite crystals are coated with a very thin film of a mineral having a brilliant metallic luster and a copper color. Enough of this was obtained to color a borax bead with the yellow-green color of iron. The substance is doubtless hematite.

Sections of the reibungsbreccia are chiefly interesting in showing, in addition to what is observed in hand specimens, that limestone fragments are included, a single slide showing fragments of amygdaloid and baked conglomerate (in contact), red shale, and limestone, thus furnishing representatives of the three lower members of the Newark system. (Pl. VII, *B*.) The calcite which has formed the cement is in its coarser facies plumose, with curving planes which under the microscope are found to be twinned polysynthetically in curving lamellæ of microscopic fineness.

SECTION 5.—MAIN BASALT.

Two rather distinct types of this rock are recognized in the field—the dense black rock of the lower zone, found chiefly in the western ridges, and the more open-textured and weathered type of the upper zone, found in the eastern areas and in occasional exposures in the southwestern portion of the region. Additional distinguishing characteristics are made out for each of these zones by microscopical examination.

By a microscopical examination the fresher rock from the lower zone shows some variation in coarseness of texture, the extreme western ridges of Pine, Rattlesnake, and East hills showing the coarsest textures.

In the coarser varieties the naked eye detects stout white feldspar laths in single individuals or in knots, each a few millimeters in length, embedded in a green base in which the lens reveals fine felt-like laths of a second generation of the feldspar. A little higher up in the sheet of basalt elongated cavities with a rusty-brown appearance are noted in these feldspars. In the northwestern portion of the Pine Hill ridge spherical masses the size of a small pea, possessed of a more or less pearly and superficial luster, are found scattered through the rock. These cut glass readily and are clearly agates.

Under the microscope the rock is found to have an ophitic texture, similar to that observed in the anterior basalt. The feldspars of the first generation are stout crystals with a zonal structure, representing an extreme variation of about 5° in extinction angles. They are frequently in knot-like aggregates of a few individuals, and are generally Carlsbad twins with a few albite lamellæ in one of the individuals. Pericline twinning is not uncommonly combined with this. Particularly in the rock from Rattlesnake Hill these phenocrysts contain large and irregular cavities, whose principal extension is related to the crystallographic axes, such cavities as frequently result from rapid growth (see fig. 21). The feldspars of the second generation are laths twinned according to the albite law (in few stripes), and not infrequently according to the Carlsbad law as well. They are, like the crystals of the first generation, quite generally fresh, and it was found possible to determine both by the methods of Michel Lévy.[1] There seems to be but little difference between the composition of the feldspars of the two generations, measurement of extinction of albite twins in the symmetrical zone giving for both varieties double angles as high as 70°. Examination of the Carlsbad twins which showed also albite lamellæ in one of the individuals furnished the following measurements:

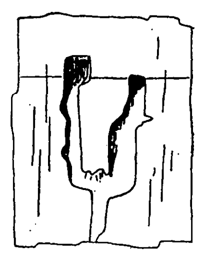


FIG. 21.—Form of cavities in feldspar of the main basalt (magnified).

Extinction angles near the symmetrical zone of feldspars.

	1.	2.	3.	4.
Albite 1	19°	20°	39°	39°
	(Av. 20.5)	(Av. 23)	(Av. 37)	Av. 36.5)
Albite 1′	22°	26°	35°	34°
	(Diff. 16.5)	(Diff. 14	(Diff. 23)	(Diff. 24.5
Carlsbad 2′	37°	37°	14°	12°

[1] Étude sur la détermination des feldspaths dans les plaques minces, etc., by A. Michel Lévy, Paris, 1894, p. 29 et seq.

Nos. 1 and 2 of the above table represent the more acid labradorite, of composition near $Ab_1 An_1$, and Nos. 3 and 4 the more basic ones, with composition near $Ab_3 An_4$.

Although usually moderately fresh, the feldspars in some specimens contain fine green uralitic and chloritic fibers in fine lines crossing the crystal. These lines have a common direction for the entire section, and since the green material can hardly have originated from the feldspar itself, but was in all probability introduced from the alteration of other constituents, it seems likely that these lines represent microscopic slipping planes (quetschzonen) located in the vicinity of and parallel to a larger dislocation (see fig. 22).

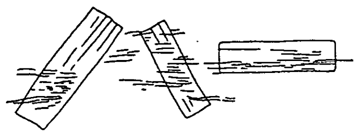


FIG. 22.—Microscopic slipping planes (quetschzonen) in the main basalt (magnified).

The principal nonfeldspathic constituent of the rock is a colorless, or at most a faint pink, nonpleochroic pyroxene. The indications of crystal boundaries are here present, although the feldspar laths pierce the grains. Cleavage is perfect parallel to the prism, with imperfect parting parallel to one or both of the vertical pinacoids. The double refraction appears to be a little lower than in the normal diabase-pyroxene. Like the feldspar, the pyroxene is almost entirely unaltered except when found in the upper zone of the basalt sheet. The serpentinized areas observed in the anterior basalt, and supposed to represent olivine "rests," are not found here, and although small areas stained with iron are found in some sections, olivine, if present at all, must be in very insignificant quantity. More opaque areas, in which magnetite (or ilmenite) fronds of skeleton-growth forms are generally present, are supposed to represent the rock base—with much probability a glass in its first solid condition. Some of the few scattered amygdules (not present in all sections) are spherical, others irregular, and both are generally filled either by uralite, by a deep blue-green chlorite (diabantite?), or by calcite. The uralite and chlorite are in radial fibrous aggregates, which not infrequently are surrounded by a zone of opaque ore material, about which is a zone of agate (fig. 23). The spherules observed in the hand specimens from the northern portion of the Pine Hill ridge, and supposed to be agates, are here seen to have a radial fibrous structure, with the low negative double refraction of that mineral.

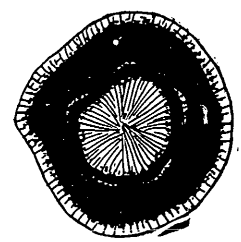


FIG. 23.—Diabantite, ore material, and agate in vesicle of main basalt. The radial mass occupying the center is diabantite, the opaque material surrounding it is magnetite or ilmenite, and the outer rim is agate. (Magnified.)

The dense rock from the summit of the cliff of Pine Hill, east of D. M. Mitchell's, has been analyzed by Dr. W. F. Hillebrand, with the following results:

Analysis of rock from summit of Pine Hill, near South Britain, Connecticut.

		Per cent.	
SiO_2		52.40	.873
TiO_2		1.08	
Al_2O_3		13.55	.133
Fe_2O_3	2.73 (.002)	*a*12.52	
FeO	9.79 (.013)		
NiO		Tr.	
MnO		.26	
CaO		10.01	.179
SrO		None.	
BaO		Tr. (?)	
MgO		5.53	.138
K_2O		.40	.000
Na_2O		2.32	.004
Li_2O		None.	
H_2O (below 105°)		.62	
H_2O (above 105°)		1.05	
P_2O_5		.12	
CO_2		None.	
FeS_2, Fe_7S_8 *b*		.13	
Total		99.99	

The Lévy-Brögger diagram of this analysis is shown in fig. 24.

The rock of the upper layers of this sheet of basalt is not only more open textured and more weathered than that which has just been described from the lower zone, but other differences are detected.

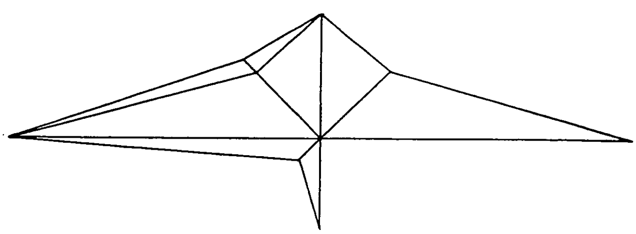


FIG. 24.—Brögger diagram to show the composition of the main basalt.

Blebs of black rock glass or tachylite several millimeters in diameter may be observed in the rock from some localities, as, for example, at the road corner southwest of the Oak Tree House at Southbury, and in the road southeast of the Ragland area. These glassy blebs turn brown and gray on strong ignition, but do not fuse.

On examination in microscopic sections the texture of this rock is seen to be generally finer and the feldspar laths of the second generation more numerous and more acicular than in the rock from the lower zone, a felty texture being the result. The feldspars of the first generation are much altered, in many a central core having the shape of the entire crystal being occupied by green uralitic and chloritic material.

a Not corrected for pyrrhotite nor for V_2O_3, if present. *b* Pyrrhotite calculated as pyrite.

The peripheral zone of these phenocrysts, and the feldspar laths of the groundmass as well, are filled with cloudy particles, indicating an incipient stage of alteration. The indications are that the more basic core of the phenocrysts was altered to calcite, and this being subsequently dissolved and removed, left spaces into which the uralite and chlorite were conducted from the alteration of the pyroxene constituent. The latter mineral has, however, suffered only a slight alteration of this kind. The fronds of ore material are generally localized in areas, but are associated in most cases with considerable leucoxene. The specimens from the road southeast of Ragland do not contain these fronds, but the ore material (probably ilmenite) is in large crystals with outlines of the rhombohedron. The many small amygdules of irregular outline are generally filled with a yellowish material which was not more definitely determined. One of the largest spherical blebs of glass was included in a slide, and while nearly isotropic, it shows the presence of small fronds of opaque ore material.

From the foregoing it is probable that the anterior basalt differs in its original composition, and to some extent also in its structure, from the basalt of the main sheet. Instead of a labradorite, its prevailing feldspar is a basic oligoclase or an acid andesine. The older rock contains also a considerable quantity of serpentinized olivine, which is nearly or quite absent from the main sheet. The analyses recalculated so as to exclude water and carbon dioxide indicate this difference in the higher magnesia and lower calcite percentages of the anterior basalt, although the smaller quantity of the latter constituent may perhaps be in part explained by its solution and removal from the rock.

SECTION 6.—RELATION OF THE BASALTS OF THE POMPERAUG VALLEY TO THOSE OF OTHER AREAS OF THE NEWARK SYSTEM.

The quite remarkable uniformity in density and in composition observed to characterize the Newark basalts of the Atlantic border was first emphasized by the late Prof. James D. Dana,[1] and very naturally ascribed by him to a unity of origin. Everyone who has since studied the Newark rocks seems to have been impressed in the same manner. Yet recent investigations have shown that the basalt of these areas is in part intrusive and in part extrusive; that the latter not only displays some variety of texture, but was poured out at different geological epochs, and that the intrusive material is in part in heavy sills and in part in dikes.

In order to ascertain whether any chemical differences could be detected between the basalt of the extrusive and of the intrusive masses, as well as to show the average composition of the Newark basalts, the most reliable analyses of each type collected from the

[1] On some results of the earth's contraction from cooling, by Jas. D. Dana; Pt. IV, Igneous ejections, volcanoes: Am. Jour. Sci., 3d series, Vol. VI, 1873, p. 106.

northern and central portions of the province were brought together and a composite[1] of each was produced (see columns 4 and 5 of Table I).

TABLE I.

Analyses of basalt.

	1	2	3	4	5
SiO_2	47.52	47.91	52.40	52.02	52.25
TiO_2	1.19	....	1.08	....	.80
Al_2O_3	13.91	15.41	13.55	15.19	14.79
Fe_2O_3	7.06	2.72	2.73	2.05	3.39
FeO	3.76	10.01	9.79	9.01	7.31
MnO	.18	.36	.26	.26	.25
MgO	6.84	5.42	5.53	7.18	7.19
CaO	5.71	7.69	10.01	9.82	10.32
Na_2O	3.06	2.91	2.32	2.05	2.09
K_2O	.77	.66	.40	.96	.71
H_2O	6.30	4.21	1.67	1.46	.82
CO_2	3.68	2.74	....	....	....
Others	.15	....	.25	.03	.08
Total	100.13	100.04	99.99	100.03	100.00

1. Anterior basalt (weathered) from South Britain, Connecticut. Analyst, W. F. Hillebrand.
2. Composite of two altered basalts from the Connecticut Valley (Lake Saltonstall Ridge and South Durham Mountain.)[2]
3. Basalt from main flow, Pine Hill, South Britain, Connecticut.
4. Composite of two nearly fresh extrusive basalts from the Watchung Mountain, New Jersey,[3] and Mount Holyoke, Massachusetts.[4]
5. Composite of six intrusive basalts (either dikes or sills) from the Connecticut Valley and New York-Virginia areas of the Newark system. West Rock, Connecticut (sill);[5] Wintergreen Lake, Connecticut (dike);[6] Palisades, Jersey City, New Jersey (sill);[7] Rocky Ridge, Maryland;[8] Point Pleasant and Gulf Mills, Pennsylvania (dikes).[9]

These composites only confirm the impression that, regardless of their manner of occurrence in the field, these rocks are remarkably uniform in their occurrence. If we disregard the state of oxidation of the iron and consider its total amount only, there is but a single analysis in the list (that of the dike of Gulf Mills, Pennsylvania) which varies in any marked degree from the composites. The greatest

[1] Suggestions regarding the classification of the igneous rocks, by Wm. H. Hobbs: Jour. Geol., Vol. VIII, 1900, p. 11 et seq.
[2] Am. Jour. Sci., 3d series, Vol. IX, 1875, pp. 190-191.
[3] Bull. U. S. Geol. Survey No. 148, 1897, p. 80.
[4] Am. Jour. Sci., 3d series, Vol. IX, p. 191.
[5] Proc. U. S. Nat. Mus., Vol. IV, p. 132.
[6] Am. Jour. Sci., 3d series, Vol. IX, p. 189.
[7] Bull. U. S. Geol. Survey No. 150, 1898, p. 255.
[8] Bull. U. S. Geol. Survey No. 148, 1897, p. 90.
[9] Proc. Am. Philos. Soc., Vol. XXII, p. 454.

differences noted are in the alumina and magnesia (and this is in but one or two instances), and it is at least possible that this variation may be in part explained by imperfect separation.[1] This variation was in one case 2 and in the other 3 per cent from the composite, but in other constituents the differences were generally less than 1 per cent.

Hawes has shown the weathered basalt from the Connecticut Valley to agree closely in composition with the fresh specimens from other portions of the same area, provided allowance is made for the water and carbon dioxide which have been introduced by the weathering process. Recalculating our composite analysis of these altered basalts and comparing with the composite analyses of extrusive and intrusive Newark basalts (after correction in the same manner), this close agreement is set forth (see Table II).

TABLE II.

Analyses of basalt recalculated with water and carbon dioxide neglected.

	1	2	3	4	5	6
SiO_2	52.73	51.48	53.29	52.80	52.69	52.70
	.879	*.858*	*.888*	*.880*	*.878*	*.878*
TiO_2	1.31	....	1.09	....	.81	.66
Al_2O_3	15.44	16.55	13.78	15.41	14.92	14.92
	.151	*.162*	*.135*	*.151*	*.146*	*.146*
Fe_2O_3	7.83	2.92	2.77	2.08	3.42	3.06
	.004 12.00	*.001* 13.67	*.002* 12.74	*.001* 11.21	*.002* 10.79	*.002*
FeO	4.17 *.010*	10.75 *.016*	9.97 *.016*	9.13 *.015*	7.37 *.012*	8.06
	.006	*.015*	*.014*	*.014*	*.010*	*.011*
MnO	.20	.39	.26	.26	.25	.26
MgO	7.59	5.82	5.62	7.28	7.24	7.08
	.019	*.014*	*.014*	*.018*	*.018*	*.018*
CaO	6.33	8.25	10.19	9.96	10.41	10.30
	.011	*.015*	*.018*	*.018*	*.019*	*.019*
Na_2O	3.40	3.13	2.36	2.08	2.10	2.13
	.005	*.005*	*.004*	*.003*	*.003*	*.003*
K_2O	.84	.71	.41	.97	.71	.74
	.001	*.001*	*.000*	*.001*	*.001*	*.001*
Others	.16	....	.26	.03	.08	.09
Total	100.00	100.00	100.00	100.00	100.00	100.00

1. Anterior basalt (weathered) of South Britain.
2. Composite of weathered basalts from the Connecticut Valley.
3. Main (extrusive) basalt of Pine Hill, South Britain.
4. Composite of extrusive basalts from Connecticut Valley and New Jersey.
5. Composite of intrusive basalts from northern and central areas of the Newark system.
6. Composite of the Newark basalt of the northern and central portions of the province.

In the weathered specimens, however, it is noted that the lime is less in amount (8.25 as against about 10 per cent), and if allowance is made

[1] Cf. Washington, Am. Jour. Sci., 4th series, Vol. IX, 1900, p. 44.

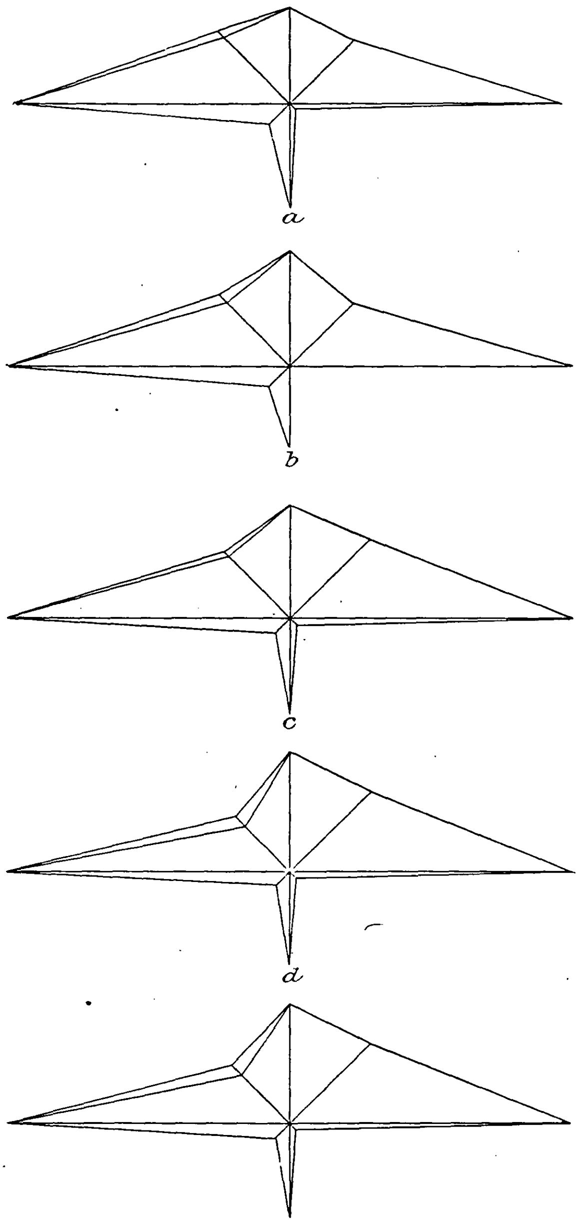


FIG. 25.—Composite diagrams to show the composition of Newark basalts. *a*, Composite diagram of two weathered extrusive basalts from the Connecticut Valley (Table II, No. 2); *b*, Brögger diagram of the basalt of the main extrusive sheet, Pine Hill, Pomperaug Valley (Table II, No. 3); *c*, Composite diagram of two unaltered extrusive basalts from the Connecticut Valley and New Jersey (Table II, No. 4); *d*, Composite diagram of six unaltered intrusive basalts from the Connecticut Valley and from the area between New York and Maryland (Table II, No. 5); *e*, Composite diagram of nine unaltered basalts (both intrusive and extrusive) from the northern and central Newark areas (Table II, No. 6).

for the lime which is in combination with the carbon dioxide, only 5.55 per cent of this constituent is found to be present in the rock, exclusive of the secondary calcite. This calcite, however, which is present in part in the vesicles and in part in the groundmass of the rock, is without doubt derived from the rock itself, largely through alteration of the lime-rich and colorless pyroxene, and hence it is not only not to be deducted from the analysis, but it is even possible that a quantity amounting to several per cent of this constituent has been carried away by solution. In the weathered olivine-basalt, studied by Watson, analyses indicate removal of the lime in this way.[1]

The weathered basalt from South Britain differentiates itself from the other basalts shown in the analyses in the greater oxidation of the iron, the total amount of iron, however, remaining normal. The water present in this rock enters largely into the serpentine and chlorite, formed through the alteration of the olivine and pyroxene.

While the basalts considered from the northern and central portions of the Newark belt within the United States show such uniformity in chemical composition, the microscopic studies have proved that there is, nevertheless, some considerable variation in mineralogical composition. The basalts of the Connecticut Valley have been found to contain either a colorless pyroxene or a colorless pyroxene with a brown one;[2] the basalt of the Palisades along the Hudson contains a diallage-like pyroxene and hypersthene in about equal quantities;[3] the basalt of Watchung Mountain, New Jersey, like that of the Connecticut Valley, has colorless pyroxene or malacolite as the principal nonfeldspathic constituent.[4] In the southern areas of the Newark, particularly those of Virginia, Campbell and Brown[5] have shown that there are important variations in the Newark basalt not only in mineral but in chemical composition, rocks so rich in hypersthene as to deserve the name "hypersthene-diabase" and "olivine-hypersthene-diabase" being found. Chemically these quite fresh rocks differ from the normal type of Newark basalt by containing almost double the usual amount of magnesia. Watson has also described basalts of abnormal composition from Culpeper County, Virginia, and although he does not mention the occurrence of hypersthene in them, it is probable from the analyses and from his petrographical descrip-

[1] Weathering of diabase near Chatham, Virginia, by Thos. L. Watson: Am. Geologist, Vol. XXII, 1898, p. 87.

[2] Dana, Am. Jour. Sci., 3d series, Vol. VIII, 1874, p. 371. Proc. Am. Assoc. Adv. Sci., twenty-third meeting, 1875, p. 44. Hawes, Am. Jour. Sci., 3d series, 1875, Vol. IX, pp. 185-192. Pirsson, Bull. U. S. Geol. Survey No. 150, 1898, p. 268.

[3] Tiefencontacte an den intrusiven Diabasen von New Jersey, by A. Andreae and A. Osann: Verhandl. des naturhist.-med. Vereins zu Heidelberg, N. F., Vol. V, 1892, p. 3. Also, Some contact phenomena of the Palisade diabase, by John Duer Irving: School of Mines Quart., Vol. XX, p. 214.

[4] J. P. Iddings, Bull. U. S. Geol. Survey No. 150, 1898, p. 254.

[5] Composition of certain Mesozoic igneous rocks of Virginia, by H. D. Campbell and W. G. Brown: Bull. Geol. Soc. Am., Vol. II, 1891, pp. 339-348.

tions that this mineral is present with the diallage.[1] In the Connecticut Valley area also two dikes of abnormal composition have been discovered, one very acid, a keratophyre or bostonite from near New Haven,[2] and the other basic and described as a fourchite,[3] though it is not quite clear that it belongs in that class. These abnormal basalt analyses are printed in Table III.

TABLE III.

Analyses of exceptional types of Newark basalts.

	1.	2.	3.	4.	5.	6.
SiO_2	52.06	45.73	51.31	50.88	46.86	60.13
	.868	.762	.855	.848	.781	1.002
Al_2O_3	13.67	13.48	13.64	13.17	13.96	20.47
	.134	.132	.134	.129	.137	.200
Fe_2O_3 }	*a* 15.97	*a* 11.60	.52	1.11	5.23	1.04
			.000	.000	.003	.001
FeO }			8.49	9.66	4.67	.72
	.010	.007	.011	.013	.006	.000
MgO	5.01	15.40	12.73	13.05	7.69	1.15
	.012	.039	.032	.032	.019	.003
CaO	8.15	9.92	12.41	10.19	9.42	2.59
	.015	.018	.022	.018	.017	.005
Na_2O	3.36	3.24	1.40	1.17	1.85	9.60
	.005	.005	.002	.002	.003	.015
K_2O	.86	.47	.32	.31	2.02	1.06
	.001	.000	.000	.000	.002	.001
H_2O	1.05	.94	....	.14	4.72	*b* 3.44
Others	....	....	....	....	3.50	....
Total	100.13	100.78	100.82	99.67	99.92	100.20

a Reckoned as Fe_2O_3. *b* With CO_2.

1. Quartz-basalt ("quartz-diabase"), Chatham, Virginia.[4]
2. Olivine-basalt ("olivine-diabase"), Chatham, Virginia.[5]
3. Hypersthene-basalt ("hypersthene-diabase"), Culpeper County, Virginia.[6]
4. Olivine-hypersthene-basalt ("olivine-hypersthene-diabase"), Culpeper County, Virginia.[7]
5. Tachylite-basalt ("basic pitchstone"), Meriden, Connecticut.[8]
6. Keratophyre or bostonite, near New Haven, Connecticut.[9]

[1] "The pleochroism of some sections is fairly strong. a = reddish-brown, b = pale greenish-yellow, c = blue-green." Op. cit., p. 88.
[2] A relatively acid dike in the Connecticut Triassic area, by E. O. Hovey: Am. Jour. Sci., 4th series, Vol. III, 1897, p. 291.
[3] A basic dike in the Connecticut Triassic, by L. S. Griswold: Bull. Mus. Comp. Zool., Vol. XVI, p. 239.
[4] Am. Geologist, Vol. XXII, p. 346.
[5] Ibid.
[6] Bull. Geol. Soc. Am., Vol. II, p. 346.
[7] Ibid.
[8] Bull. Geol. Soc. Am., Vol. VIII, p. 77.
[9] Am. Jour. Sci., 4th series, Vol. III, 1897, p. 291.

Since the only occurrences of the basalt in the southern areas are apparently dikes, and since the only abnormal rocks of the northern areas have also this manner of occurrence, it is not improbable that they represent rock which was intruded at a somewhat different period, and in this way their divergence from the normal rock of the province may be accounted for, rock of the main flow and of the sills being throughout the province remarkably uniform in composition.

The tachylite-basalt ("basic pitchstone") described by Emerson from the Meriden ash bed, Connecticut,[1] is somewhat abnormal in its composition, but this seems to be due less to differences in its original composition than to sand, lime, and other materials which it has taken up. (See Table III, column 5.) It is obtained, however, from the lower or anterior extrusive sheet of basalt, and it has been here shown that in the Pomperaug Valley area this sheet differs somewhat, both in mineral and in chemical composition, from the main sheet.

To obtain the average composition of the unaltered basalt of the north-central Newark province, analyses of the extrusive basalts of Mount Holyoke, Massachusetts; Pine Hill, Connecticut; and Watchung Mountain, New Jersey, were combined with those of the intrusive basalts of West Rock and Wintergreen Lake, Connecticut; the Palisades, New Jersey; Point Pleasant and Gulf Mills, Pennsylvania; and Rocky Ridge, Maryland. All have been corrected so far as possible to exclude the effects of weathering. This composite analysis appears in Table II, column 6, and the composite diagrams of it, as well as of other analyses represented in the same table, are given in fig. 25 (p. 79).

[1] Diabase pitchstone and mud inclosures of the Triassic trap of New England, by B. K. Emerson: Bull. Geol. Soc. Am., Vol. VIII, 1897, p. 77.

CHAPTER IV.

DEFORMATION.

SECTION 1.—ELEVATION AND TILTING OF THE AREA SUBSEQUENT TO THE DEPOSITION OF THE NEWARK BEDS.

The sedimentary rocks of the Pomperaug Valley do not lie horizontal, but have dips of 15° to about 60° E., the average dip being about 20°. As these sediments are confined in their occurrence almost exclusively to the southwestern portion of the province, near the village of South Britain, the details of this structure may be studied in the special map, Pl. VIII. Exceptions to the prevailing eastern dip are noted only in the area immediately surrounding the "Triangle." That the dip of the basalt sheets conforms to that of the sediments is apparent from the profile of the ridges when observed from the south wall of the basin (Pl. V, *A*), the gently dipping eastern slopes of the main ridges conforming roughly to the average dips of the sandstones and conglomerates.

The petrographical study of the area has shown that the basalt which is at the surface near the eastern margin of the area of exposures represents the upper portion of the flow, whereas that occupying the summits of the higher ridges on the west has textures indicating a lower zone of the sheet. Since the first-mentioned upper layer is loose textured and of a kind easily removed by the forces of subaerial erosion, whereas the material of the western ridges is, as regards the same forces, resistant in the extreme, it is evident that there has been a decapitation of the western ridges due to some more favorable conditions of degradation than have obtained on the eastern slopes. We need not concern ourselves at the present moment with these conditions, but the decapitation can be safely predicated from the facts given, and, further, it is indicated also in the peculiar curves of the present profiles. The average eastern slope of the basalt ridges would now represent, then, something less than the actual dip of the sheet. There is, however, a compensation for this in the nature of the extensive dislocation to which the area has been, as a whole, subjected, and the profiles of the eastern slopes of the main ridges may be regarded as fairly representing the dips of the sheets.

The saddle-like fault structure of the northern areas has preserved but the skeleton of the easterly-sloping monocline, but the same differences in texture of the eastern and western belts are noted.

The similar easterly dipping monocline which is characteristic of the Connecticut Valley was in the earlier studies of that area accounted for by obliquity of original deposition; but no geologist of the present period would for a moment consider this hypothesis adequate to explain the facts. To account for the present monocline, we must assume that the beds of the Newark system of rocks were raised above sea level and that either at this time or subsequently they were tilted gently to the southeastward so as to assume their present attitude.

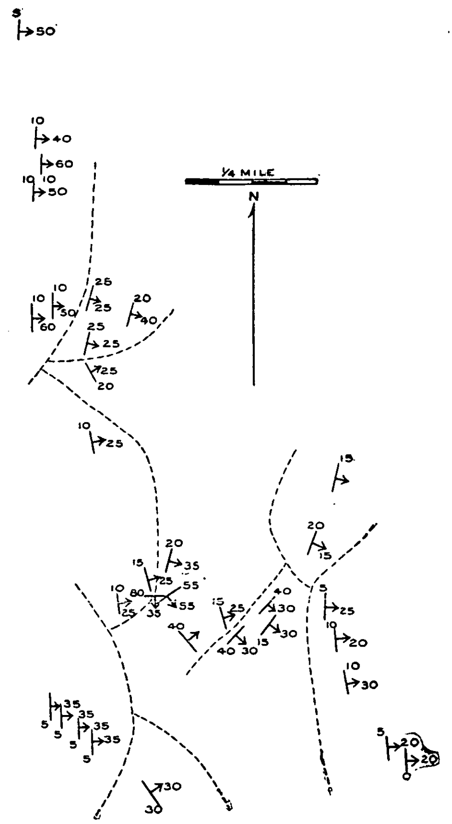
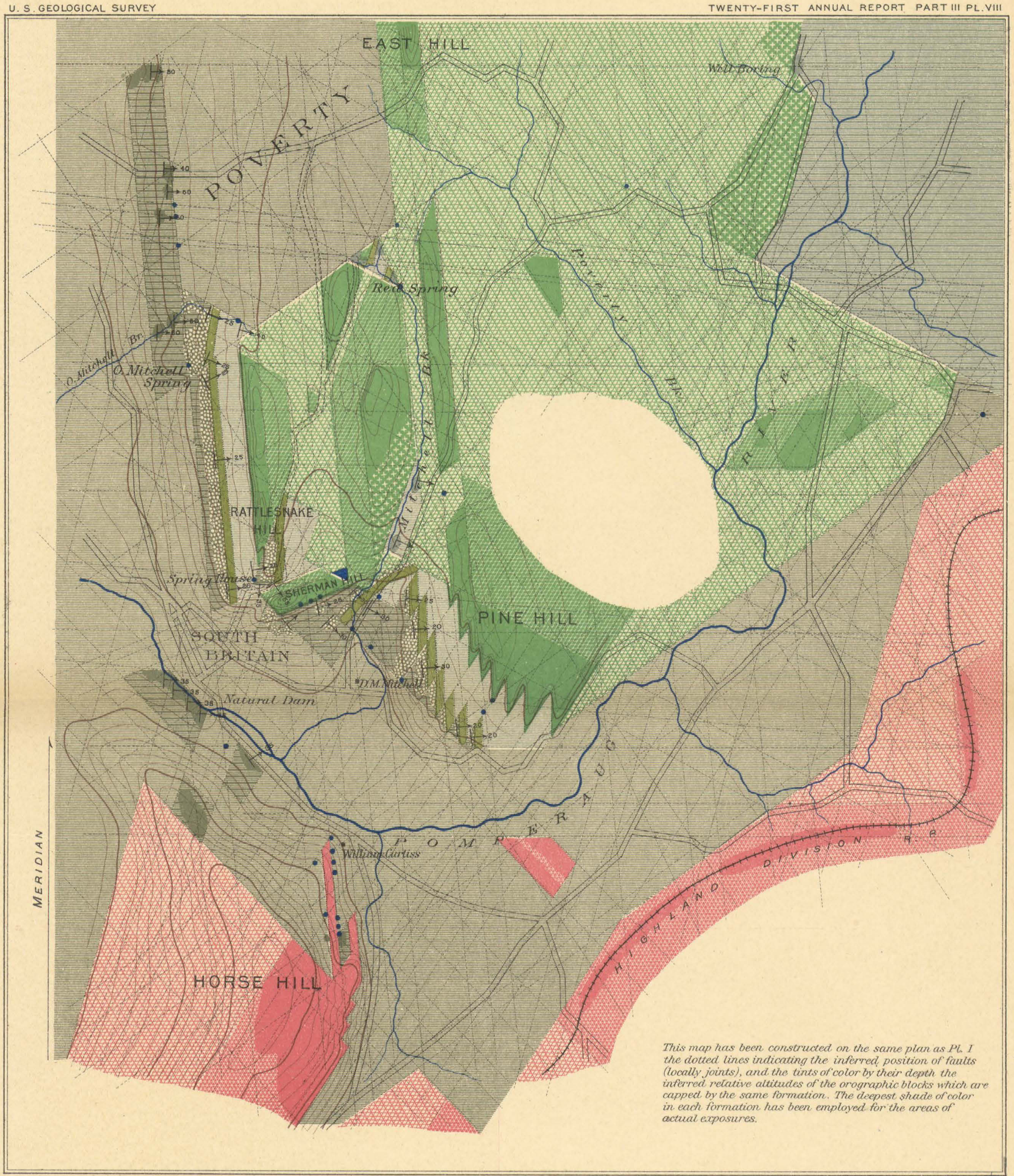


FIG. 26.—Strike and dip observations characteristic of a dislocated area. (From the vicinity of South Britain.) Within areas roughly outlined by dotted margin, both the strike and the dip of the beds have nearly constant values.

The variations in strike and dip of the sedimentary beds as recorded upon the map are often considerable, but they can not be ascribed to any notable arching or folding of the strata. The merest glance at the map reveals the fact that for circumscribed areas there is almost perfect agreement in both the strike and the dip of the beds, but that one or both of these change with great suddenness at certain points, so that the area could be easily divided into a number of fields in each of which the dips and strikes would have a nearly constant value. (Fig. 26.)

An essential characteristic of every region of folded strata is that gradational values should be obtained to correspond with every important change of dip or of strike, owing to the fact that folds appear as curves in practically all of their sections. The continuation of the outcrops of any given horizon along a broken line, or zigzag, is characteristic of a dislocated, not of a folded, region. It is believed, therefore, that the deformation of the area which brought about the variations of dip and of strike occurred under a moderate load only and in the earth's upper zone of fracture.[1]

[1] Cf. C. R. Van Hise, Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, p. 589.



JULIUS BIEN & CO. LITH. N.Y.

GEOLOGICAL MAP OF THE VICINITY OF SOUTH BRITAIN, CONNECTICUT

BY WILLIAM HERBERT HOBBS

Scale

0 — 1/4 — 1/2 — 3/4 — 1 MILE

1899

LEGEND

OROGRAPHIC BLOCKS

Gneiss (higher) · Gneiss (lower) · Arkose (higher) · Arkose (lower) · Shale (anterior) · Basalt (higher) · Basalt (lower) · Basalt (lowest) · Shale (posterior)

ROCK EXPOSURES

Gneiss · Sandstone · Conglomerate · Basalt · Shale · Basalt

FAULTS · COLD SPRINGS

This deformation of the area was accomplished subsequent to the completion of the deposition, and of the lava extrusion as well, since all members of the Newark system are affected in like manner. It is probable also, from the nearly vertical hade of faults, that the deformation occurred subsequent both to the elevation and to the tilting of the beds. Evidence drawn mainly, though not exclusively, from physiographic and stratigraphic observations in other areas of the Newark favors the view that this deformation had been accomplished in Cretaceous time; hence it is believed to have occurred either in post-Newark and pre-Cretaceous (Jurassic?) or in early Cretaceous time. It was in all probability accomplished when the great plain of erosion of southern New England was formed.

SECTION 2.—NATURE OF THE EVIDENCE FOR THE EXISTENCE OF FAULTS.

From the very nature of faults the actual planes of faulting are only in rare instances found exposed at the surface in such a way that the juxtaposition of beds known to have been formed at different times along planes transverse to their bedding can be exhibited as indisputable evidence of dislocation. Save, then, where conditions have been exceptionally fortuitous, it has been necessary to assume the existence of faults, because other kinds of deformation which can be shown to have taken place within any province under examination are incompetent to explain the observed facts. It is no surprise to find, therefore, that the fault has often been the cloak of ignorance, more especially where in regions of complicated deformation the structure has been for any reason interpreted on a wrong theory. By assuming a sufficiently large number of dislocations almost any arrangement of beds can be accounted for, provided too close attention is not given to actual exposures, and the fault becomes the last resort of geologists, when, if it had been less competent to explain the facts, further study might have revealed the correct structure.

In the reconnaissance survey of the Pomperaug Valley a considerable number of faults seemed to be indicated by the unusual topographic development of the area, by the areal distribution of the several members of the system, and by sudden changes in the dip and strike of the sedimentary members. To secure, if possible, adequate evidence for the existence of the faults the vicinity of South Britain was chosen as a favorable one for detailed study, because the presence there of the four lower members of the system offered the possibility of finding the planes of actual dislocations. For this region a map was prepared on a scale of 4 inches to the mile, on which it was attempted to locate every outcrop. In order to separate, so far as possible, fact and theory on this map, the actual exposures have been indicated in deep colors, and the supposed extension of the member to which the exposure belongs by lighter tints of the same hue.

The principal faults of the area have been determined by some one of the following methods: *A*, the offsetting of formations in outcrop; *B*, sudden changes of strike or dip, or of both strike and dip; *C*, the occurrence of scarps in the harder rocks; *D*, the local development of fault rock (reibungsbreccia); and, *E*, the development of slickensides. In locating additional faults after the nature of the structure had been largely read, the following observations were also utilized: *F*, sudden disappearance of outcrops along a rectilinear boundary; and, *G*, the rectilinear arrangement of surface springs. To illustrate these methods, as well as to aid geologists who may in the future visit the Pomperaug Valley, there will be described below localities where each of these methods has been applied in determining a dislocation.

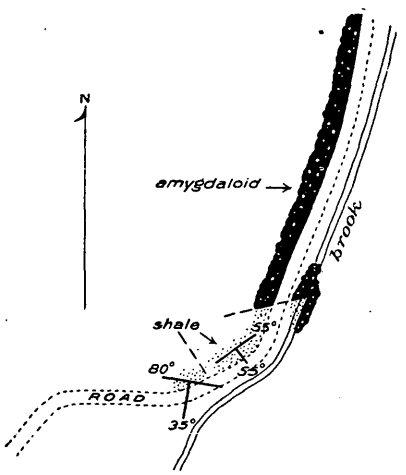


FIG. 27.—Sketch map of the spring-house section. Areas of shale exposure are stippled. Outcrops of anterior basalt are shown in black with white spots.

A. The offsetting of formations in outcrop.—The shoulder near the western and southwestern base of Pine Hill is produced by a series of exposures of indurated arkose and conglomerate, with the overlying decomposed anterior basalt. The metamorphosed conglomerate has proved very resistant to the disintegrating forces of the atmosphere, and its exposures usually project above the general level as ridges a few feet in height. A gentle swell of barren soil lies east of each ridge, and a little scratching with the hammer shows that the material of these low mounds is decomposed basalt of the anterior flow. The conglomerate ridges are each a few hundred feet long and end abruptly, the individuals in the series being arranged en échelon with parallel axes. Together they produce a crescentic series similar to that which has been so often described in the Connecticut Valley. Davis has observed the structure at this locality,[1] although he has mapped but five ridges, while seven can be made out without difficulty.

B. Sudden changes of strike or dip, or of both strike and dip.—As good an illustration of this as could be given is to be found in the spring-house section, east of Sage's creamery, South Britain (see fig. 27). A cart road from South Britain village to the Poverty district follows the north bank of a small stream between Rattlesnake and Sherman

[1] Op. cit., p. 470.

hills. On the north of the cart road shale is found in a steep wall, the beds dipping southerly at a high angle. A short distance from where the outcrops begin on the west the strike suddenly changes from N. 80° W. to N. 55° E., and the dip from 35° SW. to 55° SE. The junction between these different sloping beds is seen in the sharp prow of the exposure at the bend of the road.

C. Occurrence of scarps in the harder rocks.—These are preserved both in the basalt and in the crystalline rocks forming the walls of the basin. In the former they are shown to perhaps best advantage in Orenaug Hill (Pl. X), where nearly every boundary of exposure is a bold cliff, exceptions being found only along the southern base of the eastern twin (Pl. XIII, *B*). Few geologists would doubt, however, that the bold scarps in the other areas of the basin have also been formed by dislocations. In the schists and gneisses almost the entire western and northern walls of the basin are formed in this way. One cliff having a rectilinear face extends nearly a mile along the western wall. The evidence to show that these cliff faces are fault walls is not deduced solely from their plane surfaces and their steep inclinations, for quite as important is the observation that there are many parallel cliffs, all the scarps of the region falling into a comparatively small number of parallel series. It is rare to find curving cliff scarps, although a cliff composed of a number of parallel elements and trending in a zigzag would, on a map of small scale, produce this effect. The scale of the general map, Pl. I, is too small to indicate all the details of the faulting, and a scarp represented on the general map by a straight line (as *ab* in fig. 28) may in the exposure show a surface which is represented by a broken line (*cd* in fig. 28).

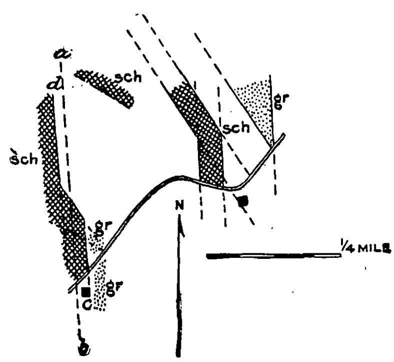


FIG. 28.—Details of a portion of the western basin wall. gr, granite; sch, schist.

D. Local development of fault rock.—At the contact of amygdaloid and anterior shale in the spring-house section (p. 52) the shale is found broken into great blocks (near contact northwest of road and brook), some of which have dimensions of several feet. True reibungsbreccias have also been discussed in the preceding section. Of the localities there enumerated for the occurrence of this rock, the most instructive is perhaps that near the Oliver Mitchell spring, where the contact of the three lower members of the series was laid open by a few feet of digging. The dislocation at this locality was clearly indicated as well by the sudden change in the strikes of the indurated north-trending conglomerate ridge as by its offsetting and that of the amygdaloid to the east of it. Examination of the locality further indicated that the fault which had produced these irregularities should trend northeasterly and would probably coincide with the northwestern face of the main basalt ridge lying to the southwest of Red Spring. The line connecting the latter with the former would, moreover, mark an abrupt change in the character of the country, an even slope of pasture land lying to the north of this marked line. The evidence was here so conclusive that at the first spot selected for digging reibungsbreccia was found in a band varying from a few inches to a foot in width, with amygdaloidal basalt in the south wall and sandy shale in the north wall. The band was uncovered for a distance of several feet and found to trend, as nearly as could be measured from this short distance, N. 50° E. A straight

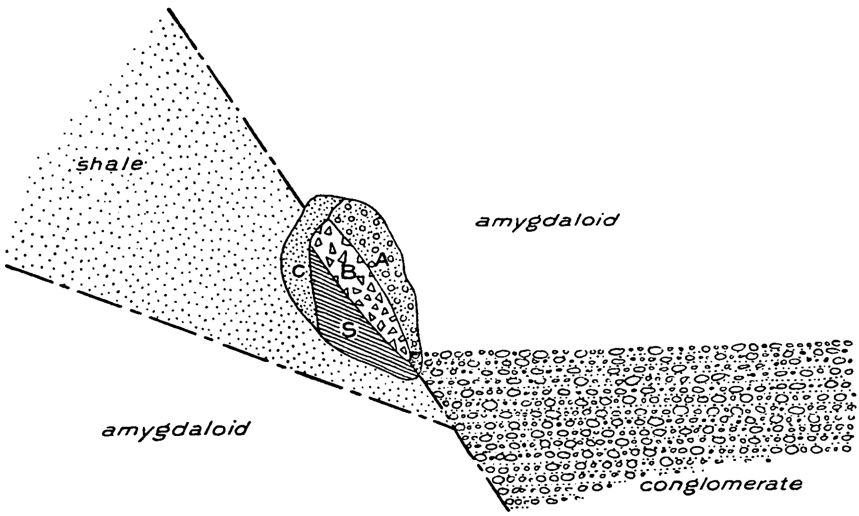


FIG. 29.—Diagram of the contact along fault near Oliver Mitchell's spring. A, amygdaloid; B, breccia between fault walls; C, arkose conglomerate; S, shale; c, cover.

line bearing about N. 55° E. extended from this point would coincide closely with the north face of the basalt exposures south of the Poverty district and west of Red Spring. Extended westward a few feet this band of breccia meets conglomerate so as to bring the three lower members of the Newark system into juxtaposition (fig. 29).

The reibungsbreccias of the Pomperaug Valley seem generally to be developed along fault planes near the junction of a harder with a softer layer, and the fragmental material inclosed in the rock indicates that material has dropped downward in the fissure; but no evidence has been discovered of any considerable upward movement of material along the fault planes (see p. 72).

E. Development of slickensides.—This method of determining the presence of faults is only of secondary importance in the area under consideration. Slickensides have been observed in the anterior shales of the spring-house section. In the main basalt sheet they may be seen to the best advantage in the cliff which is just west of Bacon Pond, at the eastern foot of the eastern twin of Orenaug Hill. Here the basalt rises with nearly vertical walls like a tower, having an almost square base. The vertical walls are covered with longitudinal fluting, the grooves of which are of a finger's width.

F. Sudden disappearance of outcrops along a rectilinear boundary.—This might seem at first thought to offer but slight evidence of a dislocation, and in certain districts of folded rocks it might not; but in a district like the one under consideration, in which no folds have been observed and which from other observations is shown to have suffered many dislocations, this method of observing comes to have very great importance. To make this clear, let us consider a series of localities which will illustrate the sudden disappearance of outcrops of each of the members of the system along a rectilinear boundary.

a. Below the road bridge over the Pomperaug River at South Britain are extensive exposures of the South Britain arkose conglomerate with accompanying beds of shale and sandstone. The entire bed of the stream seems to be occupied with the formation, the strike and dip of which is everywhere nearly the same (strike N. 5° E., dip 35° E). Some distance below the bridge these outcrops die out abruptly along a straight line which crosses the stream obliquely in a direction N.±80° W., the arkose projecting above the water at the margins of the exposures, but being immediately replaced by sand or mud, which forms the river bed for a few miles below.

The upper (southeastern) boundary of the same exposure of the South Britain conglomerate is even more interesting. The outcrops cease just below the road bridge in a natural dam with a fall of 6 or 8 feet. The arkose composing this dam and that occupying the river bed for some distance below is abnormal in that it is rather hard, giving forth a ringing sound when struck with a hammer, and altogether very difficult to break. It is also paler in color than the normal rock, but in all its characters it is like the indurated variety of conglomerate which is found near the contact with the anterior basalt, and it is believed to owe its peculiar properties to a baking process brought about through contact with that member. No basalt is now in outcrop near it, although it has been observed that the latter rock is, other things being equal, most likely to be preserved under these conditions, the hardened arkose supporting the less resistant basalt. The sharp boundary of the exposure suggests that the basalt which produced the induration has been dropped down by a fault, and the continuation of the boundary northeastward coincides at the spring house with a fault, to the southeast of which the same rocks (anterior basalt and indurated conglomerate) are found. Farther northeastward, along the same direction and near Red Spring, the anterior basalt is again encountered on the right of this line. These facts, taken in connection with one another, point to a probable depression of a block along the supposed fault referred to, which would be quite competent to explain the induration of the conglomerate in the natural dam and the absence now of basalt from the vicinity.

b. The anterior basalt is of such small thickness (where measured, only about 25 feet) that it would seem to offer small opportunity for the observation of faulting by the termination of its exposures, but its protection by the indurated arkose and the readiness with which its exposures may be followed, taken in connection with its uniformity of thickness wherever observed, makes any sudden termination of its exposures a matter of considerable significance. East of the Spring House (south of Rattlesnake Hill) its exposures may be followed northward a few hundred feet in a low swell of decomposed rock to a point where they offset to the westward, and continue an equal distance before ceasing entirely. West of the Spring House one may start northward on the low swell of basalt and walk three-fourths of a mile, always on the basalt and with the conglomerate ridge almost within touch on the west, before both suddenly cease in a little branch of the Oliver Mitchell Brook. Beyond this point a broad slope of pasture land extends to the northward for more than 2 miles without an exposure of any kind. I think the evidence is here sufficient for assuming the existence of a fault where the exposures end.

c. In the vicinity of Red Spring, limestone and red shale of the anterior shale formation outcrop, together with anterior basalt, with which they are sometimes found in contact. On every side but the northwest this rock is surrounded at no great distance by massive exposures of the main basalt, and to the northwestward stretches the even slope of the Poverty district, barren, at least so far as outcrops are concerned. The rectilinear boundaries of the shale exposures here seem clearly to indicate the location of fault planes. The Red Spring, so called from the deep brick-red mud from which it oozes, is on the border of the area of red soil, dark soils being found immediately to the south of it, and it is inferred that the bounding fault is located at this line.

d. The western wall of the basalt of East Hill is, near its southern end, a bold cliff as much as 30 feet in height. As we proceed northward this cliff falls away rapidly, but the outcrops by which it is continued and which project but a few feet above the ground terminate on the west along a rectilinear boundary which adheres with remarkable fidelity to the direction of the cliff at the south. At a point about one-third of a mile north of the Poverty road this western boundary of basalt turns sharply to the northwest on a straight line, after which offset it resumes by a sharp turn its original direction (fig. 30). The northern stretch of the Ragland Ridge is another case in point, and it would be easy to multiply examples.

e. In the crystalline rocks composing the walls of the Pomperaug Basin observations similar to those just given have been made. Two localities, however, will suffice for illustration. About 1¼ miles due west of the town of Woodbury a small area of granite outcrops from the expanse of drift, like an island from the sea. In the southeastern portion of this island the granite, by its regular serrated profiles, shows the clearest evidence of several parallel dislocations. The whole area is bounded by straight lines of variable extent, forming a polygon with one reentrant angle. Another particularly clear instance of the termination of gneiss exposures by a fault is found in the Pomperaug River above the railroad bridge. The continuous outcrops extend 600 feet from the bridge, with strikes about N. 40° W., and terminate as suddenly as does the conglomerate below the dam in South Britain, but here along a plane trending N. ± 90° E.

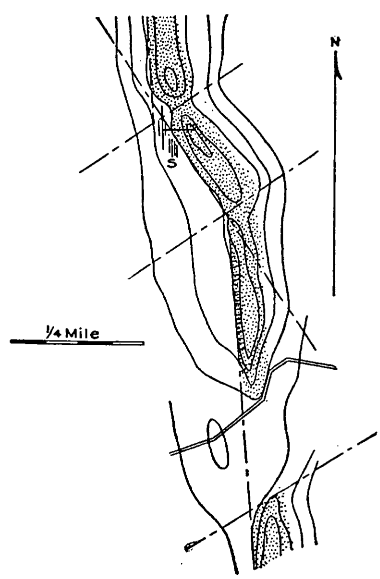


FIG. 30.—Western boundary of East Hill. Stippled area is basalt; S, sandstone. Dot-and-dash lines are faults.

G. The rectilinear arrangement of surface springs.—In contrast with the region of crystalline rocks by which it is surrounded, the basin of the Pomperaug River possesses an exceptional number of surface springs. These springs are for the most part constant in their flow, and many of them are of icy coldness, two facts which taken in connection with one another would seem to require for their explanation a moderately deep-seated source of supply. Early in this investigation it was noticed that these springs were arranged, at least in a number of instances, along straight lines, and hence careful mapping of them was undertaken. The larger number are located in the arkose-basalt-shale district of the vicinity of South Britain. One of the more remarkable series is that which is arranged along the main fault line of fig. 6 (p. 41). This fault, which trends a little west of north, passes through the icy spring on the Oliver Mitchell place. Continuing northward from this spring, three springs are encountered within a distance of one-third of a mile, and to the southward along the same direction is the spring which supplies the public watering trough located south of the road bridge at South Britain. (See Pls. VIII and XV.)

On the south slope of Sherman Hill is found a series of springs causing an elongated swampy zone. West of the Curtiss place, which is located one-half mile southeast of South Britain village, is found a linear series of at least seven surface springs, whose course is nearly parallel with the road to Bennett's bridge. Parallel with them also and but a few feet farther west runs an interrupted series of gneiss exposures, doubtless representing the upthrown limb of the fault along which the springs have reached the surface (fig. 31). One of the springs in this series, which is utilized to supply water to the Curtiss place, is reported to have been for a period covering many years remarkably regular in its flow and apparently independent of conditions of precipitation. The season of 1899 was an exceptionally dry one in Connecticut, but all springs which have been located on the map were flowing in August and September of that year.

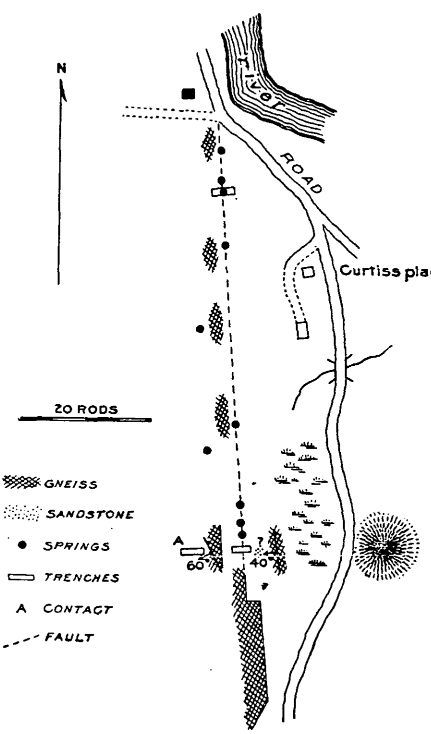


FIG. 31.—Sketch map of the vicinity of the William Curtiss place, South Britain. A is the locality where by trenching arkose was discovered in hollows below the glaciated surface of the gneiss.

It will be noted on examining the map (Pl. VIII) that a considerable number of springs are located at points from which a number of faults radiate, and it has been observed that these springs are, as a rule, both the colder and the more persistent in their flow. Of their number are the Oliver Mitchell spring, Red Spring, the spring north of the Pine Hill ridge, the spring in the spring house east of Sage's creamery, D. M. Mitchell's spring, and the one at the watering trough near the South Britain bridge. These springs seem, therefore, to be natural artesian wells, the shafts of which are the widening of fault planes at their junctions.

Since the time of Daubeny and Forbes the location of springs has been connected with fissures. Particularly throughout the West has a rectilinear arrangement of springs been interpreted to indicate their location along fault planes. Russell, in his interesting description of the faulted blocks of southern Oregon, says:[1]

> Conversely, when we find hot springs at a distance from volcanic centers, especially if they occur in a linear series, we may presume that they mark a line of recent faulting.

In his excellent report on the mineral waters of the United States,[2] Peale cites a number of regions in which the arrangement of mineral springs is along fault planes. Among these are the cold Saratoga springs of New York and the warm springs of Virginia. Referring to the area described by Russell, he says: "A map of the hot springs of the Great Basin would be, to a great extent, a map of its displacements."

Hill describes the Rio Grande Plain "fissure springs," which are ranged along lines of displacement.[3]

Russell mentions in the Surprise Valley, Oregon, the occurrence of springs at points from which faults radiate in the manner which has here been reported from the Pomperaug Valley. He says, referring to a displacement:[4]

> This in its turn throws off several smaller faults which radiate, like the rays of a partially opened fan, from a point on the eastern shore of Middle Lake. Near where these fault lines diverge there are copious springs having a temperature of 180° F., that rise through the fissures produced by the displacement.

"*The Triangle.*"—East of Sherman Hill is a triangular area of swampy meadow inclosed on all sides by dense woods, and known throughout the region as "The Triangle." (Pl. VIII.) It is, as regards its outlines, a nearly perfect triangle, and so sharp is its boundary that one could, if he chose, walk all about its three sides, keeping one foot ever on the firm ground and the other in the swamp. It is apparently bounded on all sides by faults, between which the block has been depressed; it may be regarded as the "triangle of error" occurring at the junction of three faults.

SECTION 3.—CHARACTERISTICS OF THE FAULTS OF THE POMPERAUG BASIN.

There are many characteristics other than the strike of the individual faults of the Pomperaug Basin system which need to be considered. Chief among these are the inclination of the walls (hade), the displacement by elevation or depression along the fault plane (throw, or vertical

[1] A geological reconnaissance in southern Oregon, by I. C. Russell: Fourth Ann. Rept. U. S. Geol. Survey, 1884, p. 452.

[2] Mineral waters of the United States, by A. C. Peale: Fourteenth Ann. Rept. U. S. Geol. Survey, 1894, Pt. II, pp. 63–64.

[3] Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Texas, with reference to the occurrence of underground waters, by Robert T. Hill and T. Wayland Vaughan, Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1898, Pl. XLVI.

[4] Op. cit., p. 450.

throw), the horizontal displacement along the surface (lateral displacement), and the differential uplift or downthrow (tilt).

HADE.

The fault walls throughout the area seem to have a very steep inclination—wherever observed steeper than 75°, and generally near the vertical. The bold cliffs of basalt in the Orenaug and Ragland districts furnish perhaps the most satisfactory opportunities for observing this characteristic. The slickensides with which the cliff walls

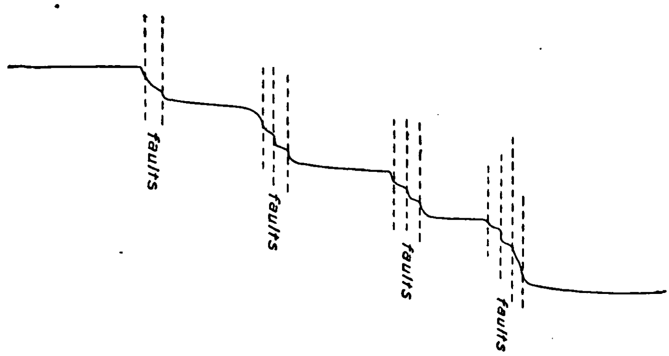


FIG. 32.—Idealized profile to show the supposed structure in the rampart slope of the basin to the west of Ragland.

west of Bacon Pond are fluted bear testimony to the fact that these faces are the original fault walls along which displacement occurred. In the more easily weathered gneisses and schists which compose the walls of the basin the scarps in many cases still present their bold, almost vertical, faces to one approaching from the valley.

THROW.

The throw of the faults of the Pomperaug area can not be accurately estimated, owing to the fact that the thickness of the Newark series has not been determined with accuracy. It is, however, safe to assume, in the instances where scarps have been preserved, that the throw has been as great as, and usually greater than, the altitude of the cliff exposed. No throw of more than 100 feet would be proved in this way. That there have been throws of much larger dimensions is, however, clearly demonstrated by the fact that at one locality in the eastern valley (east of Orenaug Hill), and at one locality in the southern valley (south of Pine Hill), exposures of the main basalt sheet approach within a few hundred feet of the outcrops of gneiss. At these localities the displacement between the exposures of the two rock masses must have been equal to the entire thickness of the Newark series below the top of the main basalt (at least 1,200 feet), plus that thickness of the gneiss which has been removed by the forces of degradation. The first mentioned of the two localities, that east of Orenaug Hill, is the more instructive, since there is ample evidence that the nearest exposures of basalt constitute an upper layer of this sheet, and, further, topographic peculiarities speak for the removal of a considerable thickness of gneiss by erosion. It is, perhaps, significant that just here, where observations point to the greatest displacement within the basin, should be found the only locality where vertical flutings (slickensides) have been observed to characterize the basalt scarps.

Distribution of throw over a zone of parallel faults.—Although the evidence points to a large throw in the case of one or two dislocations, yet it seems true that for the area as a whole throw along fault planes has been small in comparison with the figures usually given for throw along faults in other areas. As the number of dislocations has been large, the displacement along each has been small, although the combined effect in any particular zone may be considerable. This is doubtless explained by a distribution of throw over a series of near-lying

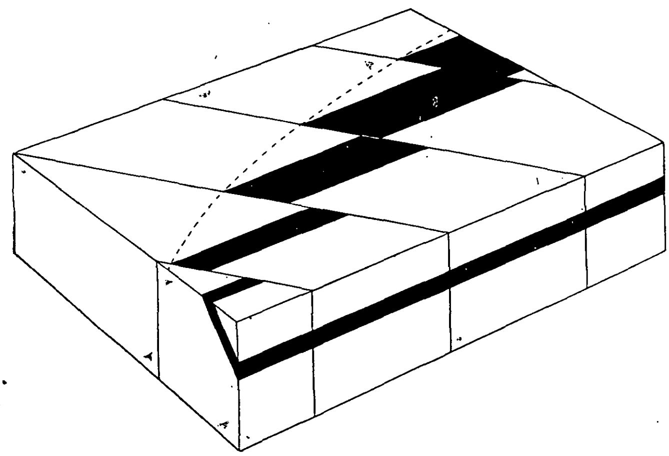


FIG. 33.—Diagram to illustrate crescentic offsetting of outcrops due to progressively increasing tilting of orographic blocks.

parallel fault planes. Such distribution of throw may be seen perhaps to the best advantage in the western wall of the basin at about the latitude of Pomperaug village. Here the wall of granite and gneiss rises in a series of steps like the ramparts of a fort (idealized in fig. 32). The nearly vertical cliffs which produce these steps trend a little west of north, one having been followed for nearly a mile. The two lower steps of the series are of granite and the upper ones of gneiss, the contact of the two rocks near the surface being evidently the fault plane itself. The profile of the slope suggests that the throw has been distributed not uniformly over the entire slope, nor yet exclusively along the planes which form the largest scarps, but rather in a series of narrow zones of parallel faults located near the larger of the present cliffs.

Another excellent example of rampart structure due to a distribution of throw seems to be afforded by the slope which rises into Castle Rock on the west of the Pomperaug River north of Pomperaug village. Here the larger steps are indicated in the topography, though too small to appear upon the topographic map (cf. fig. 41, p. 111).

LATERAL DISPLACEMENT.

The lateral displacement of the faults of the Pomperaug Basin is, as would be expected in the case of faults hading near the vertical, practically inappreciable. Apparent lateral displacement is, however, to be noted in the offsetting of beds in outcrop, as has already been described from near South Britain. This kind of lateral displacement is a well-known feature of vertically faulted regions where the beds are

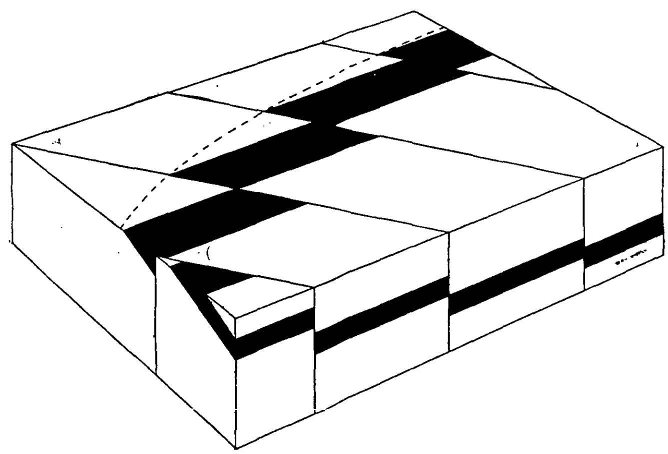


FIG. 34.—Diagram to illustrate crescentic offsetting of outcrops due to progressively increasing throw of orographic blocks.

not too steeply inclined. The lower the angle of dip of the beds the greater will be the apparent displacement due to upthrow or downthrow.

Crescentic offsetting of beds.—The successive offsetting of beds in outcrop so as to produce a crescent-shaped outline to exposures, as has been observed in the South Britain district, can be produced by parallel vertical faults in one or more of three ways. These are: First, by regular increase in the dip of the beds, due to differential tilting of the included orographic blocks (fig. 33); second, by progressive increase of the throw without differential tilting (fig. 34); and, third, by progressive decrease of the fault interval (fig. 35). The first of these processes would result in a decrease in the width of exposure to correspond with increase of dip. This not having been detected in the special case which we are considering, and the dips being, moreover, measurable and approximately identical, it is evident that differential tilting has had little part in producing the structure in question. Both the other processes, however, appear to have contributed to produce the general result, the increase in offset, indicating an increase in the throw, being especially noticeable.

TILTING.

For the Pomperaug area as a whole it is probable that the upthrow or downthrow along a fault plane has been within an individual block comparatively uniform—blocks have generally been elevated or depressed as a whole, not tilted differentially. In the small triangular area about Rattlesnake Hill, however, and especially in the portion of that area in which the "Triangle" is located, the areal relations indicate that faulting of an extremely complex nature has occurred. Mere uplift or downthrow of orographic blocks would not seem to be

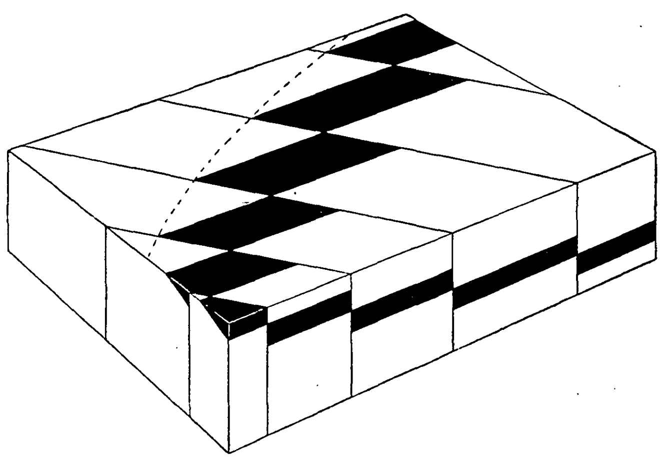


FIG. 35.—Diagram to illustrate crescentic offsetting of outcrops due to progressive decrease in width of orographic blocks.

competent to explain these relations. It is necessary to assume, I think, that in this area at least there has been a considerable tilting of the orographic blocks due to differential upthrow or downthrow. The course of the bed of anterior basalt would alone seem to require such an explanation. An attempt to set forth the supposed structure at this locality is made in fig. 36. The course of the two bands of anterior basalt near the right and rear of the block figured expresses the prevailing strike of the sedimentary rocks of the district. The broken belt of the same rock which extends diagonally across the figure, it is inferred, has been tilted about an axis nearly horizontal and nearly normal to its original strike, depression having occurred on the southern and elevation on the northern side of this axis.

If such a differential throw occurred along vertical walls it must involve a considerable amount of complex minor faulting and crushing near the important dislocations. While there is in this vicinity a lack of evidence that any considerable proportion of the fault planes stand vertical, there is no lack of evidence of the minor faulting and crushing. In the brook near the spring house the different members of the Newark series have been infaulted in a manner which can be best illustrated by the arrangement of the parts in a Chinese puzzle. The apex of a triangular block of shale infaulted in basalt is exposed in the bed of the brook. Following the northern side of this shale triangle across the road and digging to expose the contact, the shale is found crushed into a number of blocks, the principal dimensions of which vary from

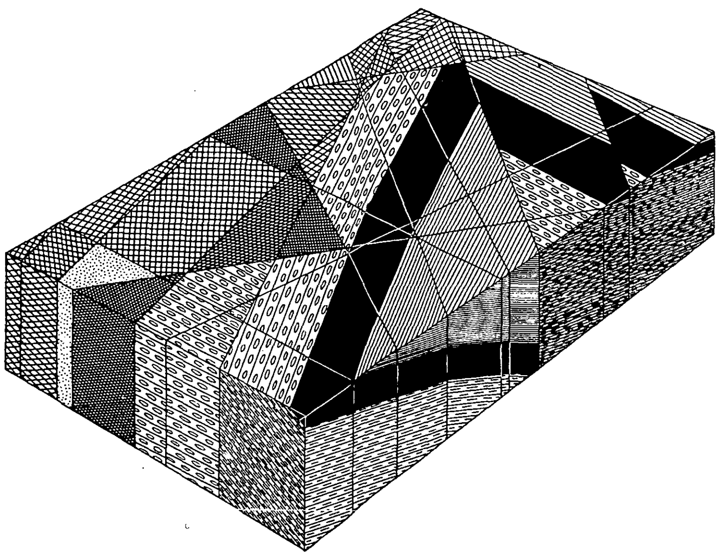


FIG. 36.—Diagram to illustrate the inferred structure in the vicinity of the "Triangle." Arkose conglomerate is represented by lines and ellipses, anterior basalt by the black areas, anterior shale by parallel lines, and main basalt by cross-hachure areas. The finer hachuring (and hence the deeper shade) corresponds to the higher blocks of the basalt. The area of the "Triangle" is shown by stippling.

a foot to a yard. The "Triangle" itself also bears testimony to the fact that the dislocations in its vicinity have been of a very complex nature.

SECTION 4.—THE FAULT SYSTEM OF THE POMPERAUG VALLEY.

APPLICATION OF PRINCIPLES.

By an application of the principles set forth in section 1 more than 250 dislocations have been mapped, and from the nature of things there must be a large number of such dislocations which have not been discovered. As regards their direction, these faults fall into no fewer than eleven series of parallel or nearly parallel dislocations, five-sixths of the entire number of dislocations belonging, however, in five series, representatives of four of which are to be found almost throughout the area of the basin.

MEASUREMENT OF THE STRIKE OF FAULTS.

In the preliminary study of the Pomperaug Basin the directions of faults were estimated as nearly as possible from observations at individual exposures, a method the accuracy of which would depend very naturally upon the way in which the dislocation had been revealed. If by a long cliff face or by a long rectilinear boundary of exposures, the result might well be correct within a very few degrees; but if based on the offsetting of outcrops or on the discovery of a band of reibungs-breccia, only a very rough approximation to correctness would be reached. It was soon learned, however, that faults observed at one locality would be encountered at others, owing to their persistence across the basin, or at least so far as outcrops extend. So many of the observed faults were thus found to persist that on the maps it has been assumed, in the absence of evidence to the contrary, that every fault observed at one locality persists across the basin or across the area of exposures.

It is possible, and even probable, that the fault encountered at one point may not represent absolutely the same surface as that encountered at another and located on the maps as its extension, inasmuch as observations seem to show that the major displacements are each distributed over a zone of near-lying planes. It is believed, however, that on the scale of the map the errors in location are moderate in amount. Although observations of direction were all taken with a 4-inch dial compass corrected to the meridian, the determinations of fault strikes have been made in many cases independent of compass readings through the location upon the map of a chain of points along the same fault plane (as defined above). While the precision of this method is great, its accuracy is no greater than the map upon which it is based, and in fact it is somewhat less, due to errors of location. While not desiring to ascribe a greater degree of accuracy to the determinations of this report than the observations upon which they are based would warrant, it is proper to say that the delineation of topographic features upon the atlas sheets here employed is considerably better than the average of such work, and, further, that the roads and the topographic breaks of sufficient relief to appear upon the map furnish numerous readily accessible bases from which to make location of most of those points where the structure can be best interpreted.

The strikes of the four series of faults which are found throughout the area of the valley have probably been determined within a limit of error of about 2°, whereas some of the less common series occurring in the southern part of the basin can hardly be assumed to be correct within double that number of degrees.

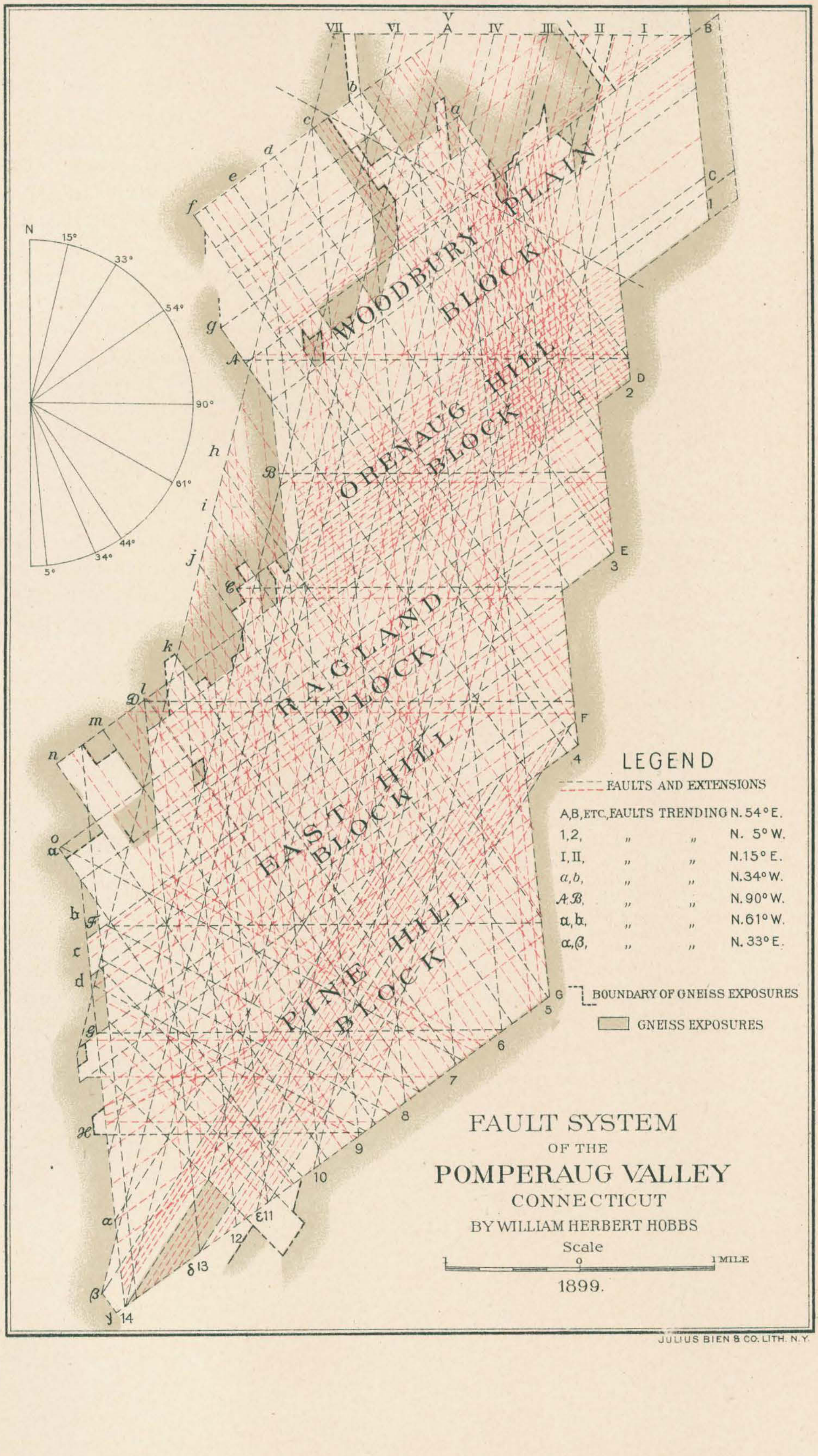
The extension of faults across the basin or across the area of outcrops is inference, based on the general observation that a considerable number clearly do persist, and on the supposition that the area has been dislocated as the result of a strained condition to which it has been as a whole subjected and from which it has been released. To indicate that the extensions have been based on inferences, the faults are throughout represented upon the map by dotted lines. Ample justification for the extension of observed faults seems, in a large number of cases, to be afforded by the coincidence of the extended faults with topographic breaks and with the courses of the important drainage lines.

The four principal series of dislocations having representatives throughout the area of the basin and a fifth having a rather wide distribution have been determined to strike as follows: N. ± 54° E., N. ± 5° W., N. ± 34° W., N. ± 15° E., N. ± 90° E. A sixth series, found only in the southern portion of the basin (the Pine Hill district), but there the prevailing one, strikes in the direction N. ± 33° E. The other five series which have been observed are practically restricted in their occurrence to a narrow triangular area in the vicinity of Rattlesnake Hill, and only a few representatives of each have been made out. For this reason their strikes have been less accurately determined. There are, of course, special localities where strike directions may be fixed to better advantage than elsewhere, and in view of their value in indicating the structure of the basin a few well-marked localities for each series will be described as briefly as possible.

NOTATION OF FAULTS.

In order that the faults of the Pomperaug Basin system may be intelligently discussed it is necessary that some notation be adopted for each series composing the system, so that an individual fault may be referred to by symbol and quickly found upon the map. The notation adopted makes use of a particular numeration for each system. It is simplified by counting in each series only important faults, which are located at nearly regular intervals, the reference to intermediate dislocations being made by use of the symbol of the last faults thus favored, after which is placed a small arabic numeral to indicate which one of the intermediate faults is referred to. This method will be clear from the scheme of Pl. IX and from the following explanation:

A, B, C, etc., are faults trending N. ± 54° E.
1, 2, 3, etc., are faults trending N. ± 5° W.
a, b, c, etc., are faults trending N. ± 34° W.
I, II, III, etc., are faults trending N. ± 15° E.
$\mathscr{A}$, $\mathscr{B}$, $\mathscr{C}$, etc., are faults trending N. ± 90° W.
α, β, γ, etc., are faults trending N. ± 33° E.
𝔞, 𝔟, 𝔠, etc., are faults trending N. ± 61° W.



FAULT SYSTEM
OF THE
POMPERAUG VALLEY
CONNECTICUT
BY WILLIAM HERBERT HOBBS

1899.

JULIUS BIEN & CO. LITH. N.Y.

To illustrate the use of this scheme, the fault which forms the southwestern wall of the Hotchkissville Valley is in the series trending N. ± 34° W. and is the third in the diagram to the west of the one designated b, hence it is referred to as b_3.

DETERMINATION OF THE PRINCIPAL SERIES.

The N. ± 54° E. series.—The strike of this series may perhaps be best determined by the fault (F) which, beginning with the cliff in the basin wall (Squaw Rock), can be followed in the band of reibungs-breccia uncovered near the Oliver Mitchell spring and in the northern boundary of the areas of the main basalt lying both to the west and to the east of Red Spring. Another fault of this series which affords some opportunity for accurate measurement is that bounding the exposures of South Orenaug Hill upon the south and continuing to the dam at Pomperaug village (D). A third and well-marked fault (D_6) forms a series of low scarps which are the northwestern boundary of the basalt in the southern portion of the Ragland district (fig. 37).

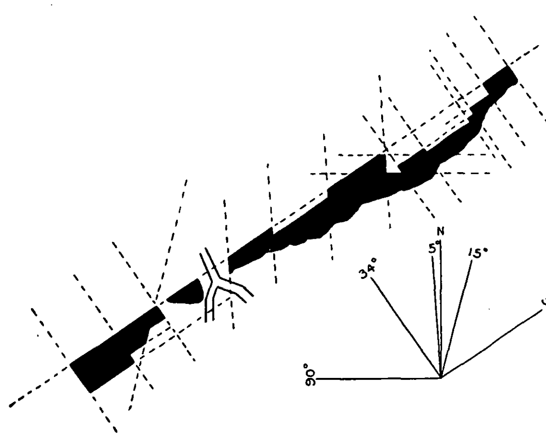


FIG. 37.—Northwestern boundary of basalt in southern Ragland.

The N. ± 5° W. series.—This series may be easily determined from the cliff of East Hill and its continuation to the southward, from the long cliff of gneiss which extends along the western border of the basin for a distance of nearly a mile in about the latitude of Pomperaug village (9_1), or from the intermontane valley of Orenaug Hill, where one may walk a full mile along cliffs that are interrupted for but short intervals (see map, Pl. X).

The N. ± 34° W. series.—A very good opportunity to measure the strike of this series is afforded by one of the scarps (a_6) which are so prominent on the eastern slope of the eastern Orenaug twin (Pl. V, *B*). Other excellent opportunities are afforded by the boundaries of exposures which line the Hotchkissville Valley on the northeast (b) and southwest (b_3), and by the fault (n) which is indicated in a line of low cliffs following the right bank of the brook entering Transylvania Brook from the west a short distance below the cascade.

The N. ± 15° E. series.—The direction of this series of faults may be determined from the southeastern margins of the exposures in both twins of Orenaug Hill (I, II), by the cliff bounding the eastern Ragland Ridge on the west (II_3), or by the western boundary of the exposures in the western ridge of the same district (IV).

The N. ± 90° E. series.—This series has been determined with less accuracy than most others, its direction being measured from a number of cliff faces which are each a rod or less in length. These faces seem to be subordinate to those formed by the faults of the four most prevalent series. At each fault of this series which has been indicated upon the map, some cliff trending roughly east and west has been observed. That the direction given is approximately correct may be indicated by the fact that in some instances lines continuing in this direction from a point of observation correspond with topographic or geologic breaks, but this may be fortuitous. Thus the fault (F) which marks the southern extension of East Hill corresponds farther west with the northern limit of the exposures of South Britain conglomerate and with the gneiss scarp north of Spruce Brook in the western wall of the basin. On the eastward, too, its extension passes through the oil well, where is the only exposure of shale on the east of the basalt ridges. Similarly the parallel fault (G_2), starting from the scarp of Squaw Rock in the western basin wall, corresponds with the boundaries of exposures in the area to the east of South Britain.

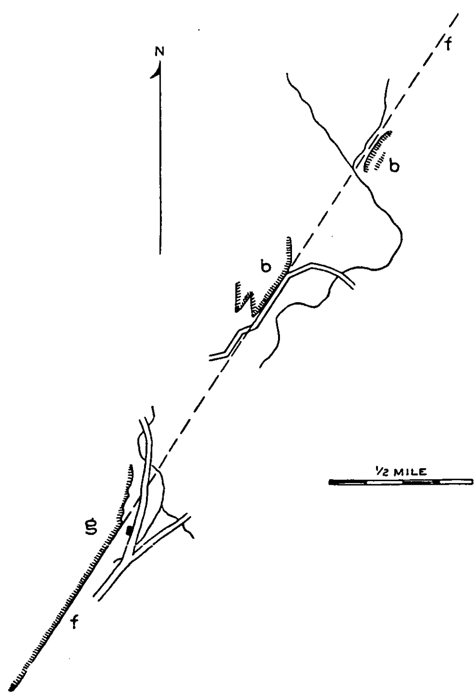


FIG. 38.—Sketch map to show the course of the master fault (N. 33° E.) which bounds Horse and Pine hills upon the southeast. bb, areas of basalt; g, gneiss of Horse Hill; broken line, ff, course of the fault.

The N. ± 33° E. series.—It is this series of faults which has brought about the crescentic arrangement of outcrops on the southwest flank of Pine Hill. The direction of the series is obtained easily and with considerable accuracy from the fault (δ) which forms an extended cliff of gneiss southeast of Horse Hill, a cliff in places 40 or more feet in height. The strike of this cliff extended northeasterly (see fig. 38) corresponds closely with the southern margin of the basalt exposures of Pine Hill (whose direction has fixed that of the highway) and with the low cliffs of the same rock lying to the south of the Pomperaug River and northwest of the railway station. These latter cliffs mark the northwesterly limit of basalt in the vicinity as sharply as do those of Pine Hill the southeasterly limit in their vicinity.

THE FAULT WALLS BOUNDING THE BASIN.

On the map (Pl. I) have been entered the exposures of granite and gneiss which lie nearest to the basin of Newark rocks. On the north and west of the basin these exposures form an almost continuous wall of rock which is much indented and which generally rises sharply from the valley. The excellent representation of the topography, particularly in the northern wall, has made the location of the principal faults of the margin of the basin a comparatively easy task.

West of Woodbury the gneiss wall rises directly out of the plain, but the rocks are exposed for only a short distance from the margin. The slope, however, continues to ascend gradually, until after more than a mile of covered ground a second wall of gneiss rises like the inner defenses of a fortification. A somewhat similar but much less marked double wall is found west of Bates Hill.

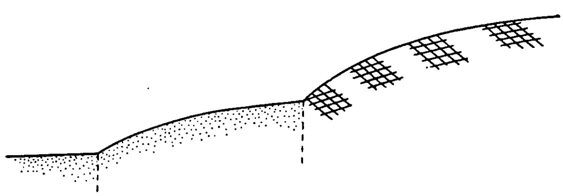


FIG. 39.—Profile (idealized) of the eastern basin wall.

At only one point do the exposures of schist and gneiss cross the valley surrounding the basalt ridges. West of Bates Rock the crystallines throw an arm across the valley and well up upon the flanks of the Bates Rock ridge. Transylvania Brook, which here occupies the valley, falls over this schist in a series of low cascades, the entire fall of which is about 60 feet. As will be pointed out in the following section, this block of schist is responsible for important modifications in the drainage history of the basin.

In contrast with the western wall of the basin, the eastern wall is formed by gentle slopes, although these meet the alluvial plain of the eastern valley in a line marked by straight stretches of considerable length. Except in a narrow zone east of Orenaug Hill the granite and gneiss exposures do not approach the valley bottom, but are first encountered at distances of a half mile to a mile up the slope. Near where they begin the slope generally assumes a steeper gradient; and no observant person who ascends this wall of the valley can fail to note that after the first rise there is a nearly level plain or bench a quarter to a half mile or more in width, which extends to the next rise, beginning with the outcrops of the crystallines. An idealized profile which fairly represents these topographic breaks in the eastern wall of the basin is given in fig. 39. By mapping a series of the nearest exposures, as has been done upon the map, they are found to be arranged en échelon in a series of ranks, which, as one goes northward, appear to retreat from the basin in regular fashion, so as to give the gneiss area a serrated margin with but few indentations.

The contrast between the rounded contours of the eastern and southern walls and the bold cliffs of the western and northern walls finds its explanation in ice movement during the Glacial period. Glacial scratches in the vicinity show that the ice here moved in a direction averaging about S. 30° E., hence it overrode the northwestern margin of the basin so as to abrade the higher points of the southeastern margin at the same time that it filled depressions, thus greatly reducing the inequalities of surface.

SECTION 5.—THE OROGRAPHIC BLOCKS.

THE FAULT INTERVALS.

The map (Pl. I) reveals a marked tendency to a regular spacing of the faults of each series, though this tendency is less marked in those series composing the second group—the faults observed in the vicinity of Rattlesnake Hill near South Britain. If we consider the total number of faults in any series, as, for example, the N. ± 15° E. series, we find that the interval is remarkably uniform, or if one interval greatly exceeds the average interval, it is by so large an amount as to suggest that it is the equivalent of two or three normal intervals, and that intervening faults exist which for some reason have not been discovered.

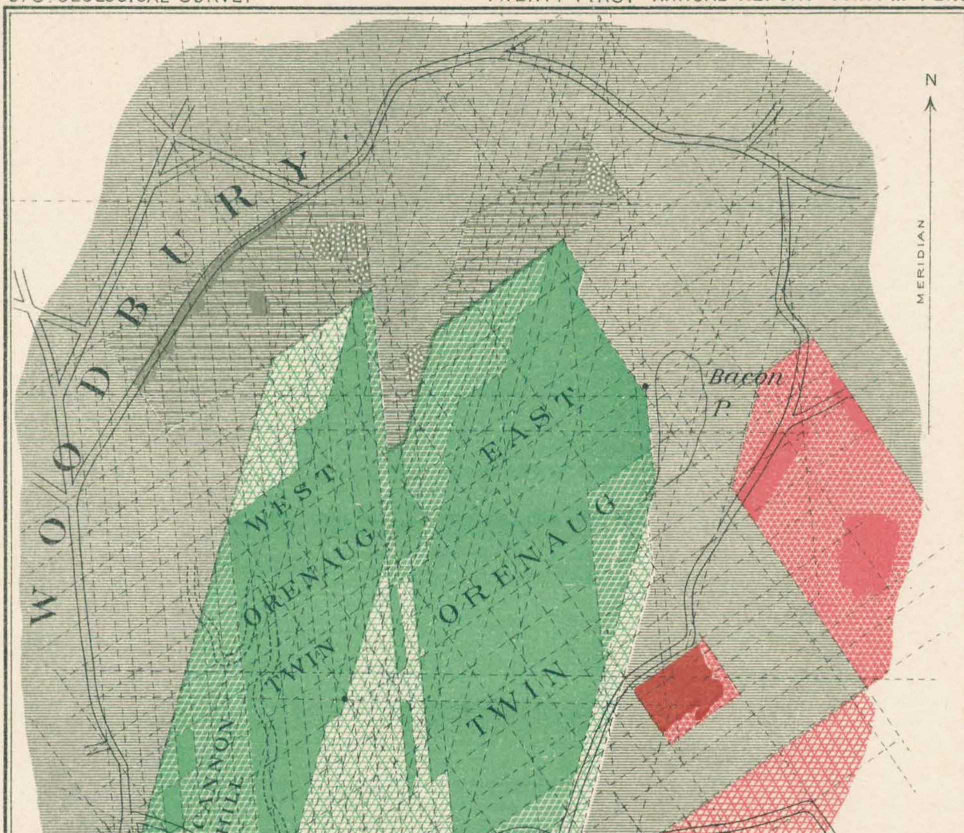
If, now, we compare the fault intervals of each of the four principal series we discover that, within any given series, they also in a remarkable degree approximate to uniformity. The N. ± 33° E. series, restricted to the southern portion of the area, has a smaller fault interval, but one which is approximately uniform. It is not believed, however, that the faults represented upon the map are the only ones which exist in each series. They are faults of an order large enough to be discovered over the greater part of the territory by a survey carried out in the manner here described. In parts of the basin where the conditions for observation are most favorable, as, for example, the Orenaug Hill district, faults of a lower order (with a smaller interval and correspondingly smaller throw) have been studied.

PLATE X.

PLATE X.

GEOLOGICAL MAP OF ORENAUG HILL.

The plan of construction of this map is the same as that of Pls. I and VIII, the dotted lines showing the inferred position of faults (locally joints) and the tints of color the inferred relative altitudes of orographic blocks. The deepest shade of each color indicates the positions of actual exposures, and in the basalt elevated exposures, since there are some low-lying exposures included in the area shown upon the map by the medium tint of that formation.



GEOLOGICAL MAP OF ORENAUG HILL

BY WILLIAM HERBERT HOBBS

Scale

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1899.

JULIUS BIEN & CO. LITH. N.Y.

THE UNIT BLOCKS OF ORENAUG HILL.

The first incontrovertible evidence of the presence of faults within the area of the basin was obtained from the vicinity of South Britain, where the presence of several members of the Newark series afforded exceptional advantages for observation. In the Orenaug district near Woodbury village, which was next studied, the conditions were quite different, but with the knowledge already acquired perhaps not more difficult. The Orenaug district consists of twin hills and a southern outlier, which I have called the South Orenaug Hill. These hills are composed of basalt, and have roughly rhombic boundaries. They are flanked upon the north by a few exposures of South Britain conglomerate, which does not, however, meet the basalt at the surface. The basalt belongs to the upper layer of the main basalt sheet. Separating the twins and cutting the South Hill in two is an intermontane valley, trending N. $\pm$ 5° W., and for a portion of its length a narrow canyon. The hard rock of the hills not only rises in steep cliffs sometimes 30 or 40 feet high at the margins of its exposures, but within these margins it is divided by bold scarps into blocks which stand at different altitudes and present a surface more like that of a jam of floating ice cakes than anything else with which I am familiar. (See map, Pl. X, and Pl. XI.)

Though on a scale greatly inferior, the structure of these hills recalls the descriptions by Russell of the faulted lava blocks of southern Oregon. Speaking of the region of the Warner Lakes, he says:[1]

In this narrow zone the orographic blocks of dark volcanic rock are literally tossed about like the cakes in an ice floe, their upturned edges forming bold palisades that render the region all but impassable.

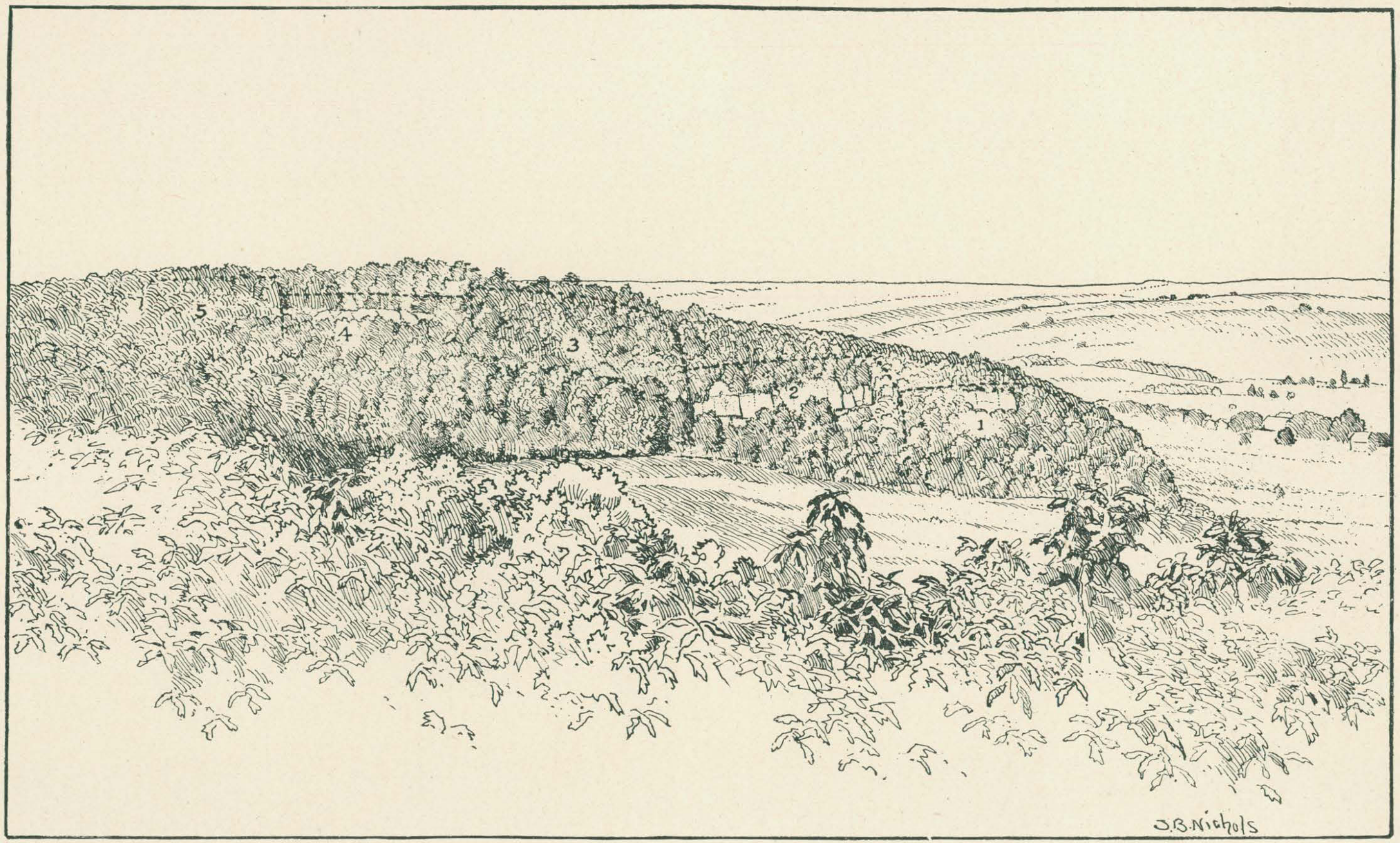
In crossing the west twin of Orenaug Hill in a direction from west to east, one encounters cliffs nearly at right angles to the course which are too steep to be scaled. From the top of these cliffs the rock surface, with its thin layer of mold, inclines gently to the eastward to the foot of a similar cliff, to which succeeds a gently sloping summit and a new cliff, as before. Approaching the eastern margin, cliffs appear upon the east, and these soon become the most important ones. If next a start be made at the northernmost point of the basalt in the same hill, where it terminates in a sharp prow between steep cliffs on both the east and west (shown in Pl. XI), and a course be taken southward through the intermontane valley, the nearly vertical eastern cliff face, which trends S. $\pm$ 5° E., can be followed on the right over a quarter of a mile, for a portion of the distance in a narrow canyon. After emerging from the canyon the cliff recedes on the right, but its direction is continued in a cliff on the left. After crossing the highway the path

[1] A geological reconnaissance in southern Oregon, by I. C. Russell: Fourth Ann. Rept. U. S. Geol. Survey, 1884, p. 445.

again enters a narrow canyon in the South Orenaug Hill between parallel cliffs to the east and west. For the greater part of the distance that this fault is thus followed, the cliffs are seen to be broken across by faults (N. ± 54° E.) transverse to the one which is being followed (N. ± 5° W.). At such points, which occur with great regularity at distances of about 100 paces (about 300 feet), the cliff, which has been dwindling rapidly in altitude, rises again to near its former height, from which it again falls away before the next cross fault is reached. It is also noted that alternate faults exhibit a larger throw, determined by the difference in cliff altitudes, and that minor faults are generally to be observed at 50-pace intervals (see Pl. XI). Where the path enters the canyon between the Twin Hills the same structure is displayed in the cliff facing west, but it is here noted that when the cliff is high on the west it is frequently low on the east, and vice versa—in other words, there is a tendency for the orographic blocks to be upthrown in alternate order, corresponding to the black and white squares in a checkerboard. This is certainly more than a local feature, for it can be observed in the main western cliff of the same hill, and elsewhere, and the Park drive, which ascends the west twin by a very uniform grade from the low southern end, does so by keeping north on the edge of one block until its northern end is reached, then turning sharply across a fault to the block diagonally to the left, and after following this to its end, utilizing the block diagonally to the right, and so on (see traverse of this drive on the map, Pl. XI).

SHAPE AND SIZE OF THE OROGRAPHIC BLOCKS.

The width of the individual orographic blocks in the west twin of Orenaug Hill was determined by pacing the width of the gently sloping summits from cliff to cliff. The average of a number of measurements, which were in close agreement, gave 43 paces, or about 129 feet. As these measurements are made at right angles to the long side of the block (N. ± 5° W.), the distance along the shorter side (N. ± 54° E.) would be almost exactly 50 paces, or 150 feet. Confirmations of these values and of the fault directions are obtained by traversing the cliffs which form the margin of this and the eastern hills, as well as by measuring the peculiar pedestal-like blocks upthrown in the area of Cannon Hill. The orographic blocks within this district are thus found to be rhomboidal prisms formed of two rhombic prisms in contact along one of their vertical faces. They measure ± 300 feet along the longer side and ± 150 feet along the shorter side. The dislocations of a lower order which were frequently observed at 50-pace intervals in the cliffs of the intermontane valley would indicate that the area is really broken into rhombic prisms, and that the rhomboidal prisms formed by faults of the same order of displacement are double rhombic blocks. Such rhomboidal blocks may be designated



FAULT SCARPS OF ORENAUG HILL (FLOATING BLOCK TOPOGRAPHY).

The view is taken from the top of a cliff in the eastern twin hill.

the unit blocks of the district, although it must not be assumed that they are the smallest of their kind.

The dislocations which trend N. ± 5° W. and N. ± 54° E. seem therefore to be here the predominant ones, not only in number but in throw, and therefore the ones which determine the shape and size of the unit orographic blocks. With them, however, occur dislocations trending N. ± 34° W. and N. ± 15° E., and in a few instances also faults have been observed which bear N. ± 90° E., and one N. ± 65° W. Careful search on a cliff angle formed at the junction of faults of the two prevailing series of this district will generally reveal one or the other of the two remaining and prevalent series of faults by a bevelment of the angle for a short distance or by a division of it. For considerable distances, however, as will be seen by an examination of the map, the N. ± 15° E. series, and less frequently the N. ± 34° W. series, forms the boundary wall of the hills.

OTHER QUADRANGULAR BLOCKS.

The unit blocks which have served as a basis for measurements in the Orenaug district are bounded by faults of the N. ± 54° E. and N. ± 5° W. series, the series which control the major blocks of the basin. This is doubtless due to the fact that the throw has more frequently been the greatest along these planes. Elsewhere in the basin, however, the throw has locally been more marked along individual faults of other series, and in such areas unit blocks of a different sort have been formed. Two striking illustrations of this are afforded by areas of granite, the one east of the main village street of Hotchkissville, the other on the southern margin of the island of granite due west of Woodbury village.

In the first-mentioned locality the faults which determine the boundaries trend N. ± 34° W. and N. ± 54° E., and the nearly rectangular blocks produced checker the slope east of the principal street in the vicinity of and also some distance north of the knife works. A locality beside the road is represented in Pl. XII, where blocks roughly measured were 50 paces (150 feet) long and 23 paces (69 feet) in width. In the foreground of this view is a block of the granite rising but a few feet above the general level. Beyond this block is a recessed area, occupied by ramshackle farm buildings (not shown in the plate), which marks the position of a depressed block of the same kind. Beyond this downthrown block are seen two upthrown blocks in line with those just described. There is found at this locality a series of nearly rectangular blocks, four blocks in length and three in width, with indications of others in the woods farther up the slope. It should be noted that these nearly rectangular blocks are only a little more than twice as long as wide, and they show indications of separation into shorter, nearly square blocks, the proportion of whose sides would be approximately 23 : 25. In the northwestern part of the basin (see Pl. I) the observed faults of the same two series (N. ± 34° W. and N. ± 54° E.) produce blocks which are likewise nearly square, the average of measurements deduced from the map being 480 feet in length and 406 feet in breadth. This would correspond to a ratio of about 22 : 26. The diagonals of the unit blocks of Orenaug Hill would produce blocks of this shape, the proportions of whose sides would be 21 : 24, so that there is a rather close correspondence in shape between the unit blocks of the Hotchkissville region, the larger blocks here described, and smaller blocks indicated in the Orenaug region. The regularity of these blocks in the northwestern part of the region is well brought out by the basalt exposures in Ragland (see fig. 37, which is drawn to scale).

At the other locality mentioned (west of Woodbury village) the blocks are likewise of granite, but are bounded by faults on but three sides, the faults trending N. ± 15° E. and N. ± 61° W. They occur on the southeast border of the island of granite and are three in number. Their breadth was roughly determined as 40 paces (120 feet) along the N. ± 61° W. boundary; but their length along the N. ± 15° E. boundary could not be determined. They have their long sides in contact with uniform upthrow of about 15 feet in the northwestern limb. This, and the dip of their upper surface (about 15° westward) have produced a serrated profile (see fig. 40).

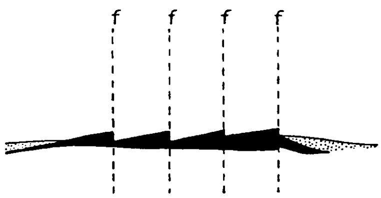


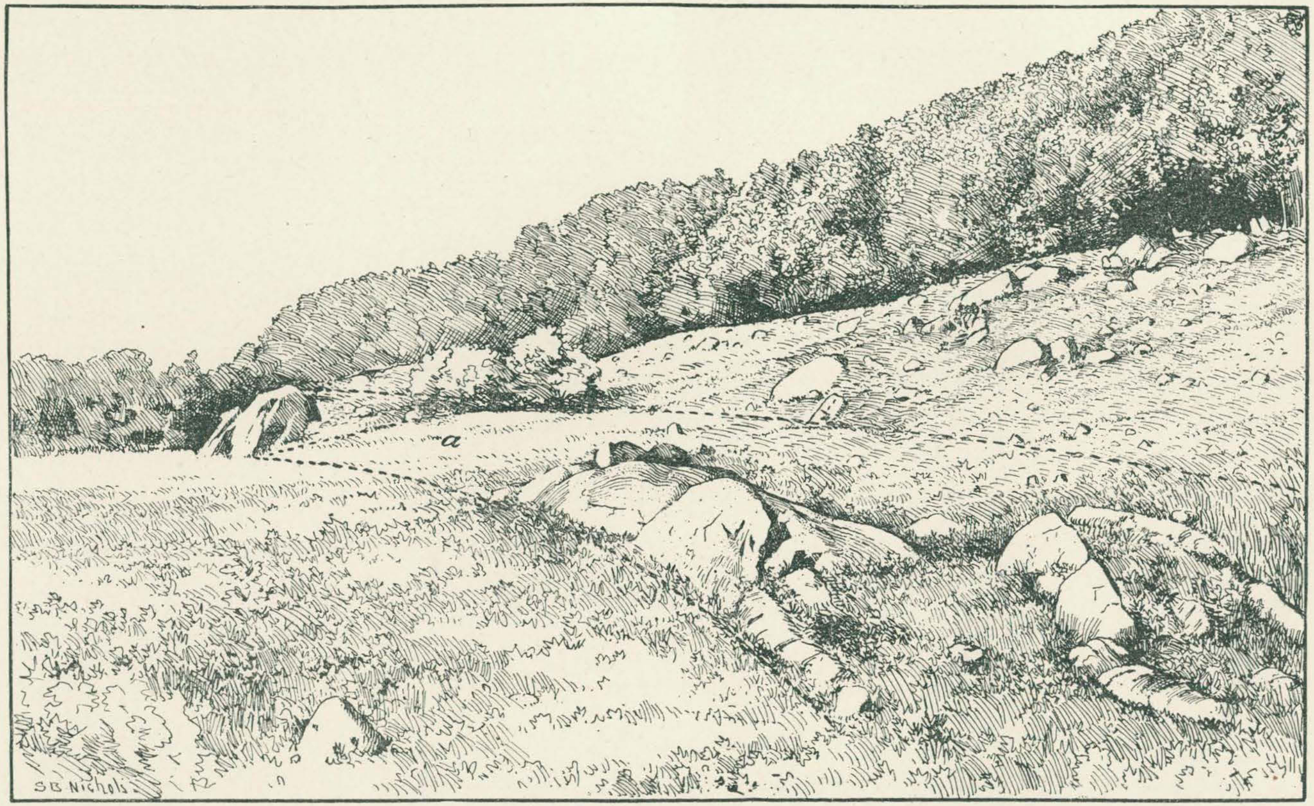
FIG. 40.—Section of unit blocks in granite west of the Woodbury plain. The principal fault scarps trend N. ± 15° E. Outcrops near are also locally bounded by faults trending N. ± 54° E., N. ± 61° W., and N. ± 90° W.

POLYGONAL BLOCKS.

The prevalence of quadrangular blocks rather than those having a larger number of sides is doubtless explained by the regularity in spacing in the system of faults within any given district. Some occurrences of polygonal blocks of a larger number of sides have, however, been noted. Perhaps the best illustration is the well-named Castle Rock, an octagonal prism composed of dense basalt which rears its sturdy form to the northwest of Pomperaug village (fig. 41). On the northern side of this block there is a sheer cliff nearly 100 feet in height, the highest that has been observed within the area of the basin.

GROUPING OF OROGRAPHIC BLOCKS INTO COMPOSITE BLOCKS.

While all orographic blocks have in some degree been either elevated or depressed with reference to all of their neighbors of the same order, yet, since the amount of the vertical displacement is different along



UNIT OROGRAPHIC BLOCKS IN GRANITE, NEAR THE KNIFE WORKS, HOTCHKISSVILLE.

a Area over downthrown block.

different fault planes of the same series, with larger throws at regular intervals, it follows that blocks will group themselves into composite blocks of a higher order. Such composite blocks will generally be outlined upon the map, either geologically by the boundaries of exposures of a given formation or in the elevated boundaries of a very resistant formation, or topographically by sudden changes in the profiles of physiographic features. These composite blocks may be of several orders, some of the larger in the Pomperaug Valley being indicated in the serrated eastern boundary. These latter blocks are bounded by faults of the N. ± 54° E. and N. ± 5° W. series, which extend practically across the basin in their projected directions. They therefore divide the Pomperaug Basin—a convenient division for reference—into the Woodbury plain, Orenaug Hill, Ragland, East Hill, and Pine Hill blocks, districts each of which has some peculiarities of structure (Pl. IX), but which, as is to be expected from their composite character, are not perfectly regular in their outlines. Composite blocks of a lower order are clearly indicated within the Orenaug Hill block (Pl. X) by the elevated basalt areas of the west twin, east twin, and south hill, the lower area of Cannon Hill, and the lowest triangular area bare of outcrops between the three Orenaug hills. In the block of the western twin the southeastern slope has an average plane surface, which is, however, marked by a regular grouping of hummocks produced by the smaller intermediate faults. The inclination of this hummocky but approximately plane surface is gently to the southeast, and one may start from the Park gate to climb on a nearly even slope along the undulating drive to the high northern points of the ridge. Toward the north, however, the throws become larger and the unity of the composite block is less apparent.

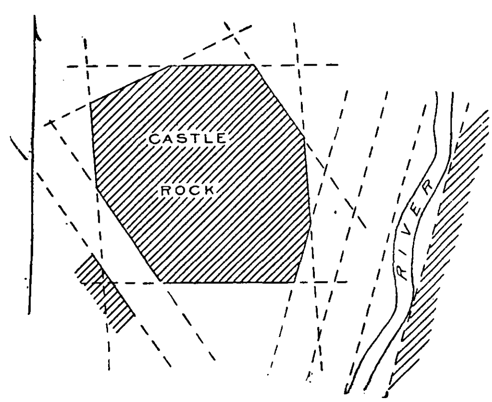


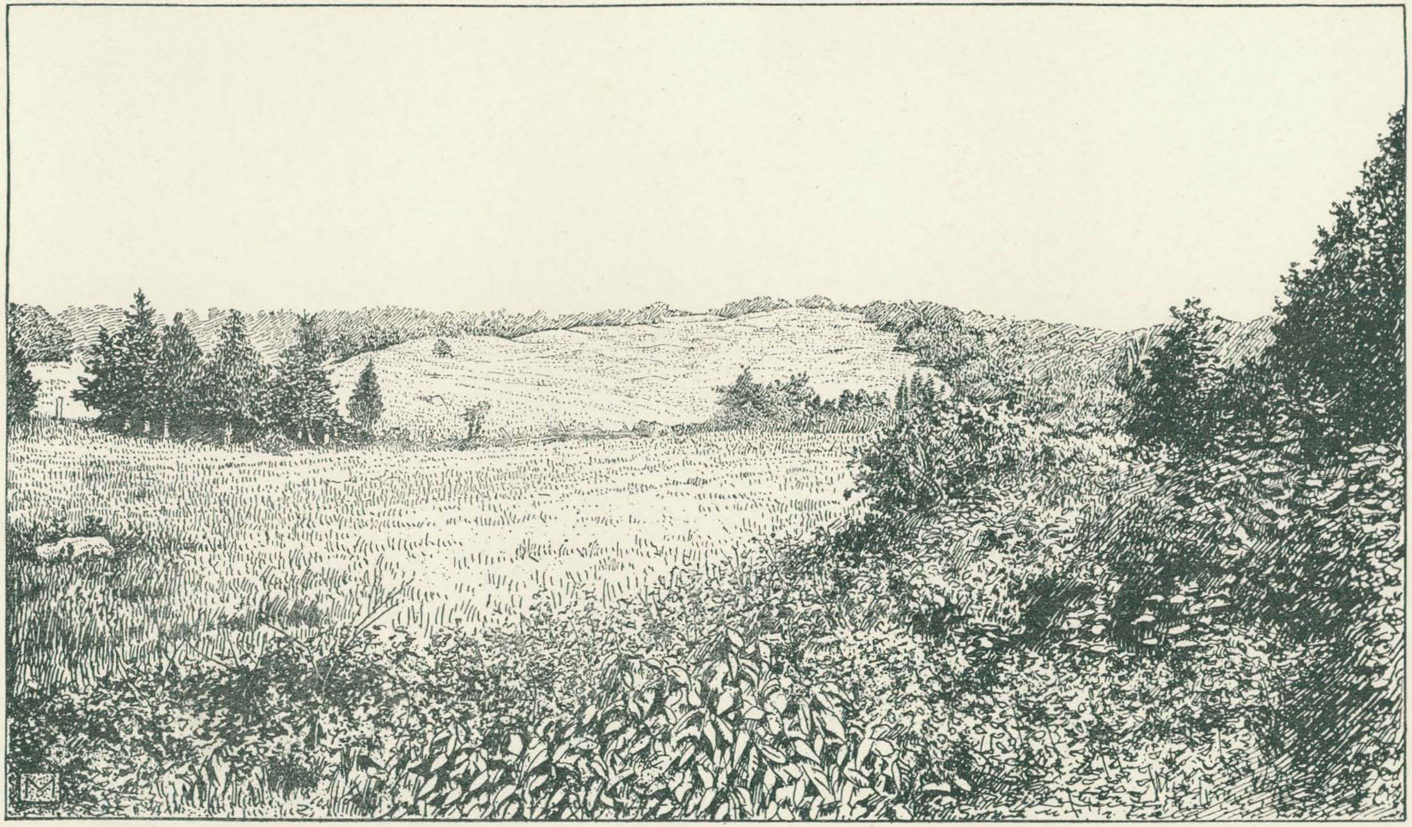
FIG. 41.—Sketch map of Castle Rock, near Pomperaug village. The bounding faults trend N. ± 5° W. on the west and east, N. ± 90° W. on the north and south, N. ± 15° E. on the southeast, N. ± 34° W. on the northeast and southwest, and N. ± 54° E. on the northwest. Southeast of the hill, which is largely wooded, an open slope descends in a series of steps to the canal-like basin of the Pomperaug River. While the directions of the boundaries have been taken, their lengths have not been measured, but only sketched.

The eastern twin also, which is nearly treeless in its southern portion, shows its unity as a composite block of the district in a very striking manner (see Pl. XIII).

The double basin walls which have been mapped west of the Woodbury plain clearly indicate that between them lies a composite block bounded mainly by N.$\pm$54° E. and N.$\pm$34° W. faults, and occupying an altitude intermediate between that of the high walls of schist and gneiss on the north and west and that of the low-lying sandstone to the east and south. This intermediate position adequately explains its mantle of drift, which has left only the eastern and southern margins uncovered. A study of the southern margin of this block has shown the existence there of composite blocks of a lower order, an observation which finds confirmation in an examination of the topographic features of the slope above. In other localities which, like the one just described, are barren of outcrops, the physiographic features yet allow a delimitation of orographic blocks to be made with some degree of confidence in its correctness. The parallelism of almost straight lines of topographic continuity with the boundaries of exposures or with the strikes of prevailing fault series finds a perfectly simple and natural explanation if they are regarded as the boundaries of orographic blocks. The sharp western and northern boundaries of the Ragland Hill are interesting from this point of view. Likewise the sharp rise of the eastern wall of the basin from a broken line, the straight elements of which are strikingly displayed in the contour lines of the topographic map, finds a natural explanation in the termination at that margin of large composite orographic blocks. It would be easy to show that these blocks, and others to be noted, have influenced in a marked degree by their modifications of topographic features the courses of highways and of the railroads as well.

RELATIVE ALTITUDES OF OROGRAPHIC BLOCKS.

In view of the somewhat novel features of the observations within the Pomperaug Valley, new methods of coloring have been introduced in all the maps which accompany this report. It was thought desirable to indicate so far as possible not only the positions of the observed dislocations, but also, to a rough approximation, the altitude of the orographic blocks which they have conditioned. In order so far as possible to differentiate fact and theory, a definite color was assigned to each member of the Newark series, and to the granite and gneiss as well, the deepest shade of each color being reserved for actual exposures. The supposed extension of each formation beneath the present surface of the ground has been indicated by a tint or by two or more tints of the same color. If more than one tint has been used for any formation, the darkest one (exclusive of that reserved for exposures) is intended to represent by its extension the area of a composite orographic block which stands at as high an altitude as any block in the district the cap of which is of the same formation. To illustrate, areas colored in the deepest tints of the crystallines (except that reserved for actual exposures) represent the blocks of highest altitude



VIEW OF THE SOUTHEASTERN SLOPE OF THE EASTERN TWIN OF ORENAUG HILL.

Fault scarps bound the hummocky surface of the block on the northeast and west; the courses of the scarps follow the fringes of trees.

within the area of the map. The areas bearing the color of the posterior shale represent the blocks capped by posterior shale, which are the lowest of all, because capped by the uppermost formation and because lying lower in the valley than any except those capped by the South Britain conglomerate. The areas colored in tints corresponding to intermediate formations represent, by their order from the posterior shales, blocks having successively increasing altitude up to the darkest shade assigned to the crystallines. The total difference in altitude represented in the basin is about 800 feet plus the thickness of the four lower members of the Newark series (±1,200 feet) and the thickness of the crystallines which has been removed by degradation. Generalization and inference have of course been necessary in this representation, but inference of the same kind that is ordinarily used in geological mapping to determine the boundaries of formations, and the areas colored with a single tint represent a range of average altitude of composite blocks and of individual unit blocks; but it is believed that the general order of altitude has been fairly represented.

In the case of the main basalt sheet, whose exposures frequently stand above the general level in such a manner as to define clearly the areas of the highest blocks which are capped by basalt, it has been unnecessary to reserve any other tint for the actual exposures. Considerably lower areas, which are indicated in the next lighter tint of green, may, and in most cases do, include numerous exposures of basalt; these, however, can not be indicated by the scheme suggested. The difficulty is not a very serious one, since the basalt areas are easily determined, and the essential continuity of the horizon may be safely predicated from the characteristics of the country. The larger rugged areas of basalt, such as those of Pine Hill and central Ragland, on the other hand, offer great difficulties when the mapping of their dislocations is attempted, because accurate location is here possible only by elaborate and time-consuming methods, owing to the jumble of orographic blocks standing at slightly different altitudes, and to the absence of any near determined base from which to measure. For this reason the central portion of Pine Hill has been left uncolored upon the detailed map (Pl. VIII), though the area in question has been examined and found to consist of basalt throughout. The difficulty here is the indicating of the relative altitudes of the different orographic blocks of basalt. Likewise, only the larger features of the north-central area of Ragland have been entered upon the map. The name of this district calls attention to the striking peculiarities presented by its topography, which might be better described, however, by comparison with the surface of floating blocks that have been closely jammed together, accompanied by slipping upon one another.

The vertical displacements along the walls of individual blocks, as has already been pointed out, may be either large or small; but in general they may be said to be very much smaller than the figures which are usually estimated. Along the walls of the unit blocks of Orenaug Hill they are in most cases of but a few feet (10 to 30 or 40). Those represented by the dislocations bounding the hummocky areas of the same hills must be smaller than this, and, as we have seen, by a reduction in the throw these faults pass into joints.

There is no reason to expect that, because a particular limb of a given fault, say the eastern, is at one point downthrown, this limb will be downthrown throughout the extent of the dislocation. It may be the upthrown limb for some distance, or the plane of rupture may for considerable distances even have caused no appreciable dislocation, the blocks on either side standing at essentially the same altitude. Thus a fault might appear to die out though really persistent. It is interesting to note, however, the persistence of throws of a given kind, either up or down, in any limb of a fault whenever this throw has been considerable.

MINOR FAULTS AND MINOR BLOCKS.

The orographic blocks whose shape and size were the basis of measurement in the Orenaug district were designated the unit blocks of that district, because they were the smallest blocks which could be conveniently examined in that way. But while these blocks are units only in the sense that they are the smallest which can be used as a satisfactory basis of measurement, there are found in some portions of the basin evidences that the complex system of faulting does not stop with these unit blocks. The southern slope of the east Orenaug twin is a surface of coarsely amygdaloidal basalt representing a superficial layer of the main sheet. By the action of frost in expanding the water which by percolation has filled the vesicles, the surface of this rock has been covered with decomposed chips of its own material. The hummocks which are uniformly distributed over the surface in question are of this material, and since they have doubtless originated from natural causes they point to an average surface which was characterized by alternate projections and depressions, arranged in a general way like the black and white squares of a checkerboard, though probably much less regularly (Pl. XIII). Such a surface, formed from blocks of a larger order, has already been described from the walls of the intermontane canyon of these hills and from the southern slope of the western twin.

GRADATION OF FAULTS INTO PRISMATIC JOINTS.

At the northern end of the eastern Orenaug twin even smaller dislocations than those just described may be observed. In fact, the dislocations here appear in such numbers and are apparently of such small displacement that they may be properly designated joints. The fracture planes, which are distant only a foot or two from one another, have strikes corresponding with the faults observed elsewhere in the region. There seems, therefore, to be every gradation from faults whose displacement measures hundreds, and perhaps a few thousands, of feet—the major faults of the basin—through the faults of only moderate displacement which bound the unit blocks of the western Orenaug Hill (estimated to be from 10 to 50 feet), and the small displacements which produce hummocks on the southern slope of the eastern twin, to, finally, the prismatic joints which have just been described from the northern end of the same twin.

RELATION BETWEEN THE SHAPE OF THE OROGRAPHIC BLOCKS AND THE FAULT SYSTEM.

The size and the shape of the unit orographic blocks have been most satisfactorily determined in the area of the west Orenaug twin, where, as already described, the bounding planes of the rhomboidal blocks trend N. ± 5° W. and N. ± 54° E., and the dimensions along the longer and shorter sides are very nearly 300 feet and 150 feet, respectively. A cross section of these rhomboidal blocks would give for the angles of the rhomboid nearly 60° and 30°. The faults which bound these blocks have about the same order of importance, but if we were to have regard to the less important faults, which can generally be found to divide them in half in the direction of their length, we should consider them as double rhombic prisms instead of rhomboidal prisms.

It is pertinent next to inquire whether any relations can be found to obtain between the size and shape of these unit blocks and the strikes of the other faults, which, with the two bounding the blocks, comprise the fault system of the basin. It could hardly escape observation that the long and short diagonals of the block correspond closely in direction with the remaining series of faults which prevail in the valley (see fig. 42). As determined from the measurement of the block shown in the cut, these directions are N. 14° E. and N. 35° W., whereas the observed values are N. ± 15° E. and N. ± 34° W.

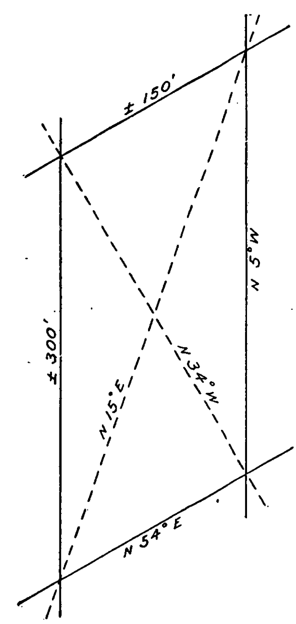


FIG. 42.—Diagram showing the shape of the unit blocks of Orenaug Hill outlined by faults trending N. ± 5° W. and N. ± 54° E. The diagonals of the blocks are approximately parallel to the two remaining series of the prevailing system (N. ± 15° E. and N. ± 34° W.).

It is natural next to inquire if the less common series of faults may not correspond in direction with the diagonals of composite blocks made up of a number of unit blocks. By assuming blocks composed

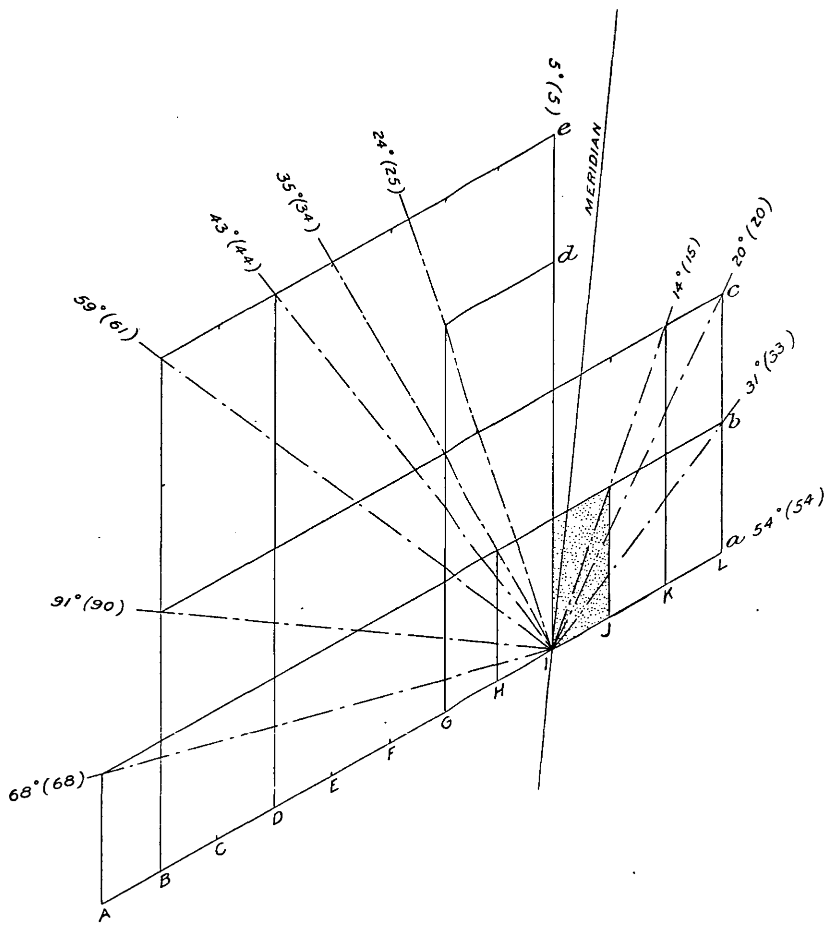


FIG. 43.—Diagram to show the relation between the shape of the unit blocks of Orenaug Hill and the fault system. The stippled area outlines the shape of a unit block bounded by N. ± 5° W. and N. ± 54° E. faults. The N. ± 15° E. fault lines correspond closely in direction with the long diagonal of these blocks, and the N. ± 34° W. to the short diagonal. The less common fault directions are the diagonals of composite blocks made up of a number of unit blocks. The figures printed at the end of each diagonal are the directions of the diagonal as obtained (graphically) from the diagram, and the figures in parentheses which follow are the actual directions of fault series (as determined in the field) with which these diagonals closely correspond in direction. Thus the N. ± 33° E. fault series corresponds closely in direction with the longer diagonal of a composite block one unit long by three units wide. The N. ± 20° E. direction, like the last-mentioned characteristic of the southern zone of the Pomperaug Basin, corresponds closely with the direction of the diagonal of a composite block two units long by three units wide, etc.

of a sufficiently large number of unit blocks, it would, of course, be easy to find a diagonal which would correspond to any desired fault direction, and such a study would be without special significance. If, however, the number of unit blocks composing the composite block be small, the correspondence of its diagonal with the fault series of the basin is a matter of some interest. The series of faults trending N. ± 33° E. is found to correspond closely in direction with the long diagonal of a composite block made up of three units placed side by side (block IL *ab*, fig. 43); the series trending N. ± 20° E. corresponds with the long diagonal of a block composed of three unit blocks in width and two in length (IL *ac*); the several westerly trending series characteristic of the zone of accommodation in the Rattlesnake Hill district require larger composite blocks in order to show correspondence with the diagonals, and the correspondence has, on the theory of chances, less significance. Thus the strike N. 25° W. is near the diagonal of a composite block three units long and two wide (IG *ad*); the strike N. 44° W., similarly of a block four units long and five wide (ID *ae*); the strike N. 61° W., of a block four units long and seven wide (IB *ae*); the strike N. 90° W., of a block two units long and seven wide (IB *ac*).

More instructive than this, however, is a study of the composite blocks themselves within the area of the basin. There are many composite blocks shaped like those of the west Orenaug twin which have as their diagonals faults trending N. ± 15° E. and N. ± 34° W. In fact, it may be said to be characteristic of the region that these faults trend along the diagonals of composite blocks whose shape is the same as the unit blocks of Orenaug Hill. In the southern portion of the area certain large composite blocks are deserving of special study. To the east of the great block outlined by crystallines, which includes Pine Hill and Rattlesnake Hill, is indicated a block of crystallines (E) along the short diagonal of which runs a N. ± 34° W. fault (*i*). Boundaries of exposures within the Pine Hill block itself indicate that it is composed of three large blocks, two of which are clearly of the type of the block E, with whose shape they are identical, but from whose size they show slight variations. These blocks can best be seen in fig. 44, which is a diagram reproduced from a portion of the general map, with, however, many of the details omitted. Both these blocks have diagonal faults, the eastern one (Southbury block) the faults k, I_1, and the western one the faults m_1, III. The extreme western block (South Britain block) has a different shape, the ratio of its sides being 19:30 (or 2:3) instead of 15:30 (or 1:2), as were the two others, and also the block of E (13½:26). To correspond with these different proportions, we find different fault directions represented within the South Britain block. In place of the N. ± 15° E. and the N. ± 34° W. directions, which are characteristic of the other blocks, we here find new directions, N. ± 44° W. and N. ± 20° E., for the strike of the prevalent faults. Two of these faults, moreover, correspond quite closely in position, as well as in direction, with the diagonals of the block. The larger block, of which this abnormal and the two normal blocks with ratio of sides

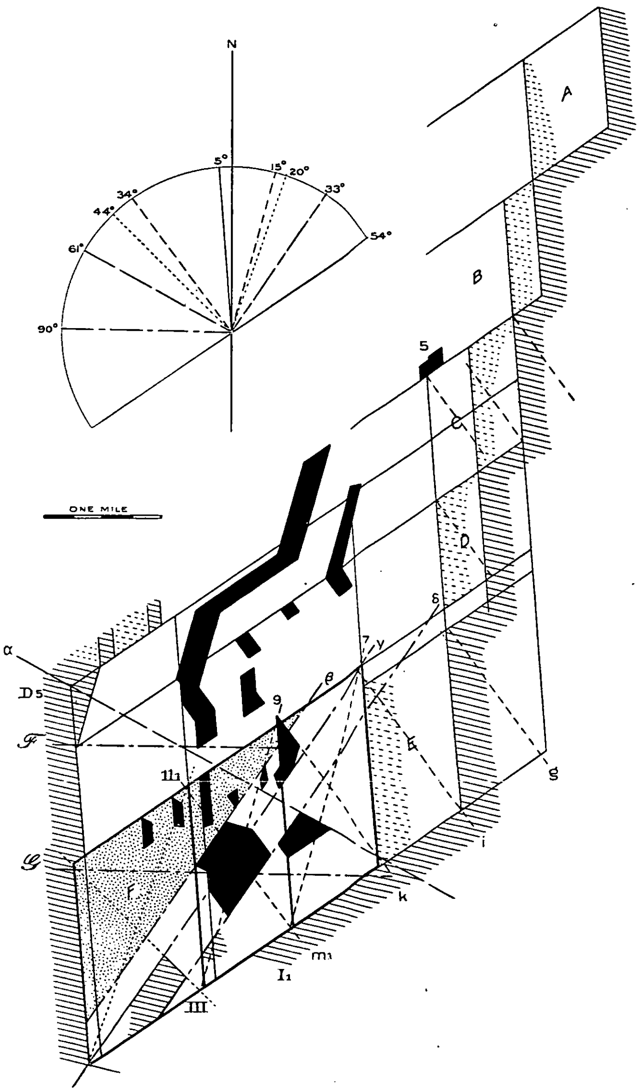


FIG. 44.—Map of the southern part of the Pomperaug Basin showing the larger composite blocks. A, eastern end of the Woodbury Plain block. B, eastern end of the Orenaug Hill block. C, eastern end of the East Hill block. E, block capped by the crystallines, in shape like the unit blocks of Orenaug Hill. To the west of the block E are two blocks of the same shape, but of larger size (Southbury and Pine Hill blocks). F (South Britain block) is a block bounded by faults of the same series as the last, but one of larger size and of different shape, the ratio of its sides being 2:3 instead of 1:2. The stippled area is the triangular zone of accommodation of Rattlesnake Hill; the black areas are the principal areas of the main basalt, and the hachured areas represent the borders of the crystallines. The areas hachured in full lines are occupied by exposures, whereas those hachured in dotted lines are, from topographic peculiarities, determined as lower blocks capped by crystallines. Compare with Pl. I, on which the geological coloring brings out the composite blocks.

1:2 are parts (Pine Hill block), has for its longer and shorter diagonals faults N. 33° E. (γ) and N. 90° W. ($\mathcal{G}_2$), respectively. The most complex zone of faulting within the basin, the triangular area which I have called the zone of accommodation of Rattlesnake Hill (F, stippled), occupies the northwestern part of this block.

The arm of the crystallines which crosses Transylvania Brook at the Cascade (D_5) and the eastward bend of the Ragland Ridge (D_6) outlines with the walls of the large Pine Hill block, a block of still larger order than any of those thus far described, and of this a fault (ℵ) of the N. ± 61° W. series coincides with its short diagonal. Thus less common directions of faulting are found to correspond to the diagonals of unusual composite blocks in the same way that the prevailing faults correspond to the diagonals of the unit blocks, and, as it has here been shown, of composite blocks as well.

Some relation between the directions of the different fault series might have been brought out if we had started from the unit blocks of the Hotchkissville district instead of from the units of Orenaug Hill; but the latter are the ones which have furnished the most reliable measurements, and the way in which the crystalline walls of the basin conform in their outlines to those shapes would seem to indicate that they are the ones along which the largest displacements have occurred.

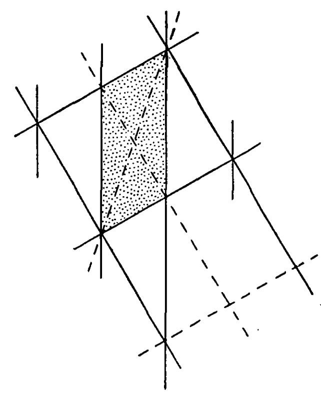


FIG. 45.—Smallest observed orographic blocks of the N. ± 34° W.-N. ± 54° E. type in the Oernaug district in comparison with the unit blocks of that territory. These blocks are nearly rectangular (angles ± 88° and ±92°), with sides in the ratio of about 21:24. They each inclose one whole and two half blocks of the unit size and shape.

In the Orenaug Hill district it seems clearly to be indicated that the interval on the N. ± 34° W. series of faults is greater than that of the other series which prevail in the district (Pl. X). Their relations to the latter are brought out in fig. 45, from which it is seen that the N. ± 34° W. and the N. ± 54° E. faults produce nearly rectangular blocks, with the ratio of their sides about 21:24. These blocks, which are the units of their kind, as heretofore defined, within the area in question, are divided by the N. ± 15° E. faults in the direction of the longer diagonal of the block, while the N. ± 5° W. faults form in a similar manner the longer diagonal of a composite block made up of two units whose longer sides are in contact; or, expressed in a different way, the N. ± 5° W. faults divide diagonally the half of the unit block. Each unit block of the N. ± 34° W.-N. ± 54° E. type incloses one whole and two half blocks of the N. ± 5° W.-N. ± 54° E. series, as is indicated by fig. 45. The blocks of the former type correspond in shape to those of smaller dimensions which were measured in the Hotchkissville district (p. 110), and they are both in shape and in size identical with those which are indicated on the map (Pl. I) as occurring over practically the entire area of the basin. It should be noted, however, that, except to a limited extent, particularly in the northwestern portion of the basin, these blocks have not determined the outlines of the larger composite blocks of the basin, whose boundaries, as already shown, are formed by faults belonging to the N. ± 5° W. and N. ± 54° E. series. Owing to the difference in the amount of throw within a given fault series, the displacements along the boundaries of the composite blocks are of a higher order than those bounding its component individuals, and hence the larger composite blocks appear to have moved essentially like individuals.

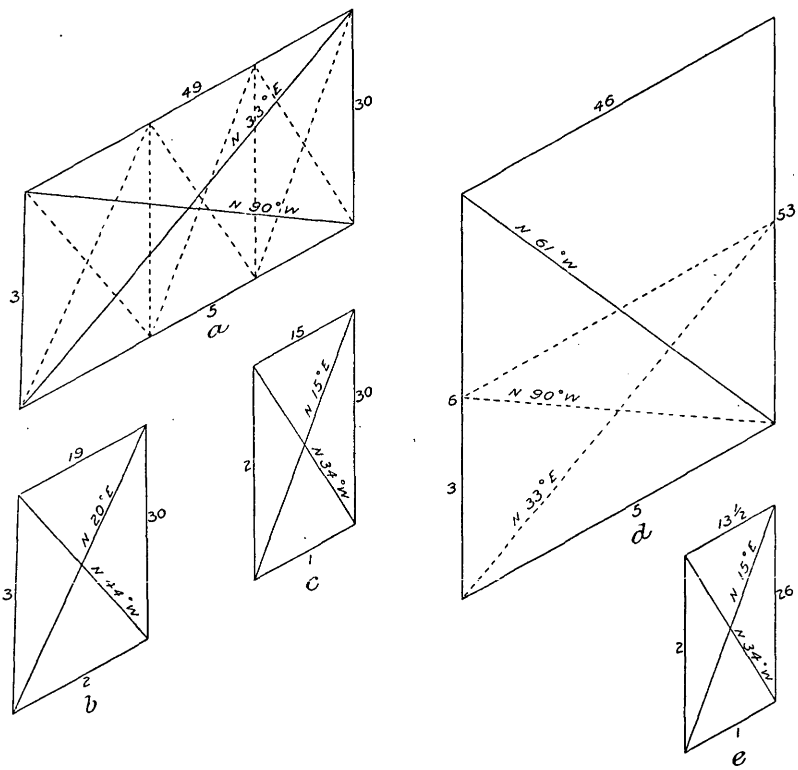


FIG. 46.—Diagram showing the shapes of composite orographic blocks in the southern part of the Pomperaug Basin. *a*, South Britain-Pine Hill-Southbury block; *b*, South Britain block; *c*, Southbury block; *d*, East Hill-Pine Hill block; *e*, smaller Southbury block. The larger figures on the sides of each block are the measurements of each as read from the map in sixteenths of an inch (one-sixteenth of a mile). The smaller figures on the opposite sides give the approximate simple proportional lengths of the same sides. The diagonals of the blocks correspond closely in direction, as they do also in position, with observed faults having the directions indicated.

The study of the composite blocks of the southern district has brought out strongly the fact that composite blocks approximate to a definiteness of shape rather than of size. The unit blocks of Orenaug Hill bounded by N. ± 5° W. and N. ± 54° E. faults have the ratio of their sides approximately 1 : 2. The composite block of gneiss (E, fig. 45 and *e*, fig. 46) has the ratio of its sides about 13½ : 26, the Southbury block (*c* in fig. 46) 15 : 30, so that each of these approximates to the shape of the unit block. The South Britain–Pine Hill–Southbury block (*a* in fig. 46), which is apparently unique in the district, has the ratio of its sides 30:49, or about 3:5. The large East Hill–Pine Hill block (*d* in fig. 46) has a ratio of its sides of 53:46, or about 6:5. It is thus seen that this block is the double of the Pine Hill block, although this was not at once apparent from the map, owing to the lack of a simple ratio connecting the sides of the two. This observation is a valuable one, since it shows that the faults trending N. $\pm$ 61° W. correspond to the short diagonal of a block composed of two Pine Hill blocks in contact along their longer side.

It is not believed to be entirely exceptional that the characteristic shapes of orographic blocks are thus found to bear such simple ratios to the unit form. It is much more likely that it is to be explained by the anisotropic condition of the rocks induced by the stresses which immediately preceded their dislocation. The analogy with the elastic properties of an anisometric crystal or with a piece of glass which has been consolidated under unequal compression from different directions is certainly a striking one.

SECTION 6.—ORIGIN OF THE FAULT SYSTEM.

Any theory which is to explain satisfactorily the faults of the Pomperaug Basin must take account of a large number of observed facts. It must explain the great number of dislocations, their steep and nearly vertical hades, their grouping into parallel series, the relations which exist between the strikes of the four prevalent series and the shapes of the unit orographic blocks. It must further take into consideration the distribution of throw over a zone of parallel faults, in which zone there are throws of a higher order separated by fairly uniform fault intervals, and others of a lower order along faults included within the intervals. Locally, at least, these minor faults must pass into joints. The composite blocks included between the faults of larger throw must be elevated or depressed, with reference to the neighboring composite blocks, essentially as though they were units, although within each the composite blocks of a lower order (or perhaps the unit blocks) must be elevated or depressed in a similar manner with reference to their neighbors. In fact, the theory must be made to explain the origin of a composite system of orographic blocks, of which the largest are composed of smaller blocks which have component blocks of a lower order, and they of a still lower order, etc. The correct theory will account for this structure (or certain features of it) not only within the area of Newark rocks, but in the crystalline walls of the basin as well.

Thus far in the present study no evidence has been presented either for or against the presence of faults in the crystalline area, except in the walls of the Pomperaug Basin; but the theory must be framed to explain, in a general way, the structural characteristics common to all the areas of Newark rocks. In the introductory chapter to this report I have called attention to the prevalence of faulting in all the areas of Newark rocks that have been carefully studied. As Russell has shown, fault walls largely surround many of the Newark basins. Davis, too, has emphasized the common structural features of the different areas. It seems fairly clear that a system of faulting possessing certain, at least, of the features observed in the different Newark basins obtains also in the areas connecting them. There is, however, a lack of evidence that great areas have been bodily depressed, except where the Newark rocks are to-day preserved. We are therefore called upon, as it seems to me, to explain by adequate forces the systematic deformation of a large area of crystalline rocks, together with whatever superincumbent beds they support, and in special regions (the present areas of Newark rocks) to explain in addition the depression, by some thousands of feet, of considerable areas of the earth's crust—depressions which have quite likely been attended by dislocations of their own.

THE DAVIS THEORY.

The theory proposed by Professor Davis to explain the faulting in the Pomperaug Valley and the Connecticut Valley regions[1] supposes the underlying crystallines to be separated into slabs by a series of parallel planes (whether original bedding or secondary structure planes), which slabs strike northeast and southwest and incline steeply to the eastward throughout the areas. The upper zone of the crust, and hence the upper ends of these slabs, is supposed to have been moved to the eastward or southeastward with reference to the lower zones, and hence to the lower ends of the same slabs, through the action of a couple (lateral compression), and release from these strains is obtained by faulting along the structure planes separating the slabs from one another. This faulting produces a serration in the surface form of the upper edges of the slabs, slices the overlying Newark deposits, and tilts each slice so that (with slabs of uniform thickness) it is upthrown as much with reference to its neighbor on the west as it is downthrown with reference to its neighbor on the east. Variations from this uniform upthrow on the east are explained by the existence of certain curving lenticular slabs, which, on being straightened out under the lateral compression, project beyond the straighter slabs.

The name of the distinguished founder of this theory and the ingenuity of its conception, but even more the lack of adequate data on which to found a rival theory, must, I think, be responsible for the ready acceptance which it has found, for there is much which the theory fails to explain in the areas to which it was originally fitted. Some of these defective elements in the theory I will briefly mention.

[1] Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 481-490.

1. It explains the occurrence of a single series of faults only, although Professor Davis's map shows at least two series, which make large angles with each other. In the eastern wall of the Connecticut Valley Professor Davis's map shows a clear indication of a structure similar

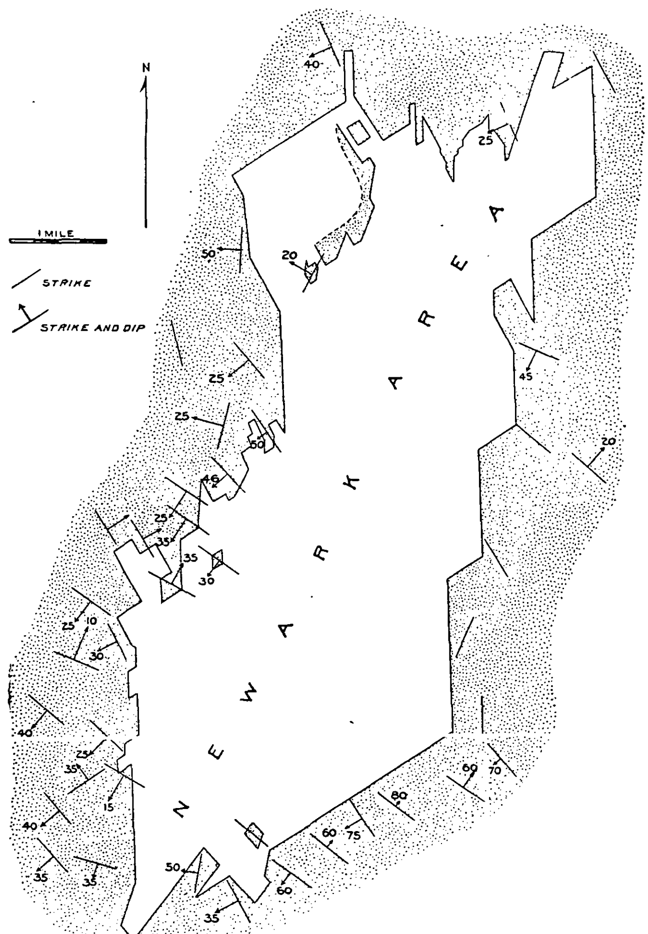


FIG. 47.—Map showing the strike and dip observations of the prevailing laminated structure (not necessarily bedding) in the exposures of crystalline rocks nearest to the Newark basin.

to that which has been determined to characterize the eastern wall of the Pomperaug Valley.[1]

2. While explaining the regular upthrows of blocks in the eastern limb of each fault—and it is this special feature which the theory seems framed to explain—it fails to take account of the depression of the entire areas below the level of the crystalline rocks by which they

[1] Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1898, p. 123, fig. 25.

are surrounded, and hence an additional supplementary theory is made necessary—the "local basin" theory for the sediments of the Newark. These theories are thus intimately connected and supplementary to each other in the areas under consideration.

3. The Davis theory requires a "ready-made" geology for the great uplands of Connecticut, since it is only fair to assume that the structure of the crystallines beneath the Connecticut and Pomperaug valleys is not unlike that of the uplands which surround them. At the time the theory was promulgated nothing definite was known of the geological structure within these uplands. As the result of some ten years' study devoted to the western upland, during which time the larger portion of it has been examined with some regard for detail, I may say that there is not found to be such a regularity of structure as seems to be demanded by the Davis theory. The structure planes of the region change their strikes and dips with remarkable frequency, and great batholiths of granite and of other igneous rock occur in such forms as to interfere with the regularity and the continuity of the supposed slabs of gneiss.

The Pomperaug Valley affords, however, the best opportunity for testing the hypothesis, since the strikes and dips of the prevailing structure have been recorded in the nearest exposures to the valley. This strike is not necessarily that of bedding, but that (if I correctly interpret the theory) is not intended by Professor Davis. His theory requires simply that there be planes of separation, or even of little cohesion, in the positions which he has indicated. An examination of the figure (fig. 47) will show that the average strike of the prevailing structure in the zone of crystallines surrounding the Pomperaug Valley is northwest and southeast, instead of northeast and southwest, as required by the theory, and that, moreover, it changes locally with great frequency.

But if the Davis theory is incompetent to explain the facts observed in the Pomperaug Valley a decade since, it is even more unsatisfactory if fitted to the larger knowledge of today.

THE PROPOSED THEORY.

As already pointed out, the facts seem to indicate that a large area of the earth's crust, in which the several Newark areas are included, has been throughout systematically dislocated by external forces, and that, further, in special regions—the Newark areas themselves—areas of considerable size have been downthrown along these dislocations by an amount measuring some thousands of feet. To account for the downthrow of the special areas, the surrounding rocks being essentially the same, we may assume that, for some reason, in these areas the support was less or the load greater (perhaps both) than in the surrounding territory. The downthrow of these great orographic blocks by such an amount may well have been attended by local dislocations secondary to the primary dislocations of the area as a whole. These latter dislocations are not described as "primary" with the intention of conveying the idea that they occurred in an earlier period, but as to some extent at least controlling the secondary dislocations and preceding their formation by at least an infinitesimal interval of time. These secondary dislocations may be of more than one kind, and may be traced to different causes.

We must first seek, therefore, a system of stresses competent to produce the primary dislocations of the Pomperaug Valley; and, second, the primary dislocations being formed, a force must be sought which will account for the depression of portions of the area in the form of great composite blocks below the level of the crystalline rocks, and probably, also, for the formation of secondary dislocations.

A. Discussion of the conditions necessary to the formation of a network of vertical joints or faults.—The perfection of the system of faults within the Pomperaug Valley indicates that the deformation took place under light load, well up in the earth's upper zone of fracture.[1] The resemblance of the primary fault system to a system of joints, and, in fact, its gradation into such a system, has already been pointed out. According to the accepted definition, joints differ from faults in their greater number (smaller interval) and in their inconsiderable throw.[2]

Joints have been brought about by Daubrée and Tresca,[3] both by a torsional stress and by unequal compression of a very elastic and brittle medium (glass), and the theory has been promulgated that rock joints have been formed by similar forces, jointing being supposed to occur where the system of stresses induces shears so great as to pass the ultimate strength of the rock. Crosby has supplemented the theory in an important way[4] by showing it to be unnecessary to assume that the rock is continuously strained to near the point of rupture, a temporary shock, if communicated to the medium and adding its stresses to those already existing, being competent to release the stresses by dislocation. He has modified Daubrée's experiments by straining glass plates to a point well below that of rupture, and through a shock communicated to the end of the plate by the blow of a hammer brought about fractures identical with those obtained by Daubrée. If the expression may be used, the shock transmitted acts as a fulminate to set off the charged system. Becker[5] has treated the subject of the compression of an

[1] Principles of North American pre-Cambrian geology, by C. R. Van Hise; Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, p. 589.

[2] Études synthétiques de géologie experimentale, by A. Daubrée; Pt. 1, Paris, 1879, pp. 300–301. See, also, Finite homogeneous strain, flow, and rupture of rocks, by Geo. F. Becker: Bull. Geol. Soc. Am., Vol. IV, 1893, p. 73; and Van Hise, op. cit., p. 672.

[3] Op. cit., pp. 300–374.

[4] The origin of parallel and intersecting joints, by W. O. Crosby: Am. Geologist, Vol. XII, 1893, pp. 368–375.

[5] Op. cit., pp. 13–90.

elastic brittle medium from a mathematical standpoint, analyzing the stresses within the strained mass previous to rupture, when, it is worth pointing out, it presents the anisotropic condition of a nonisometric crystal. He has shown that if an elastic brittle medium like a section of the earth's crust under light load be subjected to direct horizontal pressure coming from a single direction, rupture will take place along those directions subject to the greatest tangential stress. If the resistance offered to compression is for any reason unequally distributed in the plane perpendicular to the line of pressure, the strain ellipsoid will be triaxial, and rupture will occur in the plane of the greatest and least axes. In the case of the compressed portion of the earth's crust which we are considering, gravity aids in preventing the elongation of the vertical axes. In this case, therefore, the greatest and the least axes of the strain ellipsoid would lie in the horizontal plane, and the rupture planes produced would be vertical. The effect would, therefore, be to produce a system of vertical prisms.[1] According to Becker, the directions of these rupture planes in a mass having infinite resistance would make 45° with the direction of pressure, but otherwise the angles would generally be greater. He states, however, that whether the acute or the obtuse angle formed by the rupture planes is bisected by the direction of the compressive force will depend on whether finite deformation has occurred previous to rupture; in other words, upon the plasticity of the rock mass under the conditions of compression. With pressures rapidly applied he believes that rocks behave like highly elastic bodies, and that the range in the angles of rupture is small.

Hoskins,[2] however, quotes the experiments of Hodgkinson on the rupture of cast-iron cylinders under compression, in which the planes of rupture made on the average an angle of 35° with the axis of pressure, and states that if this principle holds for rocks under compression, "rupture by shearing would be expected to occur along planes oblique to the axes of greatest and least intensity of compressive stress, but (if the material is isotropic) inclined at angles of less than 45° to the axis of greatest stress."

Bouton[3] also, in investigating the rupture of cast iron, limestone, asphalt, and Milwaukee brick under compression, has assumed that the departure of the planes of rupture from angles of 45° with the axis of pressure depends upon the coefficient of friction of the substance, and that the angle of rupture is 45° plus one-half the angle of repose. His experimental results seem to be in close harmony with this assumption, the angles of rupture varying from 29° to 37° with the different

[1] Op. cit., p. 50.

[2] Flow and fracture of rocks as related to structure, by Leander Miller Hoskins: Sixteenth Ann. Rept. U. S. Geol. Survey, 1896, Pt. I, p. 873.

[3] Summary of a thesis for the degree of Master of Science at Washington University (1891), entitled, Theory and experiments on the laws of crushing strength of short prisms. Published in J. B. Johnson's The Materials of Construction, New York, 1900, pp. 24-28.

substances, while the variations from the theoretical values rarely exceed a degree.

However interesting these results of test blocks may be, the conditions of the experiments are, after all, so different from those assumed in this discussion and from those which may be supposed to obtain in a crustal block under compressive stress, that they must be applied with great allowances, if applied at all. This would seem to be shown by the fact that vertical joint planes by observation generally differ but little from rectangularity, whereas in experiments test pieces broken by compression have average angles of about 55° and 125°, while those broken by tension are found to be nearly as oblique.

To summarize, then: It seems fairly clear that relief from the simple compression of a crustal block in a horizontal direction would

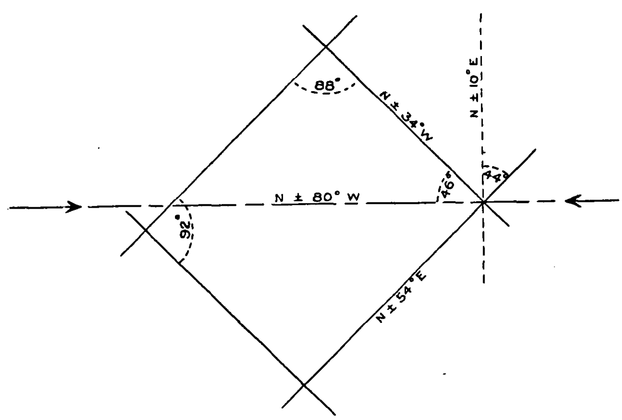


FIG. 48.—Diagram showing the probable direction of the force which produced the nearly rectangular faulting of the Pomperaug Valley and its vicinity.

result in a system of vertical prisms whose angles would approximate 90°; and, further, that it is not yet known whether in any given case the acute or the obtuse angle of the prisms (if not perfectly rectangular) would be bisected by the direction of pressure.

The fault system of the Pomperaug Basin would seem to furnish an illustration of such a compression of a crustal area as has been discussed, though with modifications, which will be pointed out. The area in question is found to be subdivided by four series of parallel fault planes into a system of vertical prisms. Two of these fault series (striking, respectively, N. ± 34° W. and N. ± 54° E.) are very nearly at right angles to each other (88°). These directions are not the ones along which the greatest displacements have occurred, but that may be explained on other grounds. If, then, it be true that these nearly rectangular faults have been formed in the same manner as rectangular joints, it follows that the compression (the resultant force) acted in a direction either N. ± 80° W. or N. ± 10° E. (fig. 48).

The extensive compression of the area as a whole during an earlier age having been such as to produce folds whose average strike in the New England region has been not far from N. 10° E. (corresponding to a compression along the direction N. ±80° W.), it is most probable that the direct compression of the Newark rocks acted approximately along the same direction, which is one of the two directions suggested by the theory. Even if it were known whether the acute or the obtuse angle of the rupture planes is the one bisected by the initial direction of the pressure, no certain conclusion could here be drawn from the angle included between the rupture planes, since this is so near to 90° that the difference from that value falls within the possible limit of error in the determination of the fault directions.

Accompanying the relief of strain by dislocation, there would occur a readjustment of stresses, accompanied by a fall in the potential energy of the system. The two series of prevailing dislocations which remain to be considered, and which trend N. ± 5° W. and N. ± 15° E., would seem to have been produced by a stress system secondary in regard to time to that which produced the primary dislocations, since these faults reveal in their strike directions the closest relations to the nearly rectangular system (see p. 119). So far as the dislocations themselves are concerned, they might have been formed as the result of a compression of the area either immediately following or long subsequent to that which produced the primary system of dislocations. The study of the area has shown, however, that the principal downthrows have taken place along the N. ± 5° W. and N. ± 54° E. fault planes, and hence it is certain that both these dislocations occurred previous to the general depression of the area. The simpler explanation for the depression of the basin is one which connects it with the dislocation of the area, because by that dislocation a condition is set up which favors local depression. A compression of the already dislocated area by a force acting in the same horizontal plane as the first would bring about a resolution of the force of compression along directions parallel and perpendicular to the planes of dislocation, the former producing a shear along the planes themselves and the latter a shear along the diagonals of the block formed by the primary system of dislocations. Whether these shears would result in rupture along one or both of the diagonals of the blocks would be dependent primarily upon the amount and the direction of the pressure before resolution. Torsional forces also would doubtless be set up, the effect of which would be to produce fracturing at the edges of the prisms, and these torsional stresses would be greater the greater the deviation in direction of the new force of compression from that which produced the earlier set of joint planes. The fault series which trends N. ± 15° E. corresponds in direction to the long diagonal of the nearly rectangular block formed by the primary system of dislocations, and the N. ± 5° W. series corresponds similarly in direction with the long diagonal of a group of two such blocks in contact along their longer sides. Such a double block, it will be remembered, was the type encountered as the unit of the primary system in the Hotchkissville area (see p. 109 and Pl. XII), which affords an indication that the alternate faults in the N. ± 54° E. series are characterized by larger throws. As no faults have been found in the area which correspond in direction with the shorter diagonal of the rectangular blocks (N. ± 85° W.), and as only one or two rather doubtful faults have been found to correspond with the shorter diagonal of the double blocks (about N. 65° W.), it would perhaps indicate that the second compression of the area was, like the first, along a direction a little to the north of west and to the south of east. Such an adhesion of the later compression to the direction of the earlier one would also result in a minimum of crushing, brought about by torsional stresses at the edges of the block, and would help to explain the small development of fault breccias within the area of the basin. The assumption, moreover, that the second compression of the area followed the same general direction as the first, is at the same time the simpler and more natural assumption, provided the one compression followed closely after the other.

B. Discussion of the conditions attendant upon the local depression of a crustal block.—Wherever depression of a circumscribed area of the earth's crust has occurred it may be assumed that within that area support from below has been less or the load greater, perhaps both, than within the surrounding territory. The area of depression was therefore characterized by a stress component which acted vertically downward. If we choose to assume that the surrounding area is acted upon by vertical components of stress, the direction of which is upward, the result is the same. At points distant from the area, where on the first assumption the support has been adequate for the load, the downward-acting stress difference has not at the same time existed. Somewhere between the local area and its surrounding territory, then, there must be a closed line along which and without which there has been no vertical stress component. This line may be designated the *margin of the area of no vertical stress*, or, for brevity, *line of no vertical stress.* This line is a fulcrum line from which the moments of the load upon the included section of crust must be reckoned. If the section of the crust has an extent not too small when compared with its thickness, it fulfills, before depression, the conditions of a nearly uniformly loaded girder supported at the ends—at the line of no vertical stress. The capacity of this girder for sustaining its load will be dependent upon its rigidity and upon the distance between supports—its rigidity, size, and shape. If the section of crust is under lateral compression it will receive support from its strut condition, as does a block firmly held in a vise. If the lateral compression be equal from all directions (hydrostatic) and the block be homogeneous and without ready-formed structure planes, it should tend to rupture under the moments of its load along a line uniformly distant from and within the line of no vertical stress. If, however, the lateral compression be different in different directions the section of crust will fulfill the anisotropic conditions of an anisometric crystal—its strain ellipsoid will be either an ellipsoid of rotation with horizontal axis, or a triaxial ellipsoid with its greatest and least axes in the horizontal plane. Under these conditions there would arise, supposing the force of compression to be sufficient, directional planes of weakness normal to the directions of minimum cohesion and corresponding to the cleavage within a crystal. These planes are not fracture planes, but directions along which, other things being equal, rupture will first take place under stress.

If vertical structure planes like those of a primary system of dislocations already exist in a section of crust the lateral stress (compression) will be decomposed along the planes of dislocation into a component acting horizontally as a shear along the surface of the plane and a component acting normal to its surface. The effect of the normal components would be to produce a shear along the diagonals of the blocks inclosed by the structure planes.

So soon as a system of dislocations (properly joints) has removed the supporting capacity of the section of crust regarded as a girder, there is opposed to the downward component of stress any resistance which as a strut may result from the compression. There is further to be taken into account the fact that so-called vertical planes converge downward and impose a restraint upon the depression of a crustal block. This restraint is applied along the walls only, so that the central portions of the block tend to move downward faster. Differential stresses are thus induced within the block itself, the moments of the force at any point in the block being the downward component of the vertical stress into its distance from the nearest wall. Thus the block, if sufficiently large in comparison with its thickness, reproduces the conditions of a girder supported at the ends and uniformly loaded, and rupture, if it occurs, should take place along the diagonals of the block. The effect, therefore, of the restraint exerted vertically upon the walls, like the compression which acts laterally upon the block, tends to produce fracture planes along the block diagonals.

The theory that the crustal block behaves like a girder is based upon the assumption that its thickness is not too great in comparison with its area. The ratio of thickness to lateral dimensions which is required to induce rupture of the block under the conditions stated will depend primarily upon the ultimate strength of the rock or rocks composing the crustal block. The strength of soft shale is very small, and a comparatively thick crustal block composed largely of this material might be ruptured under the conditions stated. Some indication of the thickness of crustal block which is required in the present problem is perhaps to be found in the estimates which have been made regarding the depth beneath the earth's surface at which cavities in rocks would close under the weight of superincumbent loads. If this depth be regarded as that of potential fluidity or of rock flowage, it may perhaps be considered as the bottom of the crustal block which is here under consideration. According to Heim,[1] the depth at which cavities must close is less than 5,000 meters. Van Hise and Hoskins,[2] on better data, have estimated this depth for an area under strong lateral compression as something over 6,000 meters (case 1), or a little less than 4 miles. The sizes of the composite blocks of the Pomperaug Basin, in which the girder condition would be invoked to explain diagonal fault planes, have lateral dimensions of about 1 by 2 miles, 2 by 3 miles, and 3 by 3½ miles, respectively; so that, provided no exceptional and local influences were present tending to raise the upper surface of the zone of flowage, the blocks in question would by these estimates be each somewhat thicker than their lateral dimensions. It is highly probable, however, that special local conditions did exist tending to raise the level of rock flowage. In fact, some such condition must be invoked in order to explain the local depression. One probable cause of the local elevation of the zone of flowage may be found in an elevation of the isogeotherms due to the propinquity of the reservoir of lava which supplied the basalt for the outflows within the basin.

In order to estimate even roughly the strength of the rock girders here under discussion, it would be necessary not only to know their thickness, but to know what proportion of this thickness was composed of the weak Newark sediments. As already pointed out, the thickness of the Newark beds is unknown. In the Pomperaug Basin the thickness of the four lower members of the series has been determined from a well boring to be probably not far from 1,200 feet. The Northampton well boring, which at a depth of 3,700 feet failed to pierce the system, would seem to indicate that at that point the entire series is not less than three-fourths of a mile in thickness, and probably much greater. Of this thickness all but a few hundred feet is of weak shales, sandstones, and conglomerates, the residue being compact basalt. The lower portion of the crustal blocks must have been composed of the crystalline schists and gneisses, since they compose the walls of the basin. The most that can be said, perhaps, regarding the strength of

[1] Untersuchungen über den Mechanismus der Gebirgsbildung, etc., by Albert Heim, Vol. II, Basel, 1878, p. 110.

[2] Principles of North American pre-Cambrian Geology, by Charles Richard Van Hise, with an Appendix on flow and fracture of rocks as related to structure, by Leander Miller Hoskins: Sixteenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 1–874.

the crustal blocks would be that it was certainly much inferior to the strength of blocks of similar size composed entirely of crystalline rocks.

It is in the southern zone of the Pomperaug Basin, where the large composite blocks have been carefully studied, that they are found to be fractured by fault planes along their diagonals, although these fault directions are not generally developed in other parts of the area. The division of the area into composite blocks of a particular shape can perhaps be explained by the compression of the area both before and during its depression and the anisotropic condition which is thereby induced—a condition which, as has already been pointed out, calls for directional planes normal to the lines of minimum cohesion, like the cleavage planes of the crystal. The 1:2 ratio which throughout the area seems to have controlled the shape of the individual and many of the composite blocks, and the simple ratios observed between the sides of particular large composite blocks bounded by the same series of fault planes, have a possible explanation in this condition.

To summarize the above discussion, the facts observed in the Pomperaug Basin seem to be best explained by assuming a compression of the New England area by a force which acted in a direction about N. 80° W., or in the same direction as that which produced the Appalachian folding. The zone of the earth's crust now exposed at the surface was at the time of the compression under extremely light load, such that its elastic limit and its ultimate strength were nearly identical. In certain areas, such as the Pomperaug Valley, conditions of inadequate vertical support existed, tending toward a local depression of the crust. This inadequate support of the crust was supplemented by the rigidity of the rocks themselves, but an augmentation of the force of compression, or perhaps an earthquake shock, communicated to the charged system, carried the tangential stresses which existed in consequence of the compression beyond the limit of strength of the rocks. The rupture planes (joints) which resulted formed a nearly rectangular system of vertical prisms, one set of angles of which were bisected by the initial direction of the force. By a renewal of the compression along essentially the same direction a new system of dislocations was produced along those diagonals of the existing prisms (single and double) which are most nearly at right angles to its direction. While still under compression, probably from the same direction, depression of the area occurred, owing to the loss of rigidity brought about by the rupture planes, with the formation of composite blocks which together were bounded by fault planes of the existing systems of joints. The shape of the individual and composite blocks was possibly determined as a result of the anisotropic condition of the medium due to compression but modified by the preexistent fault planes. The depressed blocks, owing to the restraint imposed upon them in the form of vertical stress along their walls and of lateral stress decomposed parallel and normal to their walls, were fractured along their diagonal planes. Depression of the area continued until a stable condition was secured as the result of a decrease in the vertical stress component within the area.

SECTION 7.—SYSTEMS OF FAULTS IN OTHER REGIONS.

While it is perhaps only rarely that areas of dislocated strata have been examined with the amount of detail of the present study, indications are not altogether lacking that the complexity of the dislocations is in the area under discussion no greater than in some other areas, in most of which, however, the conditions are not so favorable for study. The complete isolation of the relatively small area within inclosing walls of crystalline rock, the alternation of markedly different beds in the Newark system, the ice denudation and the preservation of structures due to the resistant quality of the heavier basalt sheet, the nearly vertical position of the fault planes, but, more than all, the light loads under which dislocation was accomplished (as shown by the absence of folding in the Newark beds), must be accounted conditions greatly favoring a determination of the system of dislocations.

Some indications, however, of a conjugate system of dislocations is afforded by the Cretaceous rocks of the vicinity of Banon, in central France, though these dislocations are believed by Kilian[1] to be purely local. He says:

> To summarize, we see that there exists in the region of fractures of Banon two conjugate systems of faults sensibly parallel, and directed the one N. 10° to 35° E., the other N. to N. 25° W. These accidents are purely local and disappear promptly in becoming progressively attenuated to the northward and southward
>
> These fractures recall the networks obtained by MM. Daubrée and Tresca, by submitting glass plates to a strong torsional force.

Only after the manuscript of this paper had been completed did I learn of the very interesting monograph by Prof. W. C. Brögger upon the system of faults of the Langesund-Skien region of Norway,[2] which area in a somewhat remarkable way furnishes a parallel to that of the Pomperaug Valley. As this important paper seems to have been so generally everlooked by structural geologists, and since it is somewhat inaccessible to readers, I shall consider its contents rather fully and translate below certain portions of the paper which describe features similar to those herein described from the Pomperaug Valley. The interpretation put upon the observed facts, I have been pleased to see, corresponds closely, in so far as the facts

[1] Description géologique de la montagne de Lure (basses-alpes), by W. Kilian, Paris, 1889, p. 366, Pl. B.

[2] Spaltenverwerfungen in der Gegend Langesund-Skien, by W. C. Brögger: Nyt Magazin for Naturvidenskaberne, Vol. XXVIII, 1884, pp. 253–419.

are the same, with that which has been made from the facts observed in the Pomperaug Valley.

The region is one of Paleozoic sediments surrounded on three sides by upland areas of the crystalline complex and of igneous rocks, while to the south is the sea, which enters the low-lying region itself in a system of fjords. The Paleozoic beds are everywhere intersected by an elaborate system of joints which fall always into at least two parallel series nearly normal to each other. These two series are described as striking the one N. 5° to 10° W. and the nearly normal series east-northeast. In addition to the prevailing joint series diagonal series are locally developed, as are also in some localities radial fan-like systems. That one of the prevailing series of joints which strikes nearly east-west hades near the vertical, whereas the conjugate series is inclined 55° to 75° to the westward. Since the northerly striking fault series coincides closely in direction with the strike of the Paleozoic strata, and since the average dip of these beds is fom 20° to 25° to the eastward, these joint series are both nearly perpendicular to the bedding plane. Regarding the relation of the observed faults to the principal joint series (Hauptzerklüftungssystemen), the author says:[1]

> The observations have shown that the dislocations at each locality follow the principal joint systems, and that, exceptionally, larger or smaller dislocations are present parallel to less common joint systems. * * *
>
> Less common are the dislocations parallel to the diagonal joint systems. * * *

In seeking a cause for the elaborate system of joints and faults observed in the Langesund-Skien region Brögger accounts first for the joints, and cites Daubrée's experiments to show that rectangular systems of dislocations may be produced either by a torsional force or by compression. Accepting, as he does, the probable cause of the joints to be in part horizontal compression of the strata, it follows that the direction of the compression must be one of the two directions which bisect the network of prevailing joints and their parallel faults. Of these two directions, the one trending N. 30° E. corresponds closely in direction with the axes of the mountain chains of Scandinavia, of the Paleozoic flexures of the Christiania region east of the area studied, and also with the direction of the fissures through which the great masses of igneous rocks of the region have been extruded; hence he has assumed that the pressure which resulted in the formation of the joints acted in a direction normal to this, or N. 60° W. Against an assumption that compression is alone adequate to explain the system of joints and faults, Brögger points out that in widely separated parts of the area important differences in the direction of the fissure planes are noted, and, further, that joints are found parallel

[1] Op. cit., p. 240.

to open fissures, which he would therefore ascribe to tension. The bending down of the Paleozoic strata near the igneous extrusions on the eastern border is invoked to aid in accounting for those joints which are not vertical. Since the joint fissures are so frequently filled by dikes of igneous rock, Brögger is inclined to connect the formation of the main series of joints with earthquakes.

To explain the formation of the faults, which, as stated, follow the direction of the joint planes, or, in other words, to explain the displacements along planes parallel to the jointing, a relative sinking of crustal blocks due to gravity is assumed. Under this head three cases are distinguished:

(1) The dislocations can occur either through simple depression along vertical joint planes of a sufficiently heavy mass of strata which is not hindered by its attachment (Befestigung).

(2) Or, when the joint planes are inclined a slipping down of the hanging wall can occur; or when a block slipped down between two parallel joint planes a gliding of the foot wall can occasionally occur.

(3) Or, simultaneously with the depression or gliding down of a mass of strata a rotation of the same may occur, which may take place in two ways. Either (a) the axis of rotation can lie more or less perpendicular to the fault plane, in which case the throw of the dislocation would not be the same in the entire extension along the fault plane; or (b) the axis of rotation may lie approximately within the fault plane, in which case the formation of open fissures along the fault plane must occur.

Since the formation of dislocations can not go on along a single fault plane, but naturally along a number of intersecting planes, so, naturally, a sinking may occur along one, a gliding along a second, a sinking or gliding combined with rotation along a third plane, etc.

Sometimes we find that between two approximately parallel joint planes a strip of crust is relatively more depressed than the portions of land on either side. Thus a gutter (Rinne) is formed [examples given]. These can naturally be evened off by later erosions. Conversely, a ridge (Rücken) can remain between two deeper sunken blocks on either side.

When between four joint planes which cross in pairs, or, to be more general, between three or more intersecting joint planes, a block of crust is sunk relatively deeper than its entire surroundings, a deep (Tiefe) is formed [examples given].

Conversely, a block of crust surrounded by faults can remain relatively behind while the surrounding land has been depressed. Such crustal blocks (Landstücke) can be designated islands or towers (Thürme) [examples given].[1]

Regarding the elaborate development of the fault system Brögger says:

In the little strip of Paleozoic formations between Langesund and the Skiensthal we have before us, then, a section of country which is penetrated through and through by faults along already formed joint planes. We have seen that the lines of landscape are given by the principal joint systems. These have reduced in part the work of erosion, in part they have allowed numberless dislocations to form which offered new points of attack to the erosion. * * *

The dislocations, that is to say, the faults, have in fact cut the landscape through and through and not alone parallel to one system of lines, but first chiefly parallel to

[1] Op. cit., pp. 392-393.

two principal systems (Hauptsystemen), and then also parallel to other less prevalent directions. * * *

If we consider how thickly the rocks are penetrated by very small faults, it follows in fact that a portion of crust cut up in this fashion is built up like separate blocks of masonry (Quadern).[1]

In a later paper describing the formation of the Christiania fjord, Professor Brögger[2] describes structures similar to those reviewed above from his paper on the Langesund fjord, which is but a short distance farther to the westward.

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[1] Ibid., p. 401.

[2] Ueber die Bildungsgeschichte des Kristianiafjords, by W. C. Brögger: Nyt Magazin for Naturvidenskaberne, Vol. XXX, 1886, pp. 99, 231.

CHAPTER V.

DEGRADATION.

SECTION I.—THE DRAINAGE SYSTEM OF THE POMPERAUG VALLEY AND ITS VICINITY.

THE CRETACEOUS PLAIN OF EROSION.

The Pomperaug Basin lies within the area of the great Cretaceous plain of erosion of southern New England which has been so fully described by Professor Davis.[1] This plain of erosion has here an altitude of something less than 1,000 feet and an inclination of a few degrees to the south. The view from any of the hills in the vicinity exhibits in the even sky line the position of this plain. The highest point of the basalt ridges within the basin is Bates Rock, whose altitude is 700 feet; whereas the hills surrounding the valley rise to altitudes of 900 to 1,000 feet. This fact points to a more rapid degradation within the basin since the time when the erosion plain was elevated and tilted. During this period subaërial erosion has plainly degraded the soft sedimentary formations of the basin at a more rapid rate than it has the surrounding crystalline rocks, but the dense prisms of basalt seem competent to withstand in an exceptional manner the action of atmospheric agencies. Their narrow mural and tower-like masses are not, however, so well adapted to withstand a mechanical force exerted horizontally against their vertical surfaces. In the ice mantle of the Glacial epoch they have been subjected to a force of this nature, and in the succeeding section I shall introduce evidence to show that at least a portion of this reduction in their height has been brought about by the breaking off of portions of their summits in the form of huge blocks, which have been transported to considerable distances. The horizon line of the basalt is, however, notably regular, which, in view of the considerable irregularities which it must have presented before its degradation, is an observation of much significance. The view of the ridges from the railroad station is sufficiently striking in this respect. This planation I am inclined to ascribe, therefore, more largely to ice action than to the ordinary type of subaërial erosion.

The development of the new geologico-geographical science of physiography, which treats of the sculpture of land forms under atmos-

[1] Nat. Geog. Monographs, Vol. I, No. 9, pp. 269–304. See, also, Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. II, 1898, p. 157 et seq.

pheric influences, has focused the attention of geologists upon a series of geographic cycles marked off by epeirogenic movements of the earth's crust. In the contemplation of the striking results which have flowed from these studies, observations have, I believe, too often been withdrawn from the geological structure of the areas examined and the influence which this exerts upon the sculpturing of the physiographic features. In the Pomperaug Valley it is easy to see that the geological structure has exerted a profound influence upon the topographic development of the region. This appears in the peculiar outlines of topographic forms and in the drainage system, where geological structure has largely controlled the form of stream channels and the direction of the stream courses.

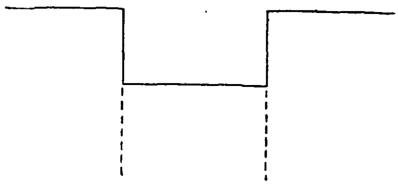


FIG. 49.—Canal-like channel of streams, type A.

CANAL-LIKE CHANNELS OF STREAMS.

With the exception of the Woodbury plain and the other wide valleys in which there has been some meandering of streams, the characteristic form of stream channels within the area of the Pomperaug Basin is that of an artificial canal characterized by a nearly level floor of uniform width and by straight margins from which the banks rise. When in rare instances the streams cross an elevated area of basalt, as does the Pomperaug River at Pomperaug village, the banks of the river may rise from the river bed in steep cliffs (fig. 49). In other cases, where the banks are sloping, the foot of the slope, by its rectilinear extension parallel to a similar line at the foot of the opposite bank, affords indications of the graben structure (fig. 50). Instances of this latter kind are furnished by the Pomperaug River east and southeast of Castle Rock (see fig. 41). When streams have flowed in sandstones or conglomerate, the ready erosion of the soft beds and the large deposits of glacial material in the widened channels have destroyed or covered the original graben walls. In the crystalline rocks surrounding the valley, however, canal-like channels are often very strikingly shown. Particularly is this true of the northern wall of the basin, where the topographic map, Pl. XIV, reveals long rectilinear stretches of stream of uniformly low grade, which suddenly come to an end in an abrupt change in declivity and usually by change in stream direction as well. By the broad curves of the contour lines where they intersect the streams, the topographer has correctly portrayed the floor-like bottoms of the stream channels, which are here so

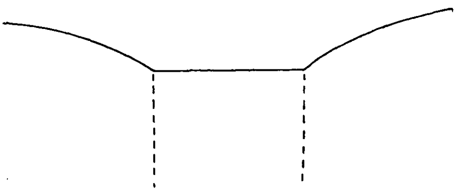


FIG. 50.—Canal-like channel of streams, type B.

JULIUS BIEN & CO. LITH. N.Y.

TOPOGRAPHIC MAP OF THE POMPERAUG VALLEY, CONNECTICUT

Topography by J. H. Jennings,
Frank Sutton and Marcus B. Lambert
Surveyed in 1889-90

Scale $\frac{1}{62,500}$

1 ½ 0 1 2 Miles

Contour Interval 20 feet

Datum is mean Sea-level.

characteristic a feature. The form of these channels is probably in many cases explained by the presence of faults at the margin of the river bottom, and by the downthrow of the included orographic block, or, which would amount to the same thing, the upthrow of its walls. In the Pomperaug Basin the channel margins in many cases coincide in position with the faults which have already been described in the last section. It should not, however, be forgotten that revived drainage is characterized by sharply cut channels.

ZIGZAG STREAM COURSES.

In some places the streams of the Pomperaug Basin have long stretches, approximating to a uniform direction, as, for example, Nonawaug Brook, near Minortown, or the Pomperaug itself, near Pomperaug village. Represented upon the map of the basin, these river stretches appear usually as nearly straight lines. Examined at the locality, however, it is found that this general direction is very frequently maintained through a series of zigzags, first to the right and then to the left, or perhaps for short distances along the general direction itself. This zigzaging of the stream course differs from the ordinary meandering of streams in alluvial bottoms in its greater regularity, but chiefly in the clear indication which it affords in many cases that the course is a broken line slightly rounded at the angles, and not an undulating line, as is the course of stream meanders. In other words, the stream course makes sudden changes in direction to produce elbows like those of an eaves gutter, instead of sinuous turns like the bends in a flexible hose. A good illustration of the structure is furnished by the canyon of the Pomperaug River below Pomperaug village. Similar elbows, but of a higher order, appear upon the map (Pl. XV).

RELATION OF DRAINAGE TO PREEXISTING FAULT PLANES.

If now the drainage system of the entire valley is studied as regards stream direction, it is found that this is in harmony with the fault system of the region. Not only do the stream courses have long stretches which coincide in direction with the direction of some one of the prevailing fault series, but in many instances one or more individual faults of this series have been observed in immediate proximity to the stream. Pl. XV has been prepared by tracing the drainage system from the topographic atlas sheets of the United States Geological Survey, and then locating from the geological map the position of observed faults which are in proximity to water courses. The same data are to be found on the geological map of the region (Pl. I), although they are there much obscured by the details of geological coloring and by the numerous fault lines.

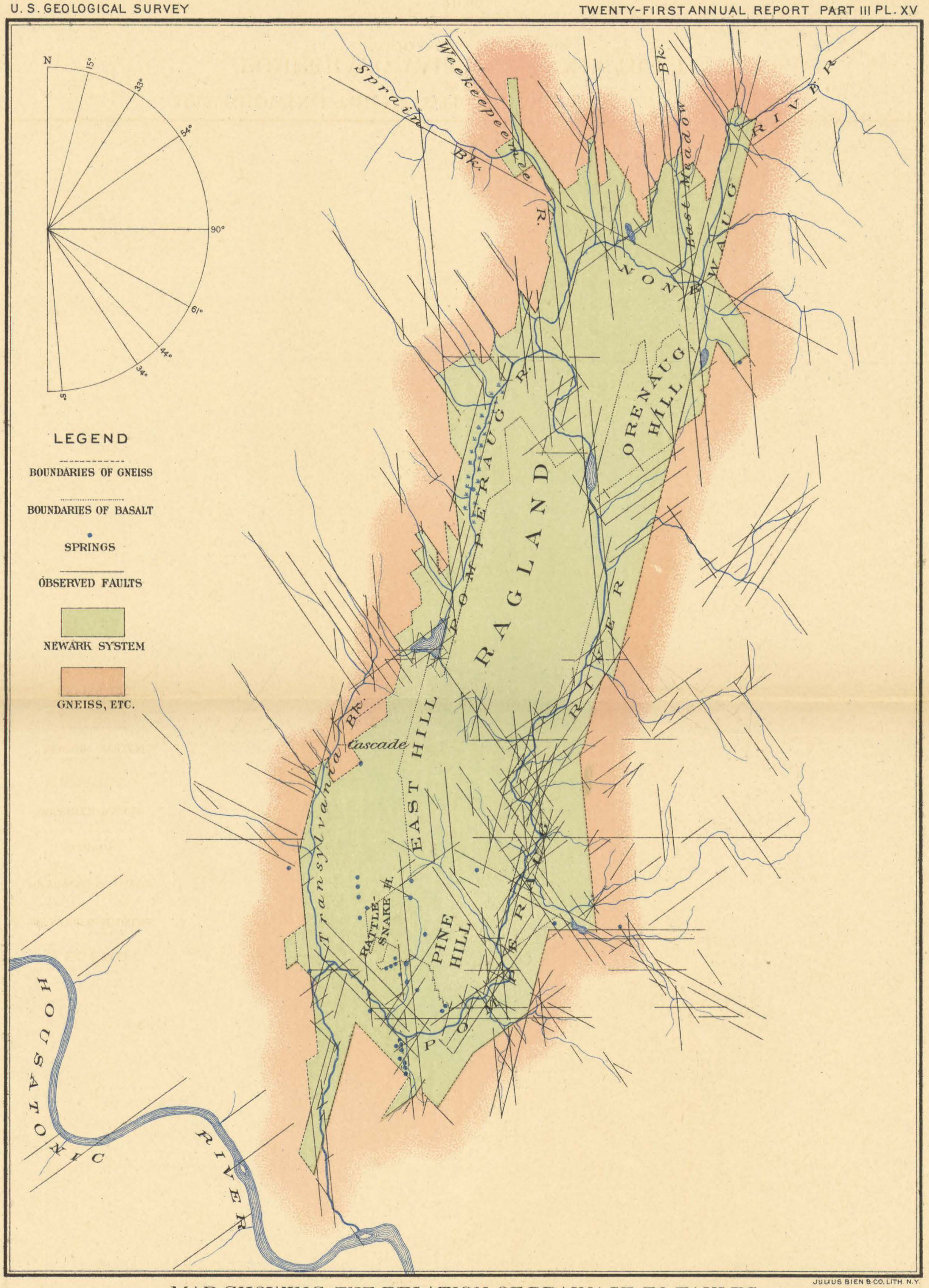
As a whole the river courses of the basin show the same subdivisions as the geological map. For the greater portion of the area the streams follow in a rough way mainly the directions of the four prominent series of faults, viz: N. ± 5° W., N. ± 54° E., N. ± 15° E., and N. ± 34° W. In the southern portion the streams follow the N. ± 44° W. and N. ± 61° W. and to a small extent the N. ± 33° E. directions, as well as the prevailing ones of the region. The Sprain Brook Valley, northwest of Hotchkissville, and the streams by which its strike is continued to the southeast furnish the only important instance within the basin in which these abnormal fault directions appear to have influenced materially the drainage outside of the southern zone.

The main trunk of the Pomperaug and Transylvania Brook, its principal tributary within the area of Newark rocks, for the greater part of their courses flow N. ± 5° W. (or S. ± 5° E.) and N. ± 15° E. (or S. ± 15° W.). The tributaries which enter them from the crystalline walls of the basin flow in the western wall along directions approximating to S. ± 34° E., in the northern wall along S. ± 5° E. faults, while in the northeastern wall they follow more frequently the direction of the dislocations trending N. ± 54° E., in each case directions nearly normal to the trunk streams into which they empty. In the southeastern wall of the basin less uniformity of direction is observed, the peculiar fault directions of that zone apparently in large part controlling the drainage. The only important tributary of the Pomperaug which rises in the inclosed elevated Newark area is Poverty Brook (see also Pl. VIII), which for more than a mile flows with almost mathematical accuracy in the direction S. 34° E.

The large regular elbows of the Housatonic River above the mouth of the Pomperaug correspond in position to the extension of important dislocations observed in the Pomperaug Basin, and it is likely that the course of the river has here been directed by the same structural conditions.

The general harmony of the stream courses with the series of dislocations already mapped having been determined, the question may well be asked whether such an adjustment of the drainage system to the fault system can be accidental—whether the parallelism observed is a mere coincidence. With a sufficient number of fault directions and the assumption of sufficiently short elements of the stream courses, it would, of course, be possible to find at least a partial parallelism of any two systems whatsoever. The establishment of a causal relationship of the one system to the other will be the more certain the smaller the number of fault directions employed and the longer the stretches of stream course within which essential parallelism to any of the fault directions obtains.

Within the Pomperaug Basin, and except in its southern zone, where other and special directions of faulting are discovered, we find prac-



JULIUS BIEN & CO. LITH. N.Y.

MAP SHOWING THE RELATION OF DRAINAGE TO FAULTS
IN THE
POMPERAUG VALLEY, CONNECTICUT
BY WILLIAM HERBERT HOBBS

Scale
1 0 1 2 MILES

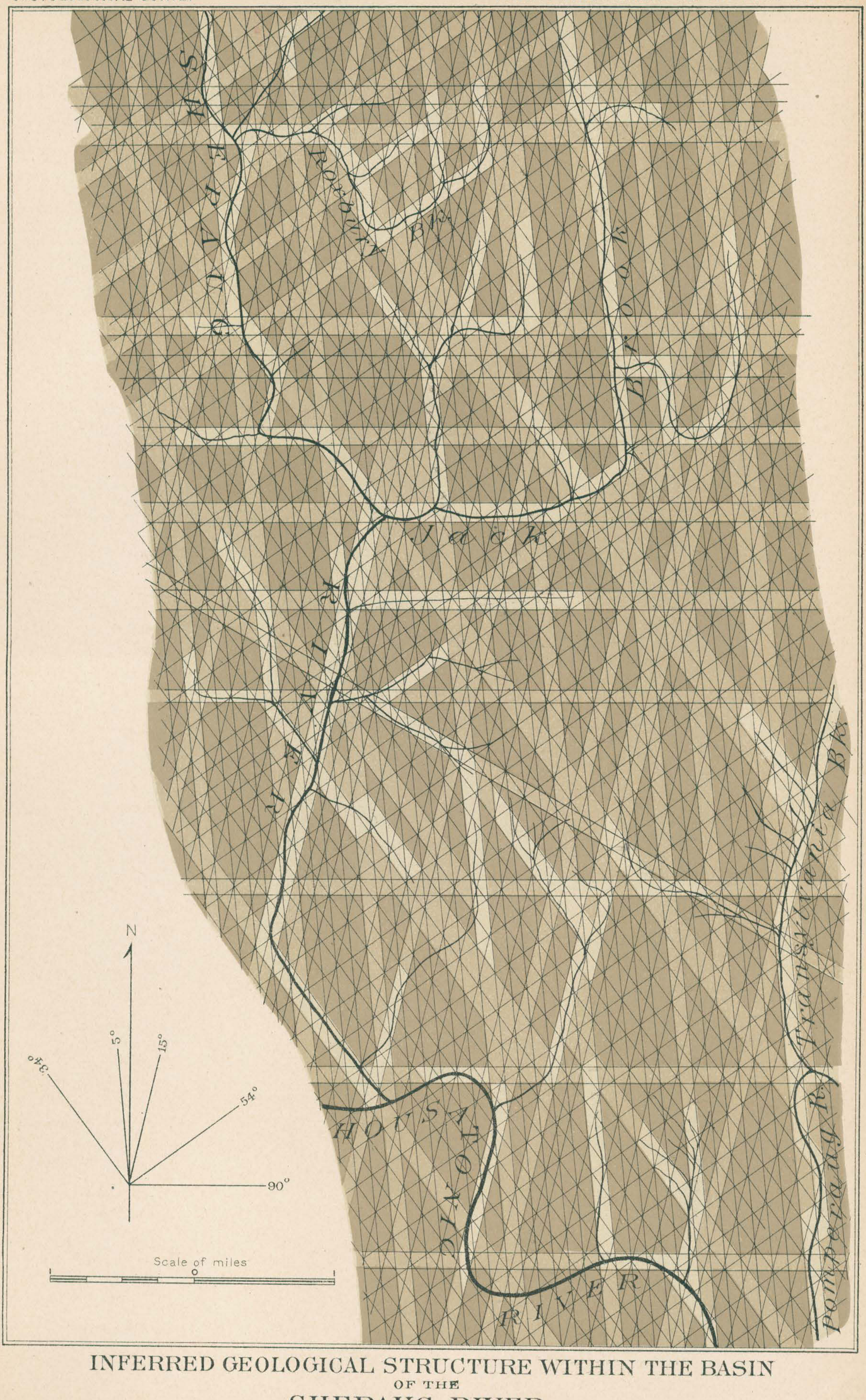
1899

PLATE XVI.

PLATE XVI.

HYPOTHETICAL GEOLOGICAL STRUCTURE (DIAGRAMMATIC) WITHIN THE BASIN OF THE SHEPAUG RIVER, TO ACCOUNT FOR ITS DRAINAGE PECULIARITIES.

The region is assumed to have been dislocated by a system of faults similar to that observed within the Pomperaug Basin. Upthrow and downthrow of individual blocks and grouping of these on the basis of throw into composite blocks has also been assumed to have occurred in a similar manner. Individual faults are represented on the map by lines trending, like those of the Pomperaug Valley, N. $\pm 5°$ W., N. $\pm 54°$ E., N. $\pm 15°$ E., N. $\pm 34°$ W., and N. $\pm 90°$ E. The altitude of individual blocks is indicated by the depth of the shades, the deepest shades representing blocks standing at the highest altitudes. The nearly white areas are the blocks at the lowest altitudes, and the areas colored in intermediate shades are blocks ranging in altitude between these extremes. The lighter bands upon the map represent, therefore, canal-like trenches (formed by graben) which the river discovered and utilized for its channel. No attempt has been made to explain the deflecting of streams from one canal to another. An individual block at a higher altitude than its neighbors may have caused the deflection, but other causes might be suggested. The map is intended to suggest a cause of the directing of courses in correspondence with the general fault system which is indicated. The river itself has been traced from the New Milford and Danbury topographic atlas sheets of the United States Geological Survey.



INFERRED GEOLOGICAL STRUCTURE WITHIN THE BASIN OF THE SHEPAUG RIVER

tically four prevalent series of parallel faults, which diverge from one another (their nearest neighbors in the system) at angles of about 39°, 20°, 29°, and 92°. A difference in angle between a fault direction and any element in a stream course of 7°, or about one-third of the smallest of the angular intervals in the fault system, would produce in the distance of a mile a divergence of the two directions of an eighth of a mile, or one in eight, a divergence which platted upon the general map (Pl. XV) would hardly be accepted by the eye as an indication of causal relationship of the one direction to the other. The instances where streams adhere with great fidelity to one of the four fault directions for considerably longer distances are, however, not rare, and, considered as a whole, the relationship of the two systems is too close to be accounted for solely on the theory of coincidences. This subject will be further elaborated under the next heading, where the drainage system of the Shepaug River, whose basin adjoins that of the Pomperaug upon the west, is treated.

There must have been many conditions which have brought about the minor irregularities of stream courses other than the one which has just been discussed. Though the crystalline rocks of the upland, regarded as a whole, present as great uniformity of hardness as almost any area of gneisses that could be selected, yet there are minor differences which can hardly have been without effect in shaping the courses of streams. More important, perhaps, than these have been the accumulations of the Glacial epoch, which in the form of barriers have profoundly affected the drainage of the region. In a few known instances, and in a large number of inferred examples, within the general area here under consideration, the waters of one stream have been diverted to another, or the course of a stream has been reversed so that it is compelled to flow in the opposite direction. Important as such changes have been, they have yet, in the majority of instances, affected but little or for but short distances the orientation of stream channels. This would indicate that the streams had become firmly intrenched in the tilted Cretaceous plain of erosion prior to the glacial invasion, and that the present drainage, moreover, is probably adjusted to older channels.

EVIDENCE THAT FAULTS HAVE CONTROLLED THE DRAINAGE IN THE AREA OF CRYSTALLINES SURROUNDING THE POMPERAUG BASIN.

The detailed examination of the crystalline walls surrounding the Newark area has revealed the position of faults belonging to the system which obtains in that area itself, and it has just been shown that these have controlled the directions of the water courses of the vicinity. It is but natural to inquire whether any evidence has been discovered which indicates that this system of dislocations extends beyond the immediate borders of the basin into the great area of the crystalline uplands.

The Newark rocks being there lacking, the discovery of actual faults within the crystalline territory is attended with great difficulty and uncertainty. A relation having, however, been established between the drainage and the geological structure within the Pomperaug region, a possible method is suggested for inferring the structure of the surrounding territory through its system of drainage. It is easy to determine whether a drainage system like that of the Pomperaug is of the same type as that of the surrounding territory, or, if this proves not to be the case, whether by a persistence of streams along certain directions any indication is afforded that their courses were subjected to a directing influence through the presence of preexisting troughs or channels.

Adjoining the drainage basin of the Pomperaug on the west is the basin of the Shepaug River, both rivers alike flowing southwest and emptying into the master stream, the Housatonic. A portion of the Shepaug River system is represented in Pl. XVI, the distant headwaters not being, however, included in the plate. This course of the river is here traced from the New Milford and Danbury topographic atlas sheets of the United States Geological Survey. In the system of this river the alignment of streams in correspondence with the prevailing fault directions of the Pomperaug region is not less strikingly shown than is the case in the original area. Starting at a point about 12 miles above its mouth, the course of the river is nearly S. ± 34° E.; then for about 4 miles S. ± 5° E.; after which it again turns S. ± 34° E., and, reenforced by the waters of Jack Brook, it pursues a course S. 15° W. nearly 3 miles before beginning its final reach of a mile in a direction S. ± 34° E. and entering the Housatonic. Jack Brook for nearly 3 miles flows S. ± 5° E., and after turning westward at nearly right angles to this direction it receives a tributary which faithfully adheres to the direction of its own initial course. It is worth noting that the general course of this tributary of the upper part of Jack Brook, the course of Jack Brook itself, and the middle reach of the Shepaug River, not only run parallel to one another in the direction S. ± 5° E., but are also separated from one another by nearly equal intervals of about 1¼ miles. Other tributaries of the Shepaug River follow roughly the directions N. ± 34° W. and N. ± 54° E., and the same orientation of stream courses extends to the smaller as well as the larger tributaries. This is apparent particularly in the course of the main eastern branch of Jack Brook and of Roxbury Brook.

The drainage of a larger area, of which the Pomperaug Valley is the center, has also been studied from the atlas sheets. From this it will appear that the Pomperaug system of dislocations, which was shown to have influenced so largely the course of the Shepaug River, may be deduced throughout the territory studied. It is unnecessary here to call attention to more than two points in connection with this. These are, first, the way in which the master stream, the Housatonic, seems to have been controlled by the system; and, second, the conformity of the smallest tributaries to the same controlling system.

The Housatonic, after flowing S. ±5° E. for a distance of about 3 miles, by a series of sharp elbows takes the direction S. ±61° E., to which it adheres with great fidelity for a distance of 3½ miles, and then in a series of remarkably regular zigzags the same average direction is maintained for 7 miles more. The north-south limbs of the larger zigzags correspond, moreover, somewhat closely in position with the extension of the S. ±5° E. reaches of Jack Brook and its principal tributary.

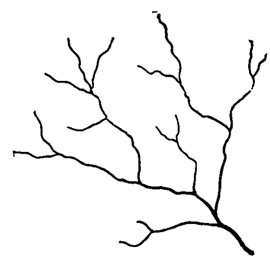


FIG. 51.—Normal twig-like branching of streamlets—the type produced in homogeneous rock material when uninfluenced by geological structure planes.

Almost as instructive is a study of the minor streamlets within the region. A normal stream etching its way into a tilted erosion plain which was formed in an earlier geographical cycle, if working upon uniform rock material, and further if uninfluenced by geological structure planes, has produced when its mature

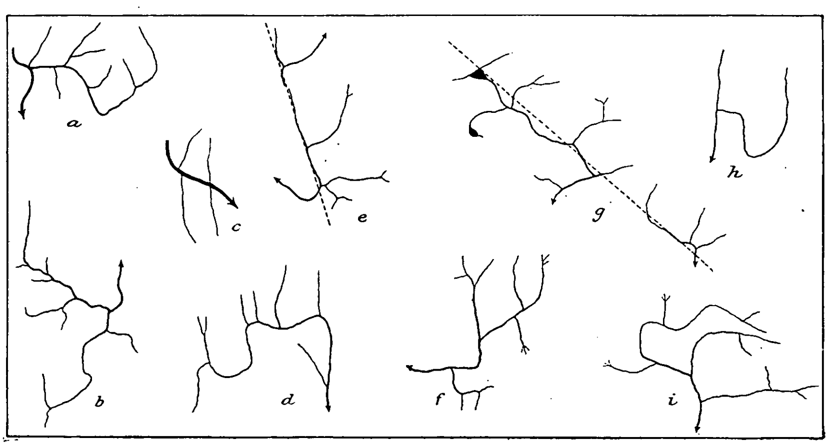


FIG. 52.—Streamlet branchings of the abnormal type found in the area in and about the Pomperaug Valley. *a* and *i*, streamlets controlled by two sets or pairs of fault planes. *b* and *c*, streamlets preponderantly controlled by a single series of parallel planes; *d*, *f*, and *h*, by a nearly rectangular system of fault planes. *e* and *g*, streamlets indicating that neighboring streamlet branchings have been controlled by the same fault plane. The side streamlets of *g* indicate control by a second series of faults.

stage is reached a ramifying system of branching tributaries, the arms of which in the primary, secondary, tertiary, or higher orders meet their respective trunk streams at acute angles, which are determined by the gradient of the original erosion plane and by the resistance of the rock material to erosion. The streamlets at the headwaters of a stream by their junction with one another will therefore under normal conditions produce a twig-like structure, which may be fairly represented by fig. 51. Variations from this normal type are the rule rather than the exception in the region we are studying, variations which can in many cases at least be shown to be unrelated to the underlying rock. Moreover, these twigs display in their peculiarities directing influences along two or more rectilinear directions (see fig. 52). In some instances they indicate a simple network formed of two sets of parallel intersecting lines (*d*, *g*, *h*); at other times a third set of intersecting lines is apparent in the network (*f*). Not infrequently a majority of the minor twigs have their tips turned all in a single direction (*b*), a straight twig may meet its trunk in the abnormal (backward-pointed) position opposite a similar twig in the normal position (*c*), or, further, a twig may branch at its tip in directions nearly normal to its stem (*e*). One of the best indications that geological structure planes have influenced the direction of a stream is afforded when, having departed from an originally straight course, the stream returns to pursue it again (as may be noted of the Shepaug River), or when the streamlet twigs of different branches are arranged along a single straight line (*g*, *e* of fig. 52). Very peculiar forms result when different parts of a single twig have been influenced to take directions corresponding to the different networks (*a*, *i*).

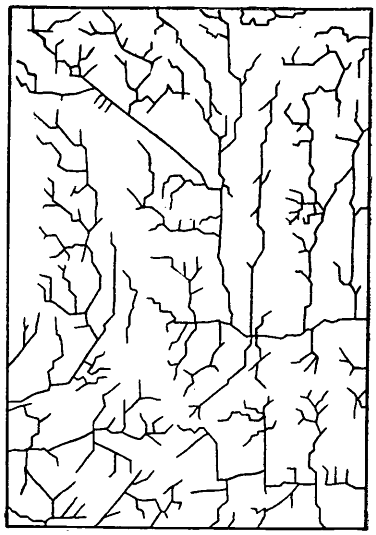


FIG. 53.—Drainage which has been influenced by joints. (After Daubrée.)

NETWORKS OF WATER COURSES IN OTHER AND DISTANT REGIONS.

Daubrée[1] has called attention to the orientation of water courses in perfectly analogous networks in a number of districts, but particularly those of France. One such locality is described in the environs of Joigny (Yonne), representing the plateau of Charny. This is reproduced after Daubrée in fig. 53. He has explained this network of water courses as due to the existence of a number of sets of intersecting joint planes (réseaux réguliers de cassures), whose strikes are parallel to the individual straight elements in the water courses. Where the

[1] Op. cit., p. 361, Pl. III.

streams have followed the joint planes, he has assumed that the joint plane was gaping, its wandering from the plane being explained by local closure of the fissures.

The dells of the Wisconsin River near Kilbourn City are tributary streams, with zigzag courses, the straight elements of which follow two nearly rectangular and one or more, though less common, diagonal directions. Van Hise[1] has explained this by assuming the existence of a regional set of joints, produced by the slight folding of the Paleozoic formations of Wisconsin. Buckley has noted[2] the joint strikes at several hundred localities within the State of Wisconsin, and finds that in the sedimentary rocks they fall mainly in two rectangular sets of pairs, which strike approximately in the directions northeast to southwest, northwest to southeast, north to south, and east to west.

The most important papers known to me which bear upon this question of oriented drainage lines are those of Brögger,[3] which have already been discussed as regards their revelations of geological structure (see pp. 133-136).

The observations and deductions of the distinguished Norwegian geologist are in many respects strikingly similar to those here described, though the Norwegian area has been partially drowned by the submergence of its deeper valleys. So far as the facts are the same the interpretations have in the main followed the same direction for the two widely separated areas. Referring to the Langesundfjord-Skien district, Brögger says:

> It is impossible to deny the great significance of the joint[4] system for the surface of the region in question.
>
> As a general rule it holds for the entire extent of territory that the steep rocky walls, like the narrow fissure valleys and clefts, are bounded and their courses determined by the joint planes, while the gentle slope of the N.-S. to NW.-SE. striking ridges is dependent upon the dip of the beds.
>
> While the cutting of the rocks into steep walls is, in the first place, dependent upon the joint planes, the faults enter as decidedly the most important factor in the formation of the valleys for the entire extent of the area. It is not exaggerated when, to my own astonishment, I must state, as the final result of my observations in this region, that almost every valley, every canyon is formed along a fault cleft. It is here superfluous to recount as examples all the observed faults.[5] In fact, the observations on the most southern stretch between Rognstrand and Langö show that each deep embayment, each valley or canyon ascending from the same, follows a larger or smaller, and, in the majority of cases, absolutely determined, fault parallel to the nearly N.-S. striking fault series; likewise that in the Brevik-Porsgund

[1] Origin of the dells of the Wisconsin, by C. R. Van Hise: Trans. Wisconsin Acad. Sci., Vol. X, 1895, pp. 556-560.

[2] On the building and ornamental stones of Wisconsin, by E. R. Buckley: Bull. Geol. and Nat. Hist. Surv. Wis., No. 4, 1898, pp. 450-460, Pl. XLIX.

[3] Spaltenverwerfungen in der Gegend Langesund-Skien, by W. C. Brögger: Nyt Magazin for Naturvidenskaberne, Vol. XXVIII, 1884, pp. 253-419, with map. Ueber die Bildungsgeschichte des Kristianiafjords, by W. C. Brögger: ibid., Vol. XXX, 1886, pp. 99-231.

[4] Op. cit., p. 341.

[5] Given in detail in earlier sections of the paper. W. H. H.

stretch almost every (perhaps every) canyon and each canyon-like valley, which near Friorfjord indents the continuous rock wall, follows a fault fissure parallel to the nearly W.-E. striking fault planes. Even the clefts (topographic forms known as "Kloven") so characteristic of Langö and Langesundstangen are formed after fault clefts; and the straits, which raised above the sea would appear as valleys, are formed along the fault clefts. * * *

The significance of the faults for the formation of the valley straits is thus as profound as possible within the stretch of land described, since almost every cleft, every vale, every bay, has been formed upon a line of dislocation; indeed, the presence of clefts was for me, at the last, the surest index for the discovery of dislocations.[1]

The explanation offered by Professor Brögger for the observed relationship of the drainage system to the joint and fault systems is as follows:

It is now common to all these canyons or canyon valleys that the bottoms of the same are always so covered over that rocks are nowhere exposed in place—a contrast to the steep plane walls, which appear as though cut out with a knife. This condition appears to me to indicate that these canyons and canyon valleys are often split very deep. Their formation can naturally be explained in different ways—either (1) in great part through simple gaping of the fissure (this has above been assumed as a partial explanation of the original formation of the sound of Brevig); or (2) through gliding down of the sunken mass of strata along a fault plane, which had a somewhat different inclination than that according to which the clefts are cut out; or (3) a generally wedge-shaped block may have been sunk between two parallel or downward converging joint planes by the masses of strata (on either side) separating a little from one another. That such sinking in has actually occurred in some instances is proved by the sunken block between Tangevaldkleven and Fjeldstadkleven, etc. Finally (4), a narrow block made by the faulting has been crushed (zerquetscht oder zerstückelt) into fragments between two or more parallel joint planes in such a manner as to be subsequently easily removed by erosion, and thus through it the loom of the valley be formed. Such strongly crushed intervening blocks I have observed as a by no means rare phenomenon.

In one of the above-mentioned ways I believe that the narrow canyons and cross valleys have been originally formed; nearly all, if not all, are related to faults (stehen mit Verwerfungen in Verbindung) and are true fault clefts. Naturally it is not my intention by this to deny that erosion also has in general gradually worked along the clefts opened in any of the mentioned ways, but erosion alone has not opened the clefts, for otherwise it would be inexplicable why faults should always occur together with them.

In most of the cross valleys we find, however, although the faults are present, the cleft formed is either no longer present or is only locally to be seen. In most cases we must then assume that erosion has erased (ausgewischt) the characteristic fault cleft. This holds also for the longitudinal valleys which occur along dislocation lines; * * * the characteristic cleft formation is only locally preserved, and indeed chiefly along the coast line. In the interior of the country, for example, between Tangvald and Langesund, one can easily walk over the faults without the landscape revealing anything of them. Only the exact knowledge of sedimentation can here serve for orientation. Thus the fault lines are in part quite generally erased in spite of the fact that they had the most profound original significance in the sculpturing of the landscape, now for the most part to be detected only by careful observation, although in many places most striking and in general so persistent that almost every valley and every depression corresponds to a line of dislocation.[2]

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[1] Op. cit., pp. 341-342. [2] Op. cit., pp. 395-397.

The former head of the geological survey of Norway, Prof. Th. Kjerulf, from study of the topographic maps of Norway, was led to believe that the bounding lines of the valleys, lakes, and fjords of Norway were, almost throughout, the courses of lines of dislocation. Except in a few small districts such as those described by Brögger this has not, so far as I know, been confirmed by actual study in the field.

ORIGIN OF THE RIVER NETWORKS IN THE POMPERAUG REGION.

There are obviously a number of ways in which the dislocations of this region might be made to account for the orientation of stream courses. The direction of streams by the joint or fault planes themselves may be competent to explain the network indicated, more particularly if the streams began their cutting in the soft Newark sediments, which easily sustain secondary fractures near fault planes. That some voids occur along the fault planes of the Pomperaug Valley would seem to be indicated by the fact that these planes have conducted the underground waters to the surface at so many places within the area of the Newark rocks. Tension joints should, however, be more effective than compression joints in the orienting of drainage lines, if it be assumed that the gaping fissure planes have directed the streams in their courses. The presumptive evidence, however, is here in favor of the former development of the Newark rocks over a considerably larger territory than that which they now occupy.

It is an observation of much interest that the minor twig-like branches of the streams, which in the deeply eroded mass of crystallines must have been adjusted after the capping of sandstones had been removed, show an equally strong tendency with the master streams to follow the special directions indicated by the system as a whole, and this may perhaps indicate that they were adjusted to the earlier drainage lines in the deeply eroded mass of crystallines after the capping of sandstones had been removed.

The study of the fault system of the Pomperaug Basin offers, however, another rational and natural explanation of the network of streams, provided the assumption is made that the drainage is adjusted to that formed in the geographic cycle which succeeded the deformation of the area. The system of parallel faults has divided the area into vertical, triangular, rhombic, or rhomboidal prisms, which stand at different relative altitudes. These prisms are found to be grouped into composite blocks of increasingly higher orders, the peculiar property of each of which is that the average altitude of its component prisms approximates (however roughly) to a fixed value—the composite blocks have an average level surface, although alternate prisms or alternate subordinate blocks project above or stand below the general level. The initial surface formed by these prisms would be marked by canal-like structure trenches (graben) which follow the direction of fault planes and which have stronger directive power as regards streams at the junction of the trenches and at the crossings with the smaller branches of other series. This will be illustrated by Pl. XVI, which, so far as its tinting and the actual location of fault lines are concerned, is hypothetical. This map is constructed on the plan of some contour maps, in so far as the areas of highest altitude are marked by the deepest shades and those of lower altitude by increasingly lighter tints. The nearly white bands on this map, and in a less degree those of medium tints, we will suppose to mark, then, the more or less persistent depressions of the initial post-deformation surface, which had been adopted by the streams before base-leveling had occurred. This plate then represents in a very diagrammatic manner the supposed structure and the original surface of the territory into which the Shepaug River has intrenched itself, and in a general way also a structure which would account for the drainage of the adjacent territory.

SECTION 2.—PHYSIOGRAPHIC FEATURES OF THE POMPERAUG BASIN.

The geological structure of the Pomperaug region may be read not in the water courses alone by their canal-like channels, their "eaves-gutter" zigzags, and the directing of their courses, but also in topographic relief forms.

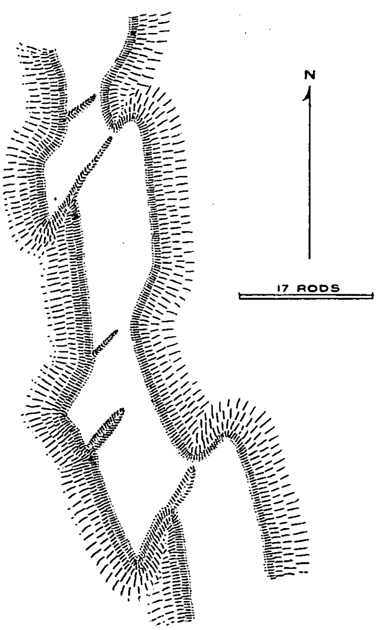


FIG. 54.—Topography of ridges near the oil well on the Truman Wheeler place, Southbury.

Checkerboard topography.—At many localities in the Pomperaug Basin, even where cliffs have not been developed and where outcroppings of rock may be few or even lacking, the modeling of the topography to the form of a checkered system is so striking as to arrest the attention of any one accustomed to observe topographic peculiarities. Perhaps no better illustration of this could be given than the wide eastward slope rising from the cascade in Transylvania Brook, a slope bare of outcrops save for a single probable exposure of the schist, but a slope on which mound-like elevations bounded by zigzags of straight elements produce at a distance the impression of artificial earthworks. This is seen to special advantage from almost any point on the opposite slope of the valley, although it exhibits too small relief to appear upon the topographic map. A modification of this structure is exhibited by the ridge of vesicular (main) basalt northwest of the oil well on the Wheeler place. So marked is the structure in this vicinity that the positions and directions of faults may be roughly determined (fig. 54).

Where developed on a larger scale such structures may be read directly from the map. In the northern wall of the basin, particularly to the north of Woodbury and in a larger way in the northwestern wall, such a checkered topography is apparent. West of Ragland a deep indentation of the basin wall reveals like characters in the relief.

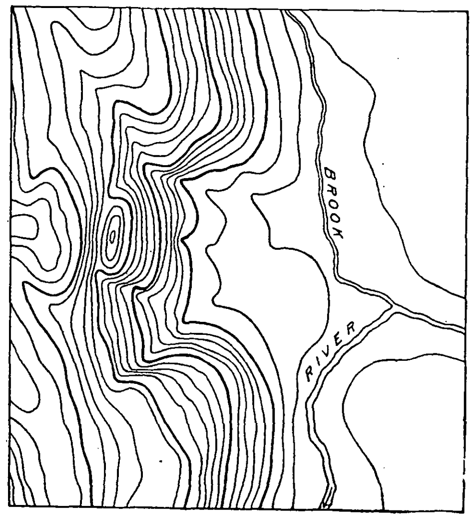


FIG. 55.—Typical inglenook of Squaw Rock, near South Britain. Scale, 3 inches equals one mile.

I have already called attention to the striking topographic peculiarities of the Orenaug district, in which a great number of tilted prismatic blocks produce the effect of tilted floating blocks. This topography, which may be referred to as the "floating block topography," except for its small scale, is similar to that described by Gilbert in the Great Basin under the name of Basin structure. On a still smaller scale the same kind of structure produces hummocky plane surfaces, such as have been described from the eastern twin of Orenaug Hill (see Pl. XIII).

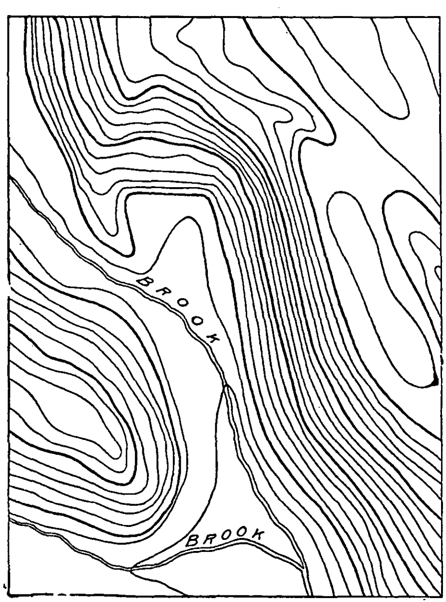


FIG. 56.—Very deep inglenook of the Hotchkissville Valley. Scale, 3 inches equals one mile.

Rampart slopes.—Particularly in the crystalline basin walls, where large displacements have occurred with distribution of throw over a comparatively wide zone, the effect produced is that of a series of steps, or better, in view of the talus slopes, of the ramparts of a fortification. The best illustration of this type of slope is furnished by the long northward-trending wall west of Ragland.

Inglenooks.—The peculiar indentations of the basin walls caused by the downthrow of orographic blocks furnish a type of physiographic feature which has not, I believe, been recognized hitherto. The peculiarities of these indentations in the basin wall, for which I propose the name "inglenook," are their approach to a prismatic form, their steep walls, their wide and nearly level floors, and the inadequacy of their present drainage to explain their formation. In some of them there are minor streams flowing, but in others streams are entirely lacking, the run off from their small drainage areas being distributed over steep slopes and passing into the loose talus or gravel of their floors. Figs. 55–57 represent three inglenooks from the Pomperaug Basin, the one at Squaw Rock near South Britain serving as the type. The deep inglenook which forms the Hotchkissville Valley has remarkably regular outlines, and it indicates that the downthrown block which has produced it is bounded by the N. ± 5° W. and N. ± 90° E.

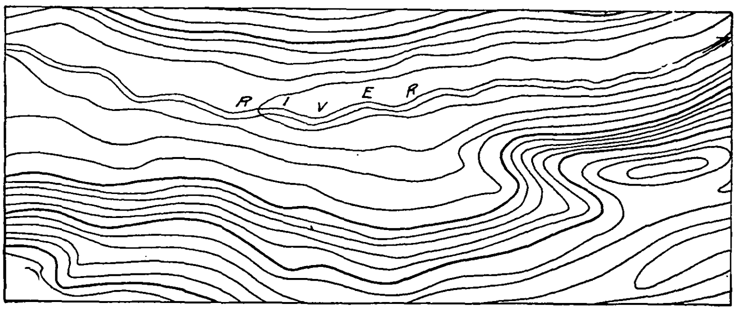


FIG. 57.—Oblique inglenook near South Britain. Scale, 3 inches equals one mile.

faults. It is prolonged southward and connected with the basin by the Sprain Brook gorge, which is formed in a similar manner by the downthrow of a block of schist having nearly the same width and bounded by N. ± 34° W. and N. ± 54° E. faults. (See general topographic map, Pl. XIV.) It is on the east of this block that the unit blocks of similar shape which have been described (p. 109) are found. A third and oblique type of inglenook is that which indents the western basin wall about 2 miles south of South Britain (fig. 57). The fourth well-marked inglenook indents the southern wall of the basin 1⅓ miles southeast of South Britain. This inglenook is bounded on the east and west by faults trending N. ± 44° W. and connecting with the boundaries of the Squaw Rock inglenook west of South Britain.

SECTION 3.—EROSION HISTORY OF THE POMPERAUG RIVER.

The erosion history of the Pomperaug River has been an interesting one, marked in a late stage by a complete reversal of the drainage in a portion of its basin. The peculiar conditions which seem to have

PLATE XVII.

PLATE XVII.

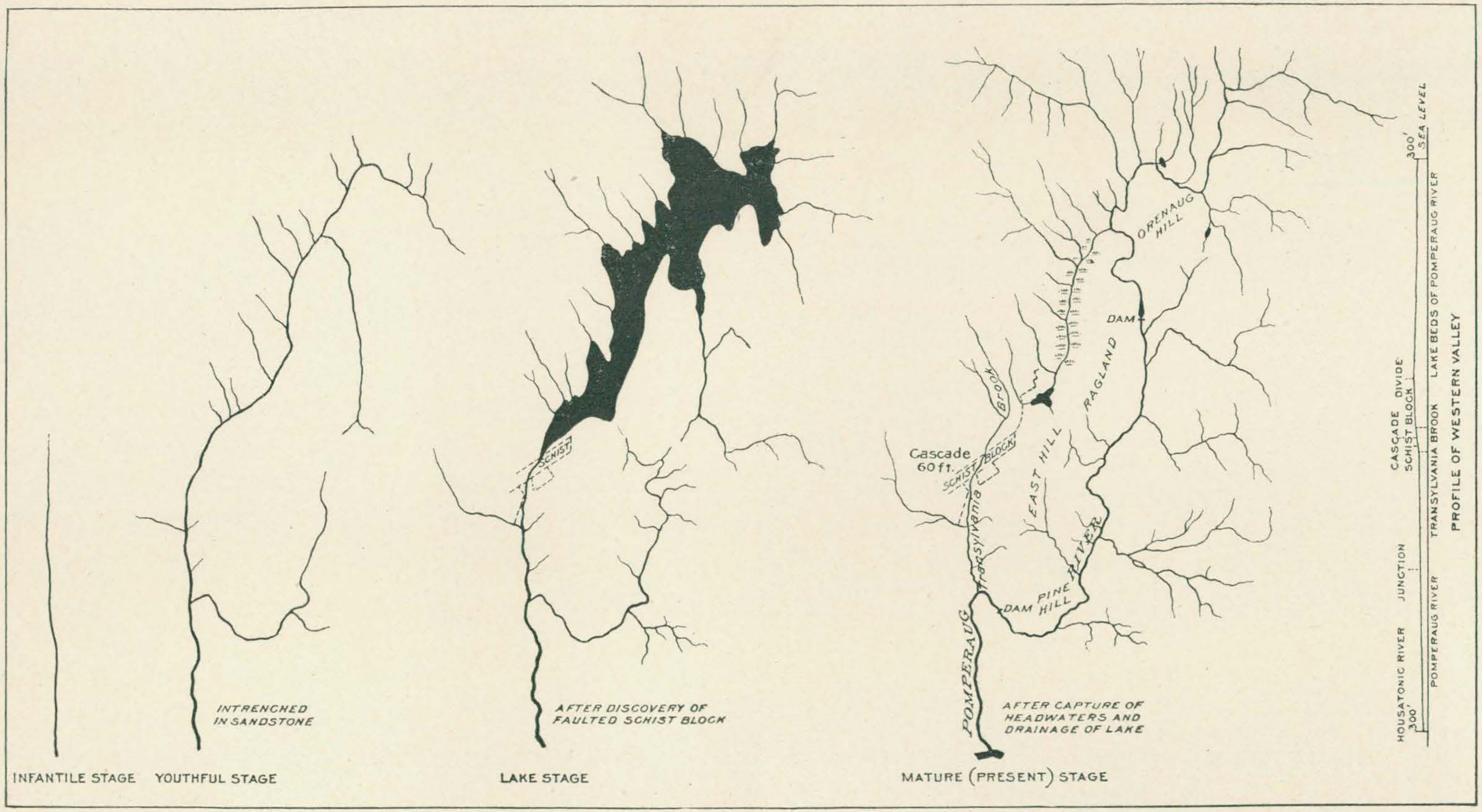
MAP TO ILLUSTRATE THE SUPPOSED STAGES IN THE EROSION HISTORY OF THE POMPERAUG BASIN IN THE CYCLE WHICH WAS INITIATED BY THE ELEVATION AND TILTING OF THE CRETACEOUS PLAIN OF EROSION.

Infantile stage. The course of the river is down the slope of the Cretaceous plain of erosion, modified by the valley of the master stream (Housatonic) to which it is tributary, and probably also by the existent drainage lines of the tilted erosion plain.

Youthful stage. The divide has become intrenched in the soft beds of shale and sandstone. Tributaries enter in the normal manner, but along fault trenches.

Lake stage. By the deepening of its bed the river discovered the underlying gneiss and schist in an upthrown block, and began to develop above it a new plain of erosion. Above this obstruction a lake has been formed either by subsequent elevation of the block or by the formation of a dam of glacial drift after a migration of the divide between the youthful Pomperaug and its main eastern tributary and the upthrown schist block.

Mature (present) stage. The main eastern tributary in the lower reach of the river having acquired an advantage in declivity of its headwaters, has pushed back its divide along the sandstone of the eastern valley so as completely to circumscribe the area of basalt, capture the headwaters of the river, and partially drain the lake. Where it has been compelled to cross the basalt (as elsewhere) the river has chosen its course over downthrown blocks lined by upthrown blocks (graben), in doing which it has discovered the upper surface of basalt in the bottom of its channel at Pomperaug village, and thus formed a new plain of erosion.



MAPS TO ILLUSTRATE THE SUPPOSED STAGES IN THE EROSION HISTORY OF THE POMPERAUG RIVER.

been mainly responsible for this are: (1) The Cretaceous plain of erosion, whose former drainage and whose gentle southeastern slope[1] conditioned the direction of the initial drainage of the cycle; (2) the downthrow of the orographic blocks of the valley below the surrounding walls of crystallines, which, in a rough way, has in the subsequent erosion determined the size of the basin; (3) the presence of soft sandstones, which fixed the general position of the trunk stream, as the canal-like trenches did its more exact direction; (4) the upthrown block of schist which projected into the basin from its western wall and brought about a new temporary base-level and ultimately the reversal of the drainage, and (5) the altitudes of the basalt block in the canyon in Pomperaug village, of the baked conglomerate blocks at South Britain village, and of the schist block which has just been mentioned, for these obstructions have determined the altitude of temporary erosion plains in the present comparatively stable stage of the river's evolution.

In Pl. XVII the features of the present river may be read. It is noted, first, that the trunk stream of the Pomperaug River with its tributary, Transylvania Brook, follows in the main the borders of the sandstone area, so as to inclose the masses of harder basalt. In the next place it is noted that the upper reaches of the river are a continuation of the valley which is occupied by Transylvania Brook, and observation on the ground shows, further, that this valley is much too large to have been caused by the brook which now flows in it. It could, moreover, hardly escape observation that the tributaries of this northward-flowing portion of the Pomperaug enter it in the reverse (backward-pointing) order, and that they are quite parallel with the tributaries of Transylvania Brook, though the latter enter in the normal way. The divide between the Pomperaug and this tributary is located in the arm of schist which projects into the basin west of East Hill, in which Transylvania Brook has formed a series of low cascades representing in the aggregate a fall of about 60 feet.

The northward-flowing portion of the Pomperaug is apparently a partially drained lake with a triangular lake nestled a little higher up in the nook formed by the sudden bend in the ridges of the central area. It is worthy of note that the central mass is, except in the southeastern portion, without any streams large enough to be represented upon the map. This is explained in part by its small area and in part by the extreme resistance to the agencies of subaërial erosion offered by the basalt of which it is largely composed. Although the Pomperaug has crossed the area of basalt in two instances, it has done so in ready-formed structure canyons (graben), within which it probably worked in an overlying cap of sandstone; for at but one of the localities, Pomperaug village, is basalt to be found in the river bed, and here it has only recently been discovered by the river.

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[1] Cf. Davis, Nat. Geog. Monographs, Vol. I, No. 9, pp. 269-304. Also, Eighteenth Ann. Rept. U.S. Geol. Survey, Pt. II, 1898, p. 157.

With the above-mentioned considerations in mind, and with the map of the river before one, the erosion history of the river during the post-Cretaceous cycle is interpreted to have been probably about as represented in Pl. XVII.

INFANTILE STAGE.

The initial or infantile course of the Pomperaug River during the post-Cretaceous cycles as a tributary to its trunk stream, the Housatonic, would be in accordance with the slope of the erosion plain on which it flowed, modified by the slope of the walls of the trench in which the Housatonic itself was then flowing, and directed also by any preexistent channel of the uplifted plain which had been formed in the previous cycles. The combined effect of these inclinations may be assumed to have been to give to the stream a southerly direction. A downthrown block in the crystallines between higher blocks is clearly indicated along the course of the Pomperaug River at Bennett's bridge, and it was probably this which fixed the present outlet of the river to the Housatonic. Owing to this canyon the river probably worked in sandstone from the outset, and steadily intrenched itself in this rock along a canal-like valley which follows the western margin of the present basin, and which was very likely present in the drainage of the preceding cycle.

YOUTHFUL STAGE.

The youthful stage of the river was characterized by a pushing back of its headwaters as the rise of the land increased, following in this the areas of sandstone into which it ever the more deeply intrenched itself. As it thus deepened its channel the modified inclination of its banks resulted in the formation of tributary streams, particularly from the west, which, while entering in the normal fashion, were yet, it is believed, largely controlled in their direction by the ready-formed trenches in the crystallines due to the depressed blocks outlined by the faults of the N. $\pm 34°$ W. series. At the northern end of what is now Ragland the river found two diverging belts of sandstone, and a branch was extended in either direction. At South Britain, also nearer its outlet, a branch of the river found a sandstone belt, through which it sank its channel and acquired advantage by increased declivity of its headwaters.

The deeper intrenchment of the main river must have been accompanied by a progressive migration of its channel to the eastward, due both to the eastward dip of the sandstone and arkose beds and to the distributive character of the displacement along the western wall. As it discovered the floors of the successive walls the river's bed would be steadily pushed eastward in the direction of the foot of the steps.

LAKE STAGE.

As already pointed out, the upper reaches of the present river (the northerly flowing portion) appear to be the basin of a partially drained lake. The course of the tributaries in the western wall clearly indicates that the drainage has in the northern portion been reversed, and the upthrown block of schist projecting into the basin from its western wall forms the present divide between the reversed stream and Transylvania Brook, which still occupies the southern portion of the old valley.

A new stage in the history of the river was inaugurated in the local discovery by the river of the schist block beneath its cover of sandstone. The many times greater resistance which this schist block offered to degradation by the river had the effect of starting the formation of a new plain of erosion near the level of its upper surface. The stage thus inaugurated was devoted to the grading of the river in two plains, one above and the other below the obstruction of the schist. As this proceeded the block itself developed a cascade, the fall of which steadily increased. The main eastern tributary of the Pomperaug, which was cutting its channel in the southern and eastern belt of sediments, thus secured an advantage over the western stream in the greater declivity of its headwaters, but either in this period or shortly thereafter it in a similar manner discovered the block of baked conglomerate at South Britain, which was so resistant as to form at its level a new erosion plain in the eastern valley.

The occasion of the damming up of the upper waters of the Pomperaug to form the lake, assuming that this occurred, may have been an uplifting of the obstruction of schist so as to form a natural dam. This could occur either through a secondary adjustment by relief of stresses not entirely released when the main dislocation of the area occurred, or it could equally well be ascribed to the action of stresses which had since developed. Another possible cause may have been the migration of the divide between the Pomperaug and its strong eastern tributary which now possessed an advantage in the greater declivity of its headwaters and subsequent damming of the course by glacial drift at some point near Pomperaug village.

MATURE (PRESENT) STAGE.

The later stages of the river would be marked by the more thorough investment of the basin and the reduction of the general level; there would be a multiplication of minor streamlets. If it be assumed that the elevation of the schist block of the cascade has caused the formation of the lake, the most revolutionary change as regards the river's history during the latter period was probably the more rapid extension of the eastern arm of the Pomperaug in comparison with the western branch, owing to its advantage in the greater declivity of its headwaters. The result was a steady pushing back of its divide and the occupancy of an increasing territory formerly drained by the headwaters of the western stream, a process which would have been continued until the site of Pomperaug village was reached and the drainage of the lake was begun. Thus the reversal of the upper Pomperaug would have been inaugurated, the original lower Pomperaug becoming the present Transylvania Brook, and the obstructing schist block becoming the divide separating the two streams.

SECTION 4.—GLACIATION OF THE BASIN.

Comparatively little attention has been given to this chapter in the geological history of the Pomperaug Basin, although there can be little doubt that it would well repay a careful study.

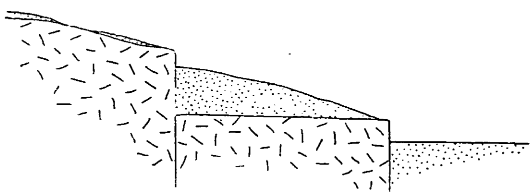


FIG. 58.—Idealized section across the northwestern wall of the Pomperaug Basin to show the drift cover.

THE DRIFT MANTLE.

A mantle of drift covers large portions of the rocky slopes. On the western and northern borders of the basin it has thinly mantled the higher areas, so as to leave exposed chiefly the cliffs and a small margin at their summits. It has accumulated, however, on the broader shelves formed by blocks at lower levels, leaving exposed, however, in like fashion their frontal cliffs and a portion of their summits (fig. 58). In the southeastern wall the effect has been different. The crystallines have here been planed away so that no cliffs now remain, and only flat or gently sloping surfaces of outcrops are to be seen. Blocks of schist standing at altitudes intermediate between the high walls and the valley floor are entirely concealed under the drift mantle (fig. 59; also map, Pl. I).

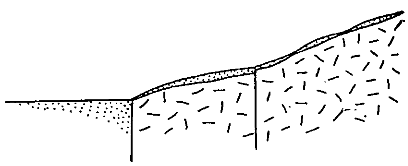


FIG. 59.—Idealized section across the southeastern wall of the Pomperaug Basin to show the drift cover.

DEGRADATIONAL ACTION OF ICE ON BASALT.

In an early chapter I have referred to the fact that the highest ridge in the basalt of the valley is 200 to 300 feet lower than the high points of the crystallines in the walls surrounding the basin. This might be in part explained by the known depression of the entire area and the rapid erosion of the posterior shales which in all probability once covered the main basalt sheet. However, as the structure of the basalt in the summit of this ridge shows that it belongs to a zone located some distance below the original surface, it is assumed that a considerable thickness of the basalt has also been here removed. The extreme resistance of the basalt to weathering, its separation by faulting into prisms which stand at relatively different altitudes, and the small drainage area in which it lies, are all conditions which tend to produce a pinnacle structure; but the flattened profiles of the summits of the ridges when viewed from the southern basin wall (Pl. V, *A*), and their very even skylines when viewed from the east or west, indicate that some planation of the summits has here occurred. Under the circumstances the most competent agent to accomplish such a planation would be the glacial ice cap, which, overriding the resistant crystalline walls, would sag into the valley formed from the erosion of the soft arkoses surrounding the basalt ridges. The higher prisms of basalt which project above the sandstone would oppose their vertical walls to the great lateral pressure of the moving ice, so that any unsupported pinnacles would be likely to be broken and carried away.

BOWLDER TRAINS OF RATTLESNAKE HILL AND CASTLE ROCK.

The evidence of ice action in transporting blocks of the basalt is found in the two bowlder trains of basalt which have been noted in the basin. The more noteworthy of these is the one which can be traced to Rattlesnake Hill. This train begins as a collection of great, irregular basalt blocks strewn south-southeast in roughly linear arrangement on the southern slope of Rattlesnake Hill. At the bottom of the slope the train ends at the level of the well-preserved river terrace, and no more blocks are encountered until the direction has been followed for nearly a mile and entirely across the valley to where the slope again rises in the principal inglenook of the southern wall. Here are found very large blocks, some having dimensions of 15 or more feet. They are six to eight in number, ranged near one another in the direction of glacial movement. Four or five of the largest would be included within a radius of 50 feet. Their direction from Rattlesnake Hill is determined to be about S. 29° E., the average direction of ice movement in the vicinity, which from the observation of the strike of gneiss scorings is ± N. 30° W.

The other indication of a bowlder train within the area of the basin is found on the slope of the eastern wall to the east and southeast of the village of White Oaks. The larger and smaller basalt blocks are found at two places, so located as to indicate that if they belong to a single narrow train its direction was about S. 13° E., and its source the high pinnacle of Castle Rock, the octagonal prism of basalt which rises to the northwest of Pomperaug village. If this is true—and it is by no means certain—it would indicate that local undercurrents within the ice mass were made to conform to the extension of the valley, a fact quite in harmony with observations which have been elsewhere made.

TERRACE FORMATIONS.

The wider portions of the valleys surrounding the central basalt area are occupied by a glacial terrace formation. Its floor-like surface is well displayed in the Woodbury plain along the southern base of the basalt area (see Pl. V, *A*). Perhaps the best section through it is to be found on the Poverty road near the corner one mile north of South Britain village. Its characteristic cross bedding is here seen to special advantage.

APPENDIX.

REPORT ON FOSSIL WOOD FROM THE NEWARK FORMATION OF SOUTH BRITAIN, CONNECTICUT.

By F. H. KNOWLTON.

In January, 1900, I received a request from Prof. William H. Hobbs, of the University of Wisconsin, to examine a number of pieces of fossil wood found in the lowest member of the Newark formation of South Britain, Connecticut. The specimens, three in number, were soon placed in my hands, and have furnished the basis for the following brief report:

According to Professor Hobbs this wood, which is more or less perfectly silicified, occurs in considerable abundance in these beds, usually in the form of fragments, although he has sent me a photograph of a trunk preserved at one of the farm houses in the vicinity which appears to be about 3 feet in length and nearly or quite 2 feet in diameter. The specimens submitted to me are mere fragments, evidently of large trunks, the largest specimen being only about 15 cm. long and 7 cm. square. Even to the naked eye it appears that the structure of the wood has not been well preserved, and when the thin sections are viewed under the microscope it is seen that considerable distortion has taken place, but by a careful study points were found in nearly all of the sections that afforded a fairly satisfactory idea of the wood. The three specimens all possess a similar structure, as well as can be made out, and are referred to the following species:

ARAUCARIOXYLON VIRGINIANUM Knowlton.

Bull. U. S. Geol. Survey No. 56, p. 50, Pl. VII, figs. 2-5, 1889.
Nineteenth Ann. Rept. U. S. Geol. Survey, Pt. II, p. 516, Pl. LII, figs. 7-10, 1899.
Twentieth Ann. Rept. U. S. Geol. Survey, Pt. II, p. 274, Pl. XXXVII, figs. 1-6, 1900.

This species was first described from the Triassic of Virginia and was later detected in the Richmond Basin, Virginia, and the well-known Triassic area of North Carolina. It is of interest to know that it is also found in the Triassic of Connecticut.

The material from Connecticut, although not very well preserved, agrees in all essential particulars with the Virginia and North Carolina material. The tranverse section shows the absence of rings of growth, and the wood cells are large and thick-walled, as shown in the above-quoted figures. The radial section, in exceptionally well-preserved areas, shows the bordered pits to be in two rows which nearly cover the wall. They are also made out to be hexagonal, but are not well enough preserved to permit of satisfactory measurements. The medullary rays as shown in this section are seen to be composed of relatively short cells. In tangential section the wood cells are seen to be without pits or other markings and the medullary rays are in a single series of from three to eight or nine cells.

In conclusion it may be stated that the characters as made out leave no doubt as to the identity of the Connecticut material with *Araucarioxylon virginianum* of Virginia and North Carolina.

THE LACCOLITHS OF THE BLACK HILLS

BY

THOMAS AUGUSTUS JAGGAR, JR.

WITH A CHAPTER ON

EXPERIMENTS ILLUSTRATING INTRUSION AND EROSION

BY

ERNEST HOWE

CONTENTS.

ILLUSTRATIONS.

THE LACCOLITHS OF THE BLACK HILLS.

By T. A. Jaggar, Jr.

INTRODUCTION.

The description of igneous intrusions of the northern Black Hills in South Dakota and Wyoming contained in the following pages is the result of two field seasons' work in the mining district, spent in mapping the area comprised in the Sturgis and Spearfish quadrangles. This work was accomplished in the summers of 1898 and 1899 under the direction of Mr. S. F. Emmons, and in the fall of 1898 a reconnaissance was made by the writer to the northwest in order to study the outlying igneous bodies, more especially the group associated with the Bearlodge Range. Valuable field assistance was rendered by Messrs. J. M. Boutwell, J. D. Irving, and P. S. Smith. As a result of field observations, experimental studies were suggested. These were carried out in the laboratory of experimental geology at Harvard University by Mr. Ernest Howe, under the instruction of the writer, during the winter of 1898–99. Mr. Howe's results, which have proved interesting in comparison with field occurrences, are recorded in Chapter V.

It is not proposed to discuss the petrography of the intrusive rocks, but rather the structure and the origin of the intrusions. The region is remarkable chiefly for the systematic recurrence of certain distinct types of intrusive bodies so exposed by favorable uplift and erosion that many gradations from dike to sheet and from sheet to lens are revealed. In other words, there is here an opportunity for the study of dikes, stocks, sills, laccoliths, and irregular modifications of each of these, and exceptionally good exposures permit conclusions concerning dynamic conditions of intrusion which are supported by abundant field evidence. As the distribution and form of the igneous bodies are of great importance in connection with the occurrence of ores, and the history of intrusion is in some sense associated with that of mineralization, it seems well to describe in some detail these masses of igneous rock from the standpoint of dynamic geology.

DEFINITION OF TERMS.

The terms dike, stock, sill, and laccolith, as here used, need some definition. These definitions are not intended to be didactic, but are presented only to render intelligible the use of the words when applied to a region where many gradations occur between different kinds of igneous bodies.

A dike is an elongate intrusive igneous body occupying a fissure in any sort of rock, the walls of which at the time of intrusion were vertical or, if inclined, at angles nearer the vertical than the horizontal. A dike must have longitudinal extension much greater than its breadth, but may vary in thickness from an inch to several hundred feet. A dike may be irregular or may follow a sinuous course; it may be intruded between the beds of vertical or steeply inclined sediments; it frequently follows joint surfaces and has smooth and plane bounding walls. It must be noted that a flat igneous mass intruded between horizontal or nearly horizontal strata and subsequently upturned with them to a vertical position is not a dike, but a sill.

A stock is an intrusive mass of irregular ground plan, with bounding walls more or less upright at the time of intrusion; it differs from a dike in having no considerable longitudinal extension and in the absence of plane bounding walls. A stock occupies an irregular rent or cavity in the country rock, produced by disruption or fusion, or both, and if it occurs in sediments the fissure filled by the intrusion bears no definite relation to the stratigraphy or joints. The word stock is usually limited to bodies of considerable size, amounting in diameter to at least several hundred feet. Irregular intrusions intermediate in form between dike and stock may occur.

A sill is an intrusive sheet forced between strata which are horizontal or which, if tilted, lie at angles more nearly horizontal than vertical. The ideal sill splits strata apart on a single bedding plane and maintains a constant thickness. Sills in nature commonly break obliquely across bedding planes and may vary in thickness, though in the short distance in which they are exposed they need not show these characteristics. A sill may thin out to its border, or it may break upward along a joint plane to form a dike, or it may end against a fault surface. Transitions between dike and sill occur when a sill breaks upward at an angle of 45° or when a dike follows the bedding planes of strata inclined at that angle. The conduit that feeds a sill may be a vertical dike or an oblique, irregular, upward-breaking extension from another sill at a lower horizon.

A laccolith (formerly written laccolite) is a dome-shaped intrusion in horizontal strata or in strata more nearly horizontal than vertical. The ideal laccolith, like the ideal sill, splits strata on a single bedding plane; in nature laccoliths may break obliquely across bedding while still being guided in a general way by the sedimentary parting planes. The ideal laccolith is a radially symmetrical plano-convex lens with the convexity upward. Laccoliths in nature may be very unsymmetrical in ground plan and cross section and doubly convex. A laccolith may be a thickened extension of a sill; its conduit may be a stock, dike, inclined sill, or a combination of these, and it may fault and otherwise deform the strata about it. Transitions of the same sort as those described between dike and sill may occur between dike and laccolith. Transitions between sill and laccolith are of course common, the laccolith being a sill thickened locally or centrally and arching the strata lying in juxtaposition.

Commonly the intrusive magma which forms a laccolith has been believed capable of "lifting the load" above it. Such might be the case in strata of uniform flexibility, free from orogenic stress, subject to intrusion through ready-made conduits. When, however, those conduits are fault fissures and ruptures produced by strains incident to movements of mountain growth and so are permissive of igneous injection from below, the eruptive liquids must be conceived to spread upward and outward chiefly along lines of weakness. The pressure exerted by a single igneous body among strata in such a case is but a minor feature, the path chosen by the lava marking the site of inherent tendencies to warp and buckle under greater orogenic stresses. Thrusting and swelling among shales, the laccolith arches beds "competent" to transmit pressure without stretching or flowing, but the dome once initiated, horizontal components producing lateral deformation become more and more efficient with increased flexure in the dome itself. The motion of uplift may be absorbed a short distance above the laccolith in lateral crumpling and faulting of the superjacent beds about the flanks of the dome, and if these are shales they are to a certain extent stretched on the crest and squeezed into the sags. Thus the laccolith below a great thickness of soft strata no more lifts the load than does a cube of pyrite or a calcite concretion[1] when crystallizing to deform the surrounding laminæ.

The term porphyry is used in the same sense with reference to an intrusive rock of porphyritic structure as "lava," applied to an extrusive. This use is prevalent in Western mining districts. The wide variation in mineralogical and chemical composition of Black Hills porphyries would make continual reference to specific types confusing to the reader, where the subject in hand deals purely with dynamic phenomena.

[1] Calcareous concretions of Kettle Point, Ontario, by R. A. Daly: Jour. Geol., Vol. VIII, No. 2, 1900, fig. 3, p. 138.

CHAPTER I.

GEOLOGY OF THE NORTHERN BLACK HILLS.

GENERAL STRUCTURE.

The Black Hills are well known to constitute the type of dome structure. They rise like an island in the midst of the Great Plains, with culminating peaks of pre-Cambrian granite intrusive in Algonkian schists, and these same schists and granite may be followed outward from the center of the Hills to an encircling escarpment of Paleozoic rocks dipping away on the northern, southern, and eastern sides, and mantling over the schists to form an extensive forested limestone plateau on the west. The center of activity of the younger porphyry intrusions is Terry Peak, a summit rising 7,069 feet above the sea, in the northern portion of the schist area exposed on the eastern side of the uplift. Northwest, north, and northeast of Terry Peak occur a large number of intrusive bodies in beds ranging from Algonkian to Benton Cretaceous. The structure and forms of these igneous bodies vary chiefly with the horizon of intrusion.

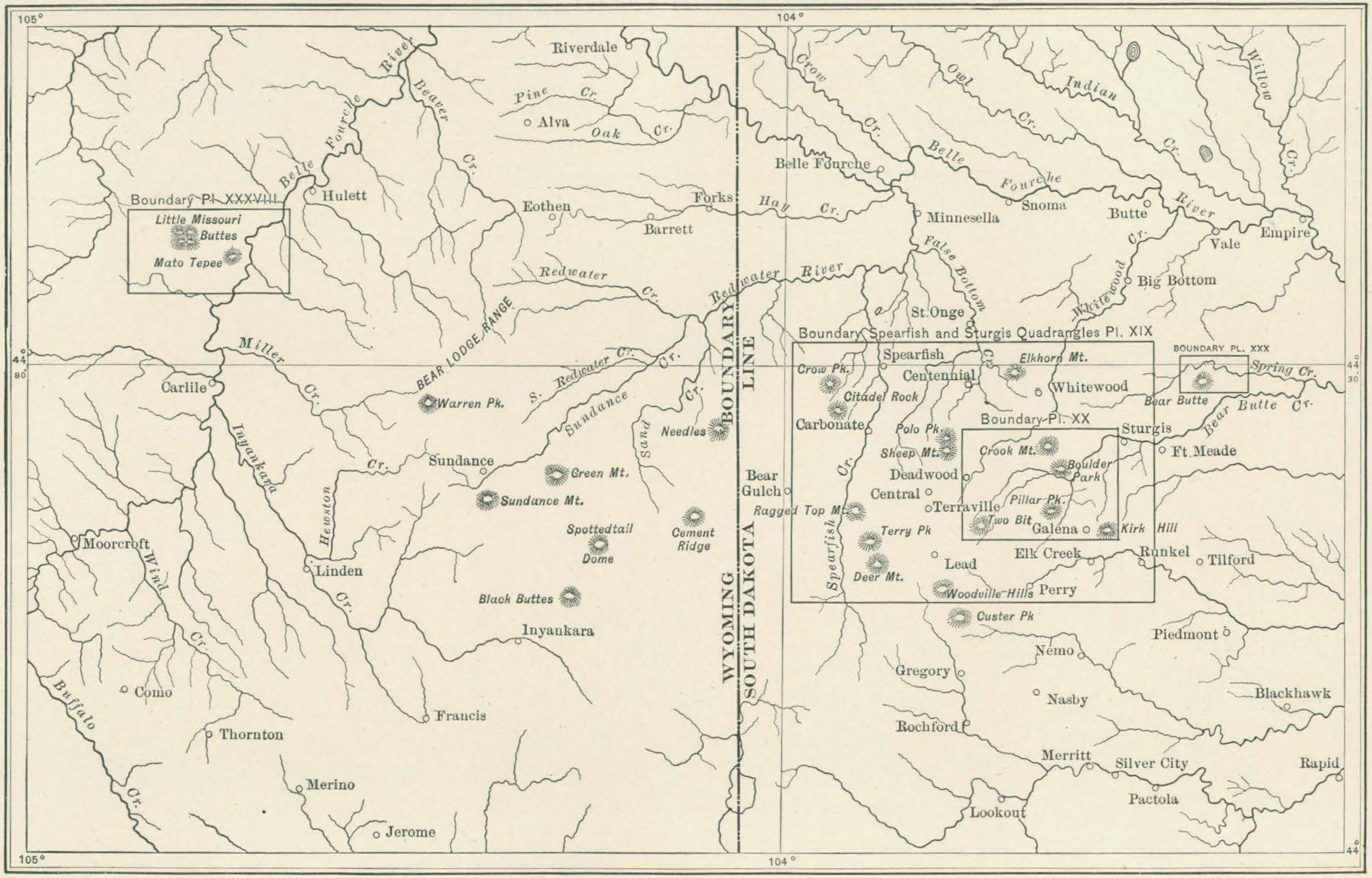
TOPOGRAPHY AND DRAINAGE.

The drainage of the northern Hills follows in general radial courses consequent upon the original slopes of the uplift as a whole. Where erosion has gone deepest this drainage has become modified by the development of valleys along the softer rocks, and, in consequence, subsequent valleys having courses concentric to the dome tend to follow along the strike of the Paleozoic and Mesozoic beds. The most conspicuous of these valleys is the well-known Red Valley, which forms a continuous depression around the Black Hills uplift.

DRAINAGE OF TERRY PEAK DISTRICT.

Four streams drain the Terry Peak eruptive center, flowing east, northeast, and north; these are Elk, Bear Butte, Whitewood, and Spearfish creeks. The drainage system of each of these has eroded away strata which capped igneous intrusives; and the porphyries, by reason of their more resistant quality, usually form prominent eminences above the general level.

The westernmost of the streams mentioned, Spearfish Creek, forms for 20 miles an impressive canyon in the limestone plateau, from which the stream emerges into the Red Valley at Spearfish. For a portion of its course this stream, which is to-day one of the most powerful in the Hills, flows along the contact of the Algonkian schists with the basal



INDEX MAP OF NORTHERN BLACK HILLS, SOUTH DAKOTA AND WYOMING.

Rectangles show approximate boundaries of areas included in Plates XIX, XX, XXX, and XXXVIII.

Scale: 1 inch=11½ miles.

beds of the Cambrian; above the mouth of Annie Creek the stream leaves the last outcrop of schist, and from here to the mouth of Robison Gulch, under Spearfish Peak, flows on Cambrian beds, cutting into porphyry masses at Annie, Squaw, and Rubicon gulches; then entering the zone of dipping Paleozoics, it progressively cuts its way across Silurian, Carboniferous, and Permian beds before emerging on the Triassic lowland of the Red Valley. (See Pls. XVIII and XIX.)

Whitewood and Bear Butte creeks, which flow to the northeast, traverse a more varied topography before they emerge from the Hills. They take their rise among Cambrian strata and porphyries, and their headwater branches have assisted in carving out the northern portion of the exposed Algonkian core of the Black Hills uplift. Through portions of their courses deep V-shaped gulches have been cut in the schist, and wall canyons in the Carboniferous limestone. Each formation in turn has its characteristic erosion form, which varies little throughout the northern Hills, and is usually directly dependent upon its relative capacity for resisting erosion. Indeed, the drainage as a whole, while retaining consequent courses in general for the master streams, shows many modifications by adjustment, more especially in the tributary branches, and occasionally striking instances of capture are evident.

Elk Creek, flowing east, drains on the south the high Algonkian plateau land which marks a portion of the area of maximum uplift. The upper portions of its course are characterized by broad meadow bottoms and gentle slopes from upland "flats" consisting of Cambrian or porphyry caps over schist. Where the stream enters the limestone, which is here of extraordinary thickness, a magnificent canyon with vertical walls rising sheer from 200 to 400 feet has been cut. Through this canyon the engineers of the Black Hills and Fort Pierre Railroad have built one of the most picturesque routes of travel in the country. Steaming through this impressive gorge the traveler moving eastward finds it difficult for some time to discover any considerable dip in the massive limestones, which retain for several miles the appearance of uniform thickness in the precipitous cliffs that wall in the torrent. Eventually, however, the canyon widens out and the limestone cliffs are replaced by bright-colored beds of the Minnelusa "alternate series," and then suddenly the characteristic gateway of Minnekahta limestone is passed and the train emerges into the broad lowland with its red marls and tilled fields.

TOPOGRAPHIC TYPES.

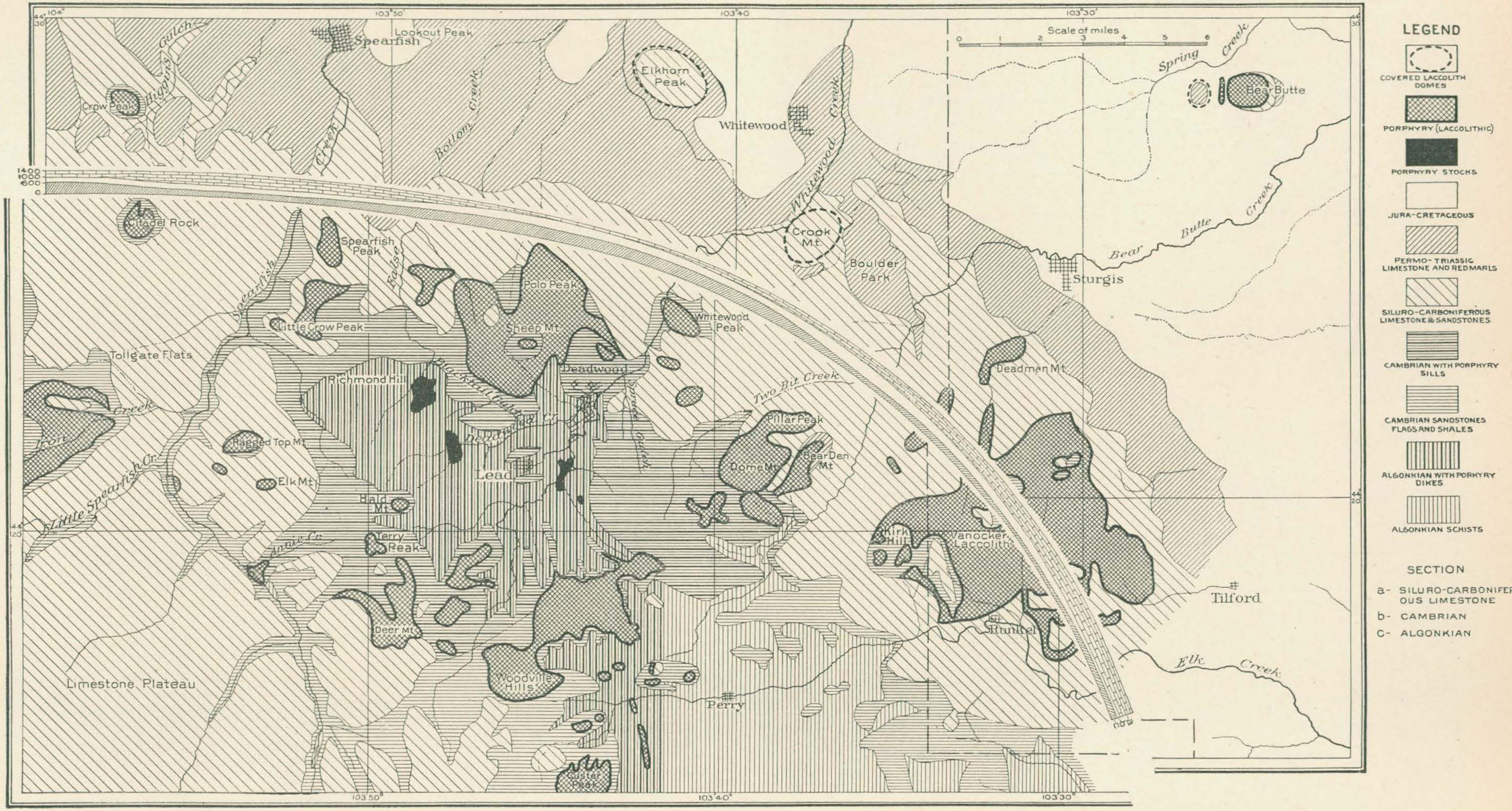
The Algonkian schists form flat uplands, and when they occur as massive upturned quartzites frequently jut out in colossal walls. Near Elk Creek one of these quartzite walls may be traced for miles, strongly resembling a dike. Elsewhere the Algonkian forms the bottoms of streams that have cut through the softer Cambrian beds, or it forms, with its characteristic steeply inclined banding, the slopes of steep gulches, like Whitewood Creek along the line of the Burlington Railroad. The many branches of the railway systems afford excellent sections of the Algonkian as they wind in and out along gullies and spurs to maintain their grade, and these railway branches and loops are now so numerous in the mining district as to form a conspicuous artificial feature in the topography; the same may be said of the innumerable tunnels and prospect holes with their dumps jutting out from the steep gulch slopes, the size of the dump an index of the depth of the digging. Thanks to this artificial "honeycomb" underground and the clean railway cuts above, much is now exposed to the geologist that was completely masked twenty years ago.

The Cambrian section where exposed beneath a protecting cover of limestone frequently forms wall cliffs of red and brown color, striped parallel to the stratification, one notable red band in the upper part of the formation being conspicuous in many places. The type locality occurs on the west side of Whitewood Creek just below Deadwood. Where its protecting limestone cover has been eroded away the Cambrian is likely to weather into rounded forest-covered hills of inconspicuous outcrop, like those occurring south of Elk Creek in the vicinity of Meadow Creek. Immediately beneath the Silurian limestone the Cambrian usually forms a bench, occasioned by the hard and salient "worm-eaten" (Scolithus) quartzite jutting out from beneath thick, soft, green shales (see fig. 60).

The Silurian limestone, in consequence of this relation and of another shale band above it, is frequently masked by talus, but, where its thickness is sufficient, forms a yellow bench, well shown in Whitewood Canyon on the route of the Fremont, Elkhorn and Missouri Valley Railroad. This bench is rarely seen west of Deadwood, and the Silurian is difficult to identify in Upper Spearfish Canyon. It occurs north of Annie Creek at several points in the canyon, at Crown Hill, and at Carbonate.

The Carboniferous, equivalent to the Madison limestone of the Rocky Mountains, is naturally the principal cliff maker, and its escarpment forms a conspicuous feature in the landscape everywhere. A more irregular and variegated cliff, colored purple, red, and white, and presenting one of the most picturesque color effects, is made by the Minnelusa sandstone, forming the "sand hills" encountered in driving out from the Hills just before reaching the Red Valley. The sandy soil of the Minnelusa frequently produces holes and sand in the roads which traverse this zone.

The Minnekahta limestone of the Permian forms one of the most conspicuous topographic features of the Hills. Dipping away with wonderful uniformity from the uplifted dome, the outflowing streams invariably cut through it a V-shaped gateway, making in the interstream spaces crescent-shaped scarps of the 30-foot limestone over the soft red sandstone that underlies it. The outer slope of the jointed limestone is usually washed bare and on the inner side of the Red



MAP SHOWING DISTRIBUTION OF DIKES, SILLS, AND LACCOLITHS, NORTHERN BLACK HILLS, SOUTH DAKOTA.

Valley forms what has been aptly called a tessellated pavement. The Red Beds themselves rarely present good exposures, though occasionally the streams which meander through the valley cut them into small buttes or mesas, capped by gypsum, which exhibit a bedded cross section. Such a section may be seen east of Whitewood.

Continuing outward from the Hills, the Jurassic beds outcrop on the inface of the Cretaceous escarpment that makes the outer wall of the Red Valley, and a conspicuous feature of these beds in the Sturgis district is a hard quartzite which forms angular blocks upon the slope. The crest of this slope is usually a rock face of coffee-colored or yellowish sandstone of Lower Cretaceous age. This sandstone slopes away toward irregular hills formed of other members of this series. The Dakota sandstone is the last hard, salient bed, and this in turn dips gently beneath a wide, arid tract of Benton black shale, the monotony of which is broken only by distant buttes of Niobrara limestone that appear upon the sky line far out across the plains.

STRATIGRAPHY.

DYNAMIC SIGNIFICANCE OF STRATIGRAPHY.

In the columnar section, fig. 60, are shown the average thickness and lithologic character of Paleozoic and Mesozoic rocks. In connection with the interpretation of dynamics of intrusion the distribution of thin-bedded and thick-bedded strata in the column is of great importance. Irving has shown the importance of shale beds as favorite horizons of intrusion; they are the readiest to yield to a viscous wedge of igneous matter. The accompanying columnar section shows three thick beds of soft material, the one at the top of the Cambrian, the Permo-Triassic red beds, and the Benton shales. The first underlies the most massive "competent"[1] member of the whole series—i. e. the great limestone, including both Silurian and Carboniferous. The lower red bed underlies the massive layer known as Minnekahta or purple limestone, which is overlain by easily deformed thick beds of red marl, while the soft, black Benton shales underlie the Niobrara limestone.

In addition to these three conspicuous shale horizons, other stratigraphic relations which would tend to influence intrusion are as follows: The Algonkian lamination abuts abruptly upward against the hard basal Cambrian quartzite or conglomerate, and this same lamination, while fairly uniform in its strike (NNW.), varies in its inclination east and west of the vertical, though it is prevailingly westerly in the Terry Peak region. An example of change in dip of the schists occurs at Central, in Deadwood Gulch, nearly opposite the De Smet open cut. Through-

[1] The mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, 1892. "A thrusting layer firm enough to transmit the effective force" in strata folding under lateral compression is called a "competent" stratum. The same word may be applied to a stratum resistant to the upward progress of an intrusive magma, and thus competent to dome upward rather than split and mash like shale.

out the Cambrian, thin-bedded paper shales alternate with flags and sandstones, forming innumerable thin parting planes. Thin shales occur also above the Silurian and in the Minnelusa, Jura, and Lower Cretaceous.

VARIATIONS IN THICKNESS.

The columnar section (fig. 60) shows average thickness for the northeastern part of the Black Hills. These figures are generalized from sections measured in Spearfish, Whitewood, Bear Butte, and Elk canyons.

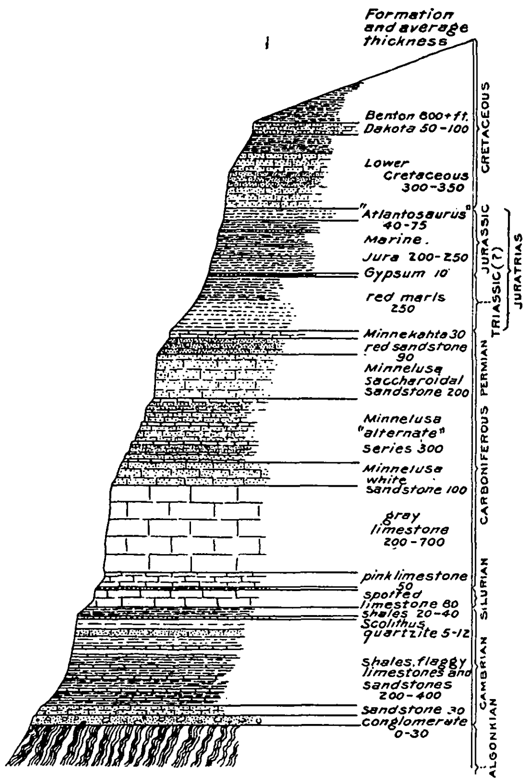


FIG. 60.—Generalized columnar section, northern Black Hills.

The progressive variation in this series of measurements, which is most significant in connection with the intrusives, is shown in the diagrammatic strike section (vertical exaggeration × 2.5) from northwest to southeast inserted on the map, Pl. XIX. From a thickness at Beaver Creek just west of the mapped area (Pl. XIX) of probably not more than 400 feet the Siluro-Carboniferous massive limestone, grouped as a single competent member, thickens to more than 700 feet in Spearfish Canyon. The Cambrian beds maintain throughout this region a rather uniform thickness, but probably diminish where the limestone is thickest. There is some evidence that the present course of Spearfish Canyon marks the axial region of a gentle syncline of deposition under the great limestone. For this reason the thicknesses in the section have been referred to an upper datum level, namely the top of the gray (Carboniferous) limestone.

The Algonkian surface thus sectioned is seen to be warped into undulations. That some such undulations occur, and of much more pronounced relief than that represented in the section, is amply proved at several points. One of these is between Englewood and Nevada Gulch, where there is a rise in the Algonkian-Cambrian contact of 400 feet in a northwest direction—that is, tangent to the curvature of the elliptical area of the Black Hills uplift. Similarly the schist surface beneath the Cambrian at Brownville on upper Elk Creek shows a very rapid rise westward toward Woodville. Coarse Cambrian conglomerate fills hollows between ancient Algonkian quartzite reefs on the upland 4 miles southeast of Virginia on Bear Butte Creek, so that irregular relief in the original Algonkian surface, as well as irregularities induced by deformation, may be safely postulated. Warping of the schist surface in post-Paleozoic time probably proceeded largely by small slippings on lamination planes. These movements, when communicated to the flat-lying Cambrian beds above, produced innumerable small fractures—the "verticals" of the mines. The coincidence in trend between verticals and Algonkian lamination planes (NNW.) is remarkable. The thickness of the Algonkian is unknown, but there is good reason for supposing that its nearly vertical structure marks a series of isoclinal folds in which eventually some recurrent horizons may be identifiable. As is to be expected in the isoclinal structure, the schistosity usually conforms to the original bedding, but in places where the axial region of a fold is exposed, the lamination is seen to be distinctly transverse to the bedding, as in Deadwood Gulch near the town of Central.

East from Spearfish Canyon the great limestone shows a remarkable thinning, from 700 feet to a total thickness of probably not more than 100 feet on the flanks of Polo Mountain, a distance of 6 miles. The Cambrian thickens, but not in the same proportion; at Deadwood it has a thickness of between 400 and 500 feet. From Polo Peak, where the limestone stratigraphically overlies the greater porphyry masses of the Terry Peak complex, this massive member steadily thickens southeastward, reaching 300 feet at Whitewood Canyon, about 500 feet in Bear Butte Canyon, and probably more than 800 feet in Elk Creek Canyon. The Cambrian beds thicken at Bear Butte Creek, and then thin away to between 100 and 200 feet south of Elk Creek; and farther south, on the flanks of the Harney Range, the Cambrian almost disappears.

Summarizing this section from Beaver Creek to Elk Creek, the thick limestone in Spearfish Canyon separates two areas of igneous irruption and Algonkian elevation, namely, the Bald Mountain and Nigger Hill mining districts. The Terry Peak center of irruption underlies the thinnest portion of the limestone. The Two Bit region of maximum development of sills is where the Cambrian is thickest, and the Runkel region of large porphyry masses in and above the limestone is where the Cambrian thins and the limestone becomes thickest. A study of the map will show these relations. The Nigger Hill Algonkian area lies outside of the mapped area, on the west (see Pl. XIX).

COLUMNAR SECTION.

The paleontologic, lithologic, and topographic characters of the geologic column are best expressed in tabular form. Local formation names are avoided except where already in the literature of the Black Hills.

TABLE OF GEOLOGIC FORMATIONS IN NORTHERN BLACK HILLS.

PERIOD.	EPOCH.	FORMATION.	LITHOLOGIC CHARACTER.	TOPOGRAPHIC CHARACTER.	FOSSILS.
Pleistocene			Stream gravels	Fills saddles and hollows, usually divides; scattered bowlders on the plains.	
Eocene	Oligocene?	White River	Clays, white, pink, or buff. Small fragments of white rhyolite in conglomeratic layers.	Similar to above, but less abundant. Often under the Pleistocene gravels.	Vertebrate remains: Mesohippus, Ischyromys typus.
Cretaceous		Benton shale	Dark shales or clay	Plains	Fish scales and teeth.
		Dakota sandstone	Brown sandstone with limonitic nodules	Outer escarpments of Hills.	Plant remains.
		Lower Cretaceous	Sandstones, buff, white, and gray; limestones; colored clays; green shale; carbonaceous beds.	Crest of outer wall of Red Valley and irregular hills and escarpments.	Plants, cycads, etc.
Juratrias	Jurassic	"Atlantosaurus"	Fresh-water deposits, green shales, sandstones, and clays.	An inconspicuous bed in outer wall of Red Valley.	Saurian remains.
		Marine Jura	Buff marl, sandstone, oyster limestones, green and red clays, marls, and shales.	Lower beds in outer wall of Red Valley.	Belemnites, Ostrea, Trapezium, Pseudomonotis, Tancredia, Cardioceras, Lingula brevirostris.
	Triassic	"Red Beds"	Red marl with gypsum	Red Valley	

TABLE OF GEOLOGIC FORMATIONS IN NORTHERN BLACK HILLS—Continued.

PERIOD.	EPOCH.	FORMATION.	LITHOLOGIC CHARACTER.	TOPOGRAPHIC CHARACTER.	FOSSILS.
Carboniferous	Permian	Minnekahta limestone	Uniform purplish banded limestone, weathers white; strong bituminous odor when crushed.	Tessellated pavement on inner slope of Red Valley, escarpment and "gateways" of streams.	Bakewellia, Yoldia?, Edmondia?
		Lower red bed	Red sandstone, soft and marly	Inner slope of Minnekahta escarpment.	
		Minnelusa	Alternate limestones and thicker sandstones, somewhat colored.	Variegated striped cliffs and sandy hills.	
		Gray limestone, equivalent to Madison.	Massive limestone, gray, pink, or buff, sometimes cherty.	Massive cliffs, the greater escarpment.	Spirifer, Syringopora, Productus, Seminula, Zaphrentis, etc.
		Eocarboniferous, equivalent to Lowest Mississippian (Chouteau or Kinderhook).	Pink or purplish thin-bedded limestone with red iron-stained fossil mollusks. Purple or green shales below.	Frequently concealed beneath talus. Shows an apparent unconformity of erosion between it and the gray limestone above, though dip is accordant.	Fenestella, Orthothetes leptæna, Spirifer, Chonetes logani, Reticularia peculiaris, Syringothyris carteri, crinoids.
Silurian	....	Equivalent to Upper Trenton.	Peculiar spotted massive limestone, usually buff with brown or reddish spots, sandy. Very large fossils.	Bench usually masked by talus.	Endoceras, Maclurea, Receptaculites, Halysites, Streptelasma, Lituites, Orthis, annelid trails, Buthotrephis, Murchisonia.
Cambrian	....	Equivalent to Middle Cambrian of the Rocky Mountains.	Conglomerate, quartzite, ferruginous sandstones, many alternations of green shale, limestone breccias, fucoidal limestone flags; at the top Scolithus sandstone or quartzite, and thick green shales.	Walls of recent canyons or old graded slopes; usually a pronounced bench.	Obolus, Hyolithes, Dicellomus, Asaphiscus, Olenoides, Ptychoparia, Acrotreta.
Algonkian	....	....	Mica, graphite, and hornblende schists, metamorphic quartzite and conglomerate, and some pre-Cambrian intrusives.	Flat-topped plateaus and headwater valley bottoms.	

The Pleistocene and Tertiary formations have an indefinite thickness, occurring, as they do, only in the form of eroded remnants. Tertiary occurs as white clay in the basin where Lead has been built and in the saddles between neighboring hills. This clay contains fossil vertebrates, and also fragments of porphyry, hence is the product of erosion after the porphyries were intruded. This is further proved by the fact that the clays are deposited in a topography eroded far below the present porphyry summits. The material here called Pleistocene consists of rounded stream bowlders and gravel occurring in masses sometimes 50 to 100 feet thick, usually filling divides between the present streams. These remnants show the location of more considerable deposits of the same sort along ancient stream channels. The courses of these ancient streams in several cases show a significant relation to elbows of capture and valley trends which mark the changes the drainage has undergone. (See Pl. XX.)

INTRUSIVE PORPHYRIES.

LITHOLOGY.

The porphyries vary in kind from rhyolite, diorite-porphyry, and syenite-porphyry to more alkaline rocks which may be classed as phonolites and grorudites. Irving has described many of the types, and there is here a remarkable series of gradations which renders the region exceptionally favorable for study of magmatic differentiation. He has distinguished the following families:

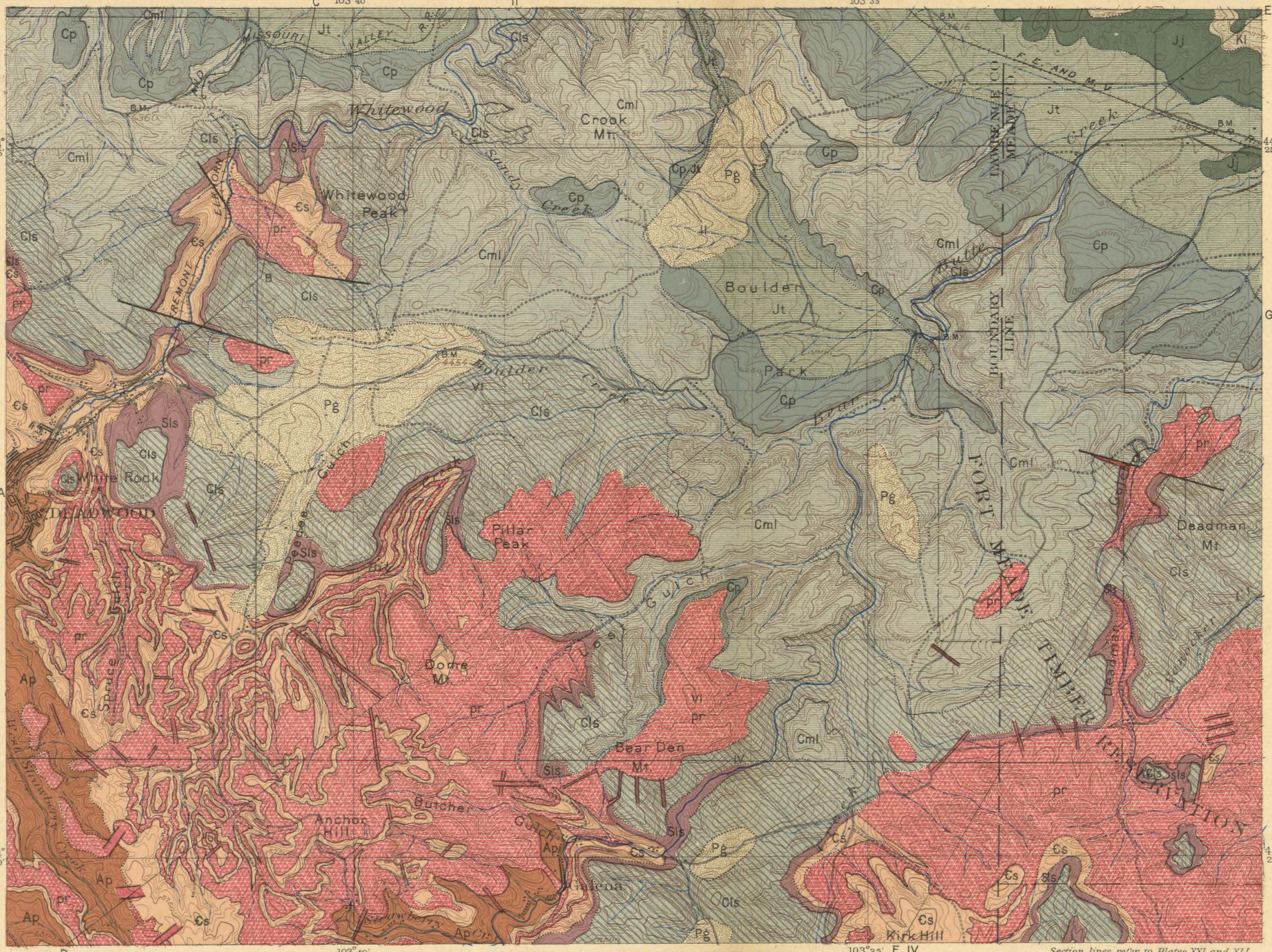
Grorudite.—Highly alkaline rocks containing orthoclase, quartz, ægirine-augite, and ægirine. In some types accessory albite, microcline, and biotite. Localities: Terry Peak, Bald Mountain, Elk Mountain, Lost Camp Creek, Annie Creek, sheet on the Burlington Railroad east of Terry Peak, and in the Sunset Mine.

Phonolite.—Rocks rich in soda, forming the more basic phase of the grorudites. Composed of orthoclase, anorthoclase, microcline, ægirine-augite, ægirine, nepheline, nosean with accessory haüyne, biotite, magnetite, titanite, melanite garnet, and possibly leucite. Localities: Ragged Top Mountain, Squaw and Annie creeks, Calamity Gulch, Mato Teepee, Green Mountain (peak next west of Bald Mountain), Whitetail Gulch, east slope of Bald Mountain, and False Bottom stock.

Rhyolite-porphyry and dacite.—Phenocrysts of orthoclase, plagioclase, and quartz in a fine-grained groundmass of quartz and feldspar; hornblende and biotite in varying amounts. Localities: Head of Squaw Creek, Foley Peak, Texana, Custer Peak, Butcher Gulch, Deadman laccolith, north side of Vanocker laccolith, Two Bit, Pluma, Bear Butte, lower portions of Sheep Mountain, Whitewood Canyon laccolith, dikes in many portions of Terry Peak district, Crow Peak, Inyankara, Sundance Mountain, and Warren Peaks.

Andesite-porphyry, diorite-porphyry, and diorite.—Porphyritic rocks containing phenocrysts of plagioclase, orthoclase, hornblende, and biotite in a fine-grained groundmass of plagioclase, quartz, and chlorite. The rock shows transitions to trachytic forms which may be called syenite-porphyry. Localities: Sills in Squaw Creek and in Ruby Basin, at the Needles, and in the region of the Vanocker laccolith.

Diorite forms the Deadwood Gulch stock above the town of Central. It is a gray



LEGEND

PLEISTOCENE

Pg — Ancient stream gravels

CRETACEOUS

Kl — Lower Cretaceous Sandstones and shales

JURATRIAS

Jj — Jurassic Sandstones limestones, and shales

Jt — Triassic Thick red marls and gypsum

CARBONIFEROUS

Cp — Permian Limestone over red sandstone (Minnekahta)

Cml — Minnelusa limestones and sandstones

Cls — Massive gray limestone

SILURIAN

Sls — Arenaceous spotted limestone

CAMBRIAN

€s — Shales, limestones and sandstones

ALGONKIAN

Ap — Phyllite, mica-shist, quartzite and amphibolite

IGNEOUS

Sills and dikes

pr — Porphyry

Faults

Observed boundaries

Approximate boundaries

Topography by W. H. Herron and Arthur Stiles

GEOLOGICAL MAP OF THE LACCOLITHIC INTRUSIVES EAST OF DEADWOOD, SOUTH DAKOTA

Geology by T. A. Jaggar Jr. assisted by J. M. Boutwell

Scale

0 ½ 1 2 3 Miles

Contour interval 50 feet

1900

JULIUS BIEN & CO. LITH. N.Y.

rock of granitoid texture, showing a tendency, however, to automorphism in the component minerals; it contains hornblende, plagioclase, quartz, biotite, and accessory orthoclase.

Lamprophyre.—A basic rock in small dikes cutting the diorite-porphyry of the Needles, and again near the head of Iron Creek; it is composed of a fine automorphic aggregate of augite and feldspar, with accessory hornblende and magnetite. Irving considers it "the final and basic representative of the soda-rich magma that constitutes the principal Black Hills eruptive series."

It will be seen from the above that the rocks represented are not unlike many others that have been described from laccolithic mountains of the Rocky Mountain region,[1] and it is not possible at present to state positively whether a sharp distinction, marking different eruption periods, may be drawn between the phonolite-grorudite and the rhyolite-andesite magmas. The evidence points rather to a gradual transition between the two. The terms rhyolite and phonolite are unfortunately associated with extrusion, and it might be less confusing to speak of these rocks as granite-porphyries and monzonite-porphyries, but their structure would hardly warrant such a terminology. In distribution the dike region of the schist area contains both phonolitic and rhyolitic rocks; the sills of Two Bit and Squaw Creek districts are in general andesite-porphyry and diorite-porphyry; the outlying thick "plug-like" laccoliths, as well as a great portion of the greater Terry and Bearlodge complexes, are mostly rhyolite. But over the rhyolite on many hills, as Terry, Deer, Bald, and Sheep mountains, occur phonolitic caps, and the mass of Ragged Top, the Spearfish Peak group of laccoliths in the Carboniferous, and Mato Teepee are phonolite. The diorite magma is represented by a great stock in Deadwood Gulch, and its porphyry forms the mass of the Needles to the west and portions of the Vanocker laccolith to the east (see Pl. XVIII).

RELATIVE AGE OF PORPHYRIES.

Differences in relative age among the porphyries certainly occur if the transection of one dike by another may be considered conclusive evidence that the second is younger than the first. This evidence, however, has no conclusive value in a single instance, for one portion of a magma might readily crystallize and split up to receive, later, injections of differentiated material originally part of the same igneous fluid. Between the solidifying of No. 1 and the injection of No. 2 the time elapsed may not have been great enough to cover the whole period of solidification of the larger masses of No. 1. If this were true a later injection of No. 1 might elsewhere cut an already solidified body of No. 2, in which case the apparent relations in age would be reversed.

[1] See The laccolitic mountain groups of Colorado, Utah, and Arizona, by Whitman Cross: Fourteenth Ann. Rept. U. S. Geol. Survey, Part II, 1893. Also, Judith Mountains of Montana, by Weed and Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898.

The preponderance of evidence would seem to show that in the Black Hills the phonolite magma as a whole is younger than the rhyolite magma. Within each of these there is probably a gradation from basic to acid, but fine distinctions are not warranted by the petrographic study hitherto given to these rocks.

Many occurrences in the field of dikes of one kind of porphyry cutting another may be cited. In the Two Bit district the greater masses of syenite-porphyry vary from a hornblende facies to one characterized chiefly by large orthoclase phenocrysts with poikilitic intergrowths of plagioclase and other minerals. Dikes which cut this rock are in general like the mass of Bear Den Mountain, which is an outlying subordinate laccolith. (See Pl. XX.) They are of trachytic, light-colored porphyry, showing pink microcline phenocrysts. They may bear some relation to the phonolites. A similar rock with amber-colored feldspar phenocrysts in a gray matrix cuts fine-grained white aphanitic rhyolite in a small dike on the Terry branch of the Fremont, Elkhorn and Missouri Valley Railroad, on the spur between Fantail and Nevada gulches (fig. 61). Near Alkali Creek, on the divide from Vanocker Creek, numerous dikes cut the fine-grained rhyolite mass. These are a purplish trachytic rock with glassy feldspar phenocrysts showing striation (probably oligoclase) and a decomposed bisilicate. Other cases of the rock with phenocrystic pink (microcline) feldspar cutting the rocks of the rhyolite-andesite series occur on the spur south of White Rock, just above Deadwood, and on the ridge west of the head of Spruce Gulch. Near the sawmill north of Kirk Hill a gray rock containing much mica and yellow feldspars occurs as a dike cutting light-gray rhyolite which shows some hornblende. It is probable that these are mostly phonolitic rocks which cut rocks of the rhyolite-andesite magma. Irving has described four cases of phonolites cutting quartz-porphyries and diorite-porphyries.

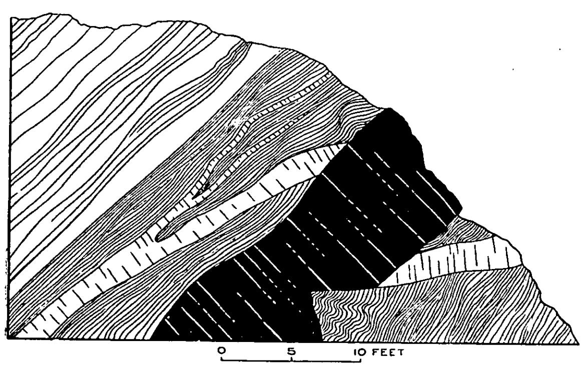


FIG. 61.—Green phonolite cutting rhyolite-porphyry, Fremont railroad, near Nevada Gulch.

A very unusual case (fig. 62) is shown in a section near Aztec on the Burlington Railroad (Spearfish branch). Here a mass of green phonolitic porphyry is apparently cut by an irregular swelling intrusion of white rhyolite of the fine-grained decomposed type so common in the region. Both occur, as shown, at a sloping dike contact with

Cambrian shales. All the evidence in this case would show the rhyolite to be the younger, or contemporaneous with the phonolite. The second alternative is the more probable. The two magmas may grade into each other, and in this case perhaps the green ægirine rock was still viscous when the stream of white rhyolite was injected through it. It is hoped that more extended study of the petrography of the region will throw light on these relations.

GEOLOGICAL AGE OF PORPHYRIES.

The geological age of the porphyries may be stated in only the most general terms. The Bear Butte and Little Missouri Buttes laccoliths were intruded into Benton Cretaceous and were unquestionably covered by Niobrara limestone. Jenney has found pebbles of Black Hills porphyries in the conglomerate at the base of the White River beds to the southeast, and similar fragments occur in the Tertiary beds at

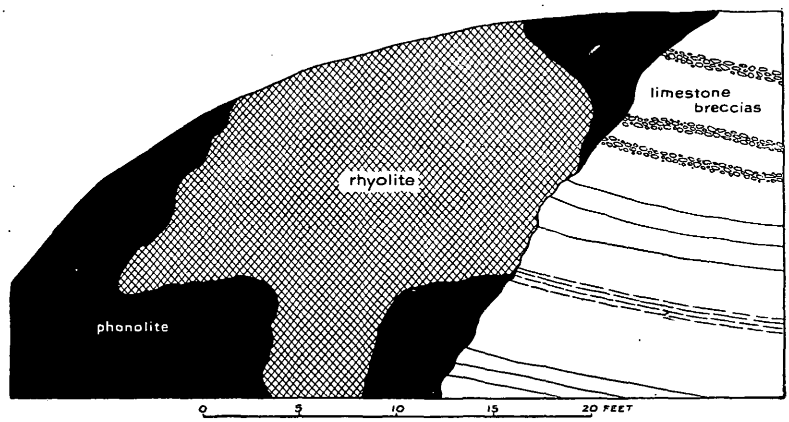


FIG. 62.—Rhyolite cutting green porphyry near Aztec.

Lead. The Lead Tertiary clays (Oligocene?) are deposited in an old topography 1,800 feet below the present porphyry summit of Terry Peak and on divides 300 feet above the adjacent gulches. As these clays were flood-plain or lake (?) deposits, of mature stage in the early Tertiary dissection of the region, an additional 200 feet may be considered a most conservative estimate of height for the original porphyry upper limit of the Terry Peak Mountains. This porphyry at the time of its intrusion was covered by a thickness of strata not less than that of all the formations below the highest beds invaded; a minimum estimate would make this not less than 2,500 feet. This would imply a total thickness of rock eroded away above the present Tertiary beds at Lead of 4,500 feet (2,000 erosion + 2,500 thickness); accordingly, the later limital epoch of the intrusion period may be expressed as the beginning of a 4,500-foot erosion period prior to the Oligocene, while the earlier limital epoch is the Niobrara. Between these there is the choice of Pierre, Fox Hills, Laramie, and Eocene times for the intrusion.

By analogy with the Rocky Mountains the greater uplift in the Black Hills probably took place after the close of the Laramie. The only evidence in the immediate vicinity of the Black Hills bearing on the question whether Laramie beds ever extended over the present site of the hills is the fact that they are tilted up by the Black Hills uplift on the west side; if they did so extend they may have attained a thickness of several thousand feet. The thickness of the Jura-Cretaceous below the Laramie is 4,000 feet.[1] If the first uplift of importance was in Eocene time and Laramie beds were present the erosion depth at Lead may be increased by several thousand feet. There are analogous intrusions of Eocene age in the Rocky Mountain district in sufficient number to render very probable the occurrence of igneous activity, concomitant with uplift, in the Black Hills at that time. That orogenic disturbances took place concomitant with intrusion is proved by the relation of the Algonkian-Cambrian contact to the porphyries at many places, the latter filling fault fissures. After the energetic erosion that led to deposition of Oligocene beds, and probably reduced the topography of the Hills to much lower relief than that of the present day, "there was a further uplift, which has given a very strong tilt to the White River deposits."[2] No porphyry now revealed can have accompanied this last uplift, which may still be in progress. By this last movement the Oligocene beds at Lead have been lifted and the present gulches have since been carved below them. The following is a summary of the evidence for the Eocene age of the eruptives:

Evidence from geology	Laccoliths in the Benton. Deformation concomitant with intrusion. Porphyry pebbles in Oligocene sediments.
Evidence from analogy	Post-Laramie uplift of Rocky Mountains. Post-Laramie intrusions of Rocky Mountains.
Evidence from physiography	Probable erosion of 6,000 to 8,000 feet of strata from above level of present Tertiary clay at Lead.

DISTRIBUTION OF IGNEOUS BODIES.

The intrusive rocks occur as stocks and dikes in the Algonkian schist, sills in the Cambrian shales where that formation is thick, and laccoliths, which in the Cambrian thin out into sills, but rise into thick domes of limited horizontal extension where the magma has broken through the massive Carboniferous limestone and escaped to higher horizons. These relations will be best understood by reference to the map, Pl. XIX, where Custer Peak, the Woodville Hills, Deer Mountain, Dome Mountain, and the Iron Creek mass represent laccoliths in the Cam-

[1] The writer is indebted to Mr. N. H. Darton for data and discussion on this question.

[2] Quoted from Mr. Darton, letter to the writer.

brian associated with the broad sill district; this in turn surrounds the schist area of stocks and dikes. Outlying masses of steep domical form which have broken through the limestone are Ragged Top, Citadel Rock, Crow Peak, Whitewood Canyon laccolith, Pillar Peak, Bear Den Mountain, Deadman laccolith, Tilford laccolith, and Bear Butte. The great mass of the Vanocker laccolith on the east is an exceptionally large body which in part has broken across the limestone. To the north Crook Mountain and Elkhorn Peak are domes of Minnelusa sandstone, where erosion has not yet revealed the porphyry.

In the schist area many hundred dikes occur, trending usually about N. 30° W., parallel to the Algonkian lamination, and this trend in a general way corresponds with that of some of the larger laccolithic groups.

Thus a line of porphyries may be drawn from Custer Peak to Crow Peak, from the Tilford laccolith to Elkhorn Peak, and from Two Bit to Polo Peak, possibly indicating an alignment of conduits beneath. At four points stocks have been indicated on the map, namely, at False Bottom Creek, Deadwood Gulch, Pluma, and a small mass east of West Strawberry Gulch; there are probably others in the hills west of Lead. The mass at Pluma is a great dike for a portion of its course, but becomes complicated with stocklike bodies, and is of such size as to warrant independent mapping. The area of sills in Cambrian shales has its best exposures on Two Bit Creek, Spruce Gulch, on the ridge southeast of Deadwood, on False Bottom Creek at Garden, along Squaw Creek, and on Annie Creek.

MECHANICS OF INTRUSION.

RELATION OF INTRUSION TO GREATER MOVEMENTS.

Many fresh cuts across contacts of porphyry with schist or Cambrian sediments afford instructive evidence with regard to the general relation of the intrusions to orogenic deformation. There are also miniature phenomena which throw light on large questions, in the same way that a laboratory experiment may be used to illustrate a principle. It has already been suggested (p. 173) that the work of an igneous body doming strata above it may be complicated with inherent tendencies in the strata to buckle under orogenic stress, and that without some such stresses fractures could not readily form to release the magma from the depths below. Throughout the Rocky Mountains igneous phenomena have accompanied colossal movements of uplift, folding, and faulting. Relative to these movements the igneous action was usually but an incident. It seems reasonable to suppose, then, that the first release of igneous matter among the Paleozoic sediments of the Black Hills took place by permission rather than by aggression. After entering the sediments doubtless the magmas under pressure acted locally as violent deforming agents. The schists, filled with dikes, were forced apart laterally, the Cambrian charged with sheets and laccoliths was greatly expanded in thickness and deformed horizontally, and the great limestone was domed up over the Terry Peak district as a whole and was locally pimpled and punctured by the small outlying masses. Thus intrusive action in the scheme of geologic deforming forces is both effect and cause; irruption is an effect of orogenic fracturing, a cause of localized doming and faulting. The fault fissures and fractures through which igneous material flowed contained necessarily more or less broken material, and the magma in its first uprush itself fractured and comminuted the rocks through which it passed. The result is a breccia, which is quite as much to be expected in association with an intrusive magma that has never reached

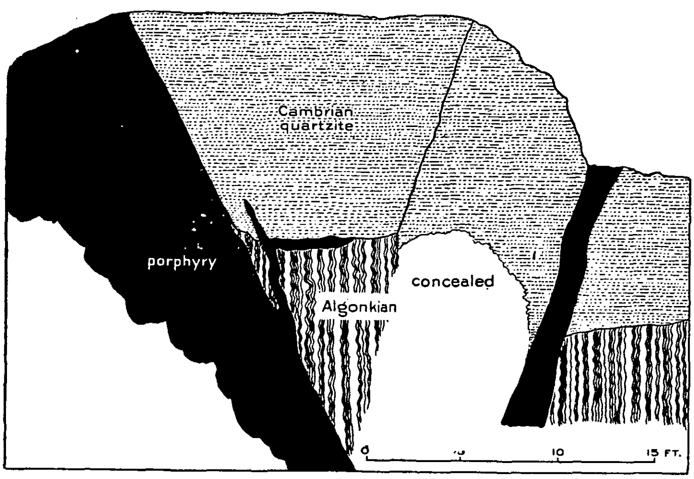


FIG. 63.—Contact of porphyry, Cambrian, and Algonkian, Nevada Gulch.

the surface as are the characteristic tuffs and breccias of volcanic eruption. Such breccias are not wanting.

FAULTING AND BRECCIATION.

In a cut on the switch line of the Fremont, Elkhorn and Missouri Valley Railroad, on the north side of Nevada Gulch, is shown a section (fig. 63) that illustrates the faulting on a small scale so frequently observed in the Ruby Basin (a local name for the Bald Mountain mining district). The sketch is made looking north. There has been slipping approximately on lamination planes of the schist to form steps with the upthrow on the west, and this movement has been communicated to the Cambrian quartzite above. Possibly the 2-foot dike on the right follows one of the slipping planes. The principal fault plane in the schist is concealed by talus. The contact of a large dike on the western side of the exposure follows an oblique joint plane across both schist and quartzite, and a small stringer from this dike penetrates the schist and spreads along the basal contact of the Cambrian. This occurrence is similar to many others in the Golden Reward mines immediately to the south, and it is in part by such step faults that the Algonkian rises so rapidly from Englewood to Nevada Gulch.

Breccias are very abundant throughout the porphyry district, but by reason of their friable nature they are naturally concealed by talus. A breccia occurring under porphyry in Hidden Treasure Gulch, and again at the head of the Homestake open cut at Lead, contains angular or roundish fragments of a banded white substance which is probably largely whitened and silicified schist. There are also fragments of graphitic schists and quartz in a brown, muddy matrix. A

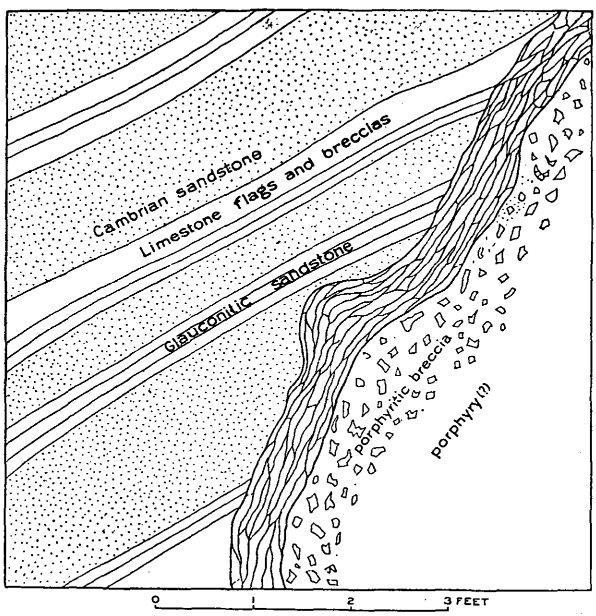


FIG. 64.—Section of contact of Cambrian sandstone and porphyry breccia near Brownsville.

similar breccia containing coarse angular fragments of hematitic schist and black graphite schist occurs near Garden. At the contact of a dike near Texana two varieties of breccia occur. One is very friable and is composed of a carbonaceous mud (evidently derived from the adjacent graphitic schist) filled with angular white fragments. The second variety contains closely crowded fragments of graphite and talc-schist and shows very little of a white chalky matrix. A specimen collected on the eastern spur of Bald Mountain shows fine-grained, white, subangular fragments (rhyolite?) in a greenish-gray matrix. The rock is hard, but contains rusty vesicular cavities. Similar breccias have been collected in Squaw Creek, Gold Run, and under the columnar porphyry capping the hill at the head of the De

Smet open cut. This relation of breccia to porphyry occurring immediately under laccolithic masses is a common one. A similar breccia containing very large fragments occurs in the Hoodoo mine, under the Union Hill laccolithic mass.

In fig. 64 is shown the contact, looking north, of a porphyry breccia with Cambrian glauconitic sandstones and limestones. The locality is a prospect hole in the southeastern end of a hill $1\frac{1}{4}$ miles northeast of Brownsville. On knolls south of this outcrop a peculiar porphyry breccia occurs in scattered outcrops for three-quarters of a mile. The breccia is probably at the base of an extension of the Custer Peak laccolith (see map, Pl. XIX), of which these outcrops are isolated remnants. A friction breccia occurs along the Cambrian contact, composed of reddish sandy material. The porphyry breccia is pink,

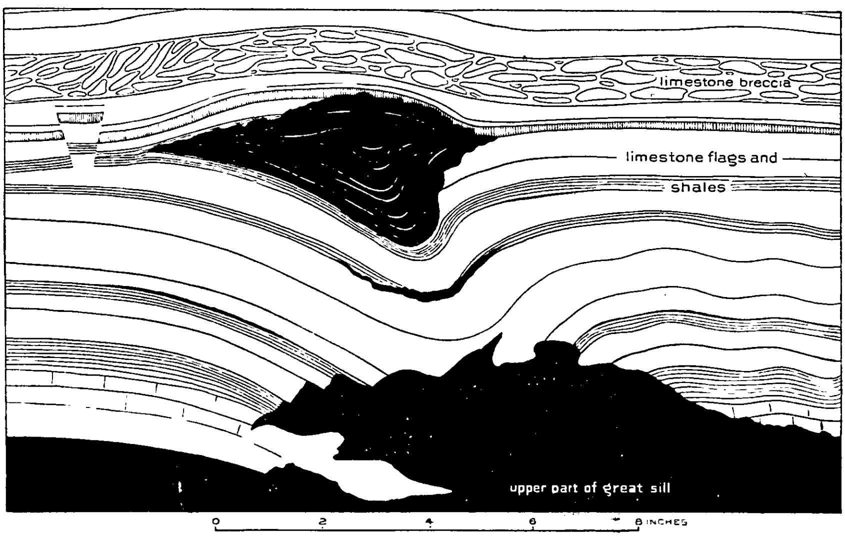


FIG. 65.—Miniature laccolith, Galena.

made up of angular fragments of banded white or pinkish rock that appears to be an altered sediment. There are many small fragments of chalcedonic substance, quartz, and pieces of dark porphyritic rocks in a hard dark-red matrix, of which very little is present. The matrix is crowded with small white angular fragments. The rock as a whole is hard and trachytic, porous, and contains rusty cavities.

That these breccias are actually contemporaneous with the igneous rock is proved by the frequent occurrence, in the matrix, of crystalline structure identical with that of the porphyry. Such breccias occur as a large dike west of upper Two Bit Creek, and on the west side of Pillar Peak. In the last case distinct feldspar phenocrysts may be seen in the matrix of the breccia. A limestone breccia from a porphyry contact on the northwestern spur of Richmond Hill shows angular fragments of gray limestone and some pieces of Cambrian sandstone in a hard, yellowish-brown siliceous matrix; here the porphyry cuts Algonkian, Cambrian, and Carboniferous. In the Little Missouri Buttes and Mato Teepee occurs a tuffaceous breccia containing fragments of many of the rocks below the horizon of intrusion, and similar fragments occur in the heart of the porphyry as well. All the breccias mentioned are occasioned by and contained in igneous rock; they must not be confused with the limestone breccias of the Cambrian, which occur as lenticular bodies among the shales and are the product of deformation quite independent of the intrusives.

INTRUSION IN MINIATURE.

It will be seen that the essential features of the intrusion of sills and laccoliths are a molten mass impelled from below and strata variously

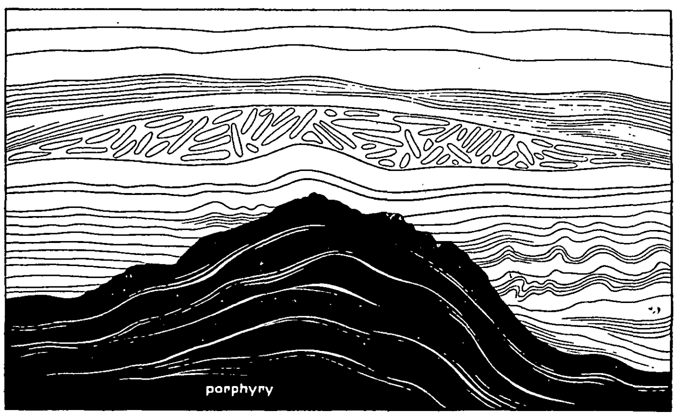


FIG. 66.—Upper contact of sill, Galena.

shaly and massive. These features may occur in miniature as well as on a large scale, where in thin-bedded series alternate bands of shale and limestone occur, as in the Cambrian, and where the intrusive is sufficiently liquid to penetrate among the individual beds. Instructive miniature phenomena occur along contact walls of sills and dikes, and it is interesting to compare these phenomena with those of larger masses, which can never be so completely observed in cross section. The upper contact of a sill, 12 feet of which is exposed under the Sitting Bull mine, opposite the smelter at Galena, shows a number of irregular offshoots, and these locally deform the Cambrian bedding. The most striking of these, shown in fig. 65, is a miniature lens or laccolith of phonolite injected obliquely through a split in the strata above the greater sill, arching up the limestone flags above and *bending down those below*, so that they are fractured and gape open in contact with the greater mass of porphyry, and have spread apart to receive the injection of a little sill *under* the lenticular body. The greater mass below was evidently liquid or viscous at the time the smaller mass opened its fissure. The latter, an offshoot of the greater mass, could not, by hydrostatic pressure alone, bend down the folia against the larger liquid body at a lower level. It seems probable that the down-bending was occasioned by differential contraction of the two masses while solidifying. Small faults and crumples at the side of these miniature domes are common along this contact, and frequently the cross section shows domelike projections from the greater sill (see figs. 66 and 67) which arch the beds above them and also cut across the flags, limestone breccias, and shales to a certain extent. The arching produced locally in this fashion is usually completely absorbed a foot or two above the eruptive, so that the higher beds are quite horizontal. Flow lines parallel to the contact are common, and in the case of the small lenticular body (fig. 65) they show that solidification

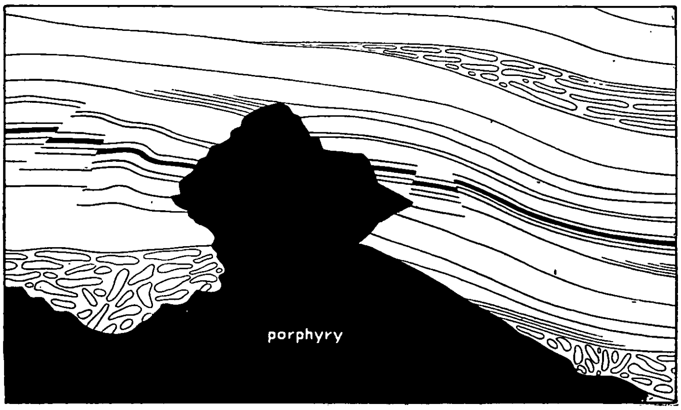


FIG. 67.—Upper contact of sill cutting limestone breccias, Galena.

on the walls was succeeded by an inflow of more of the fluid in progressively smaller cross section.

PSEUDO-CONGLOMERATES.

Besides the dip away from the core of the Black Hills, which uniformly on the rim of the uplift indicates deformation of once horizontal sediments by forces other than those immediately generated by the recent intrusives, there is interesting evidence presented by the limestone breccias which are so abundant in the Cambrian. These occur in lenticular masses, sometimes merging into unbroken limestone flags interspersed among beds of green shale, the flags carrying trilobite fragments. These fragments of trilobites may also be seen in the flat or rounded "pebbles" of the limestone breccias, and this bars the possibility, suggested by Crosby,[1] that these breccias are conglomerates derived from an Algonkian limestone. The breccias in question were

[1] Proc. Bost. Soc. Nat. Hist., Vol. XXIII, p. 497.

formed by crushing, accompanied in some cases by minute foldings of the limestone bands, the brittle laminæ breaking on the most acute flexures, or else breaking into flat pieces under the influence of pressure without any considerable flexure.

Infiltration of waters which dissolved off the edges and corners of these broken fragments, later cemented the mass by depositing crystalline dolomite as a matrix for the pseudo-conglomerate. These "intraformational breccias" are abundant in the Two Bit district, where are also many sills and dikes of porphyry, and the question frequently arises in the field whether the deformation which fractured the limestone beds and the waters which cemented them were in any way associated with the intrusives. A negative answer to this question was clearly afforded by the upper contact of the sill figured (fig. 67). In the lenticular masses of limestone breccia here shown there are developed locally distinct folds, which pass by gradations into a breccia, holding fragments tilted at all angles, frequently without order or arrangement. Careful examination shows that often these may be resolved into former folds by joining the adjacent "pebbles." The work of solution and recrystallization on the fractured bends has nearly obliterated the original crumpling.

This locality, showing distinct crumpling occasioned by the porphyry in some of the beds and the ancient crumpling associated with the development of the pseudo-conglomerates, offers an excellent opportunity to test the question whether the porphyry was immediately the occasion of the brecciation. The contact shows distinctly that it was not. The limestone breccias are irregularly cut across by the porphyry both on the old folds and in places where all trace of folding has disappeared. In other cases where fragments of the breccia still remain horizontal the porphyry cuts across fragments and matrix alike. The unbrecciated limestone bands are occasionally folded and fractured by the porphyry, and on the fractures there is evidence of some recrystallization, so that it is not impossible that in places a newer breccia may owe its origin to deformation by intrusion; but in most cases the limestone breccias of the Cambrian were formed before the intrusives. This is further evidenced by the fact that these breccias occur in many parts of the Hills where the younger eruptives are absent, so that it is fair to conclude that the evidence indicates a period of deformation later than the Cambrian and earlier than the laccolithic intrusives. Similar limestone breccias occur less abundantly in the Carboniferous and Permian limestones. Weed has figured[1] a Cambrian limestone conglomerate from the Judith Mountains that in the photographic illustration is the exact counterpart of the Black Hills

[1] Judith Mountains of Montana, by Weed and Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, Pl. LXX. Also, Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, Part III, 1900. Pl. XXXIX.

Cambrian beds. He believes it to have been formed on a shingly beach. The writer would suggest that possibly many supposed conglomerates may be intraformational breccias[1] composed of limestone fragments, formed by crushing and recrystallization of matrix, as described, rather than by uplift above sea level.

TOPOGRAPHY OF PORPHYRIES.

In general the topographic effect of the porphyries is to produce strong elevations, either by their own resistance to erosion or by concomitant induration of the adjacent sediments. Dikes in schist sometimes form conspicuous ledges, in other cases valleys, as in the case of the great dike at Pluma. Sills in the Cambrian may make slight benches on graded slopes or merely color bands in canyon walls. Laccoliths, according to the degree of their uncovering, may form hollows, hills, or mountains. Their physiography is discussed more fully in Chapter III.

The weathering of the fine-grained rhyolite is frequently more conspicuous than that of the phonolite, which in this district is notably fresh. Often the rhyolite shows a remarkable red staining in spherical shells throughout joint blocks; the large proportion of orthoclase accounts for the decomposition to kaolin. Frequently both quartz-porphyries and phonolites weather into spheres with concentric shells.

[1] C. D. Walcott, Bull. Geol. Soc. America, Vol. V, pp. 191-198.

CHAPTER II.

LACCOLITHIC INTRUSIVES.

LITERATURE.

WARREN, HAYDEN, AND WINCHELL.

The earliest references to eruptive porphyry in the Black Hills occur in the reports of Warren,[1] Hayden,[2] and Winchell.[3] Warren mentioned Inyankara Peak, Bearlodge, the Little Missouri buttes, and Bears Peak (Bear Butte) as "volcanic." Hayden described Bear Butte as an "isolated protrusion" of igneous rock, surrounded by "disturbed beds forming annular ridges." Winchell visited Inyankara and Bear Butte; the former he described as a "single isolated outburst," greatly tilting and shattering the Carboniferous limestone, and but little affecting the Red Beds, which he believed unconformable above the Carboniferous rocks. The Bear Butte igneous mass he considered "thrust up after the deposition of the Carboniferous limestone. * * * As to the origin of this rock, it is undoubtedly eruptive." In the cases of both Bear Butte and Inyankara, Winchell notes the significant facts that "on the side toward the hills, in each case, the encircling ridge [of sediments] is low or wanting." None of the earlier explorers defined clearly the intrusive nature of the eruptive rocks.

NEWTON AND JENNEY.

In Newton and Jenney's more complete report[4] explicit descriptions are given of the several eruptive peaks, and these will be referred to in the following pages. Newton and Jenney recognized the intrusive nature of the igneous bodies, though the word "extrusion," used presumably in the unusual sense of irruption, or rushing in of igneous material, leads to some confusion in Newton's text. The following quotations will show the more general facts and theories developed by the Newton survey:

The volcanic peaks are curiously limited within the region of survey by a parallel of latitude. The line of 44° 10′ divides the uplifted area * * * into equal parts.

[1] Explorations in Nebraska and Dakota in 1855, 1856, 1857, by G. K. Warren, Engineer Department, U. S. A., Washington, 1875, p. 30.

[2] Geological Report of the Exploration of the Yellowstone and Missouri rivers, 1859-60, by F. V. Hayden, Washington, 1869, p. 42.

[3] Geological Report on the Black Hills, by N. H. Winchell; Reconnoissance of 1874, by Captain William Ludlow, Engineer Department, U. S. A., Washington, 1875, pp. 17, 37.

[4] Report on the Geology and Resources of the Black Hills of Dakota, by Henry Newton and Walter P. Jenney: U. S. Geog. and Geol. Surv. Rocky Mountain region, Washington, 1880, pp. 189, 219, 283.

South of the line there is no volcanic peak either in the Hills area or in the vicinity; north of it they dot the country in every direction. They do not seem to bear toward one another any relation of distribution or intensity of igneous action. * * *

The main points of eruption are as follows: Within the area of the Hills proper, Custer, Terry, and Crow peaks, and Black Butte [Spearfish Peak]; northeast of the hills, on the edge of the plain, Bear Butte; in the Red Valley, on the northwest side of the Hills, Inyankara, Sundance Hills, a nameless peak [Black Buttes] northeast of Inyankara, and Warren Peaks of the so-called Bear Lodge Range; on the Belle Fourche, Mato Teepee or Bear Lodge; and near the head of Little Missouri River, the Little Missouri buttes.

Specimens from nearly all the prominent peaks have been critically examined by Mr. Caswell, who finds that they have a common facies, although some fall into the division of rhyolite and others into that of sanidin-trachyte [phonolite and ægirine rocks].

In the structure of the peaks the first fact that strikes the observer is their uniformly conical shape. To this rule Bear Lodge is the only exception, and this, with its symmetrical columnar shape, is the most remarkable of all. The peaks appear to be merely pointed or conical waves of igneous rock forced upward through the sedimentary strata which are found disturbed and turned up around them only in their immediate vicinity. The metamorphism of the upturned strata is limited in extent, reaching only a few feet from their contact with the igneous rocks. There was observed no evidence of any overflow of the igneous matter, but it is confined exclusively to the cores of the peaks. The view that they are the cores of extinct volcanoes or centers of igneous overflow is scarcely warranted by the observed facts. * * * It would appear that the igneous peaks, instead of being the product of violent volcanic action, are situated at a great distance from the central and maximum region of igneous action; and that instead of the material being ejected with great violence and at such a temperature as to cause it to overflow readily, it was forced forward through the sedimentary strata under great pressure and at such a temperature as to make it plastic rather than fluid. The occurrence of these trachytic peaks appears like a great *pustular outbreak*[1] on the *surface* of the northern end of the Hills, whereby the deep-seated igneous forces were relieved, or like the appearance of bubbles on the *surface* of a kettle of boiling tar.

The displacements associated with the igneous rocks modify the form and destroy the simplicity of the great displacement, but they have no discernible relation to it except the relation of superposition. Whether they were formed before or during or after the uprising of the great arch, there is nothing in their distribution to suggest that they are in any wise dependent upon it or closely related. Some of them are near the crest of the arch, some are where the rocks are steeply inclined at the sides of the arch, many are on the gentle slopes of the northern prolongation, and at least one is entirely outside of the hills. They are so much smaller than the protuberance on which they rest that they seem to be merely *superficial* phenomena—a sort of skin disease upon the *surface* of the tumor.

In the above theoretical discussion by Newton the word "surface" and reference to a "skin disease" show clearly that he conceived the porphyries to have been covered by no very deep mantle of sediments; the suggestion is of viscous fluids blistering a thin superficial layer. That this was his idea is borne out by his reconstruction of the Black Hills dome with a minimum of only 600 feet of strata above the Dakota sandstone (p. 205). Newton indicated the period in which the porphyries were intruded as lying between Benton Cretaceous, the strata

[1] The italics here and below are the reviewer's.

invaded by Bear Butte, and White River Tertiary, where porphyry pebbles occur in a basal gravel deposit; but he states clearly that "the date of igneous activity is very far from established, and its relation to the uplift of the hills is not even determined."

CROSBY AND CARPENTER.

Crosby, in 1888,[1] mentioned the presence of true laccoliths in the Black Hills. Carpenter,[2] in the same year, speaks of Bear Butte and Mato Teepee as "volcanic plugs." Of the others Carpenter writes as follows: "Some of these bodies appear to be true laccolites, among which may be mentioned Terry's Peak and Black Butte. Some upward bulges, like Little Sundance Mountain, resembling Gilbert's 'Pulpit Arch,' I formerly believed to mark the position of uncovered laccolites, but they probably marked only the position of plugs of volcanic matter like the Bear Lodge [Mato Teepee], and present, possibly, the same appearance that it did before the removal of the Cretaceous from around it."[3]

RUSSELL AND PIRSSON.

Russell (1896) proposed for these intrusions the name "plutonic plugs," without, however, defining very precisely the distinction between a plug and a laccolith. "They differ," he states, "from the laccolites described by G. K. Gilbert[4] in the fact that the molten rock did not spread out horizontally among the stratified beds so as to form "stone cisterns," although some of the hills named, which had not been examined by the writer, may reveal this structure when more thoroughly examined. * * * As they are composed of igneous matter forced into sedimentary strata and have a plug-like form, it will be convenient to call them *plutonic plugs*." Mato Teepee and Little Sundance Dome (Green Mountains) are cited as the two extreme types of plugs, the first an eroded remnant where "the arch of stratified rock which once surmounted the summit of the plutonic plug has been completely removed and the surrounding strata eroded away," the second "an unbroken dome of stratified rock arching over the summit of a concealed mass of plutonic rock."[5] Russell's view has been somewhat the subject of controversy. Pirsson[6] in commenting upon it believes "it is impossible to conceive that the tall, shaft-like mass of Mato Tepee, with a vertical columnar structure whose columns

[1] Geology of the Black Hills of Dakota, by W. O. Crosby: Proc. Boston Soc. Nat. Hist., Vol. XXIII, 1888, pp. 488-517; Vol. XXIV, p. 11.

[2] Preliminary Report of the Dakota School of Mines, Rapid City, 1888, by F. R. Carpenter. Notes on the Geology of the Black Hills.

[3] Ibid., p. 50.

[4] Report on the Geology of the Henry Mountains, Washington, 1877.

[5] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, 1896, p. 23.

[6] Geology and mineral resources of the Judith Mountains of Montana, by W. H. Weed and L. V. Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, p. 582.

are several hundred feet long, can be a volcanic plug in a condition anywhere near approaching its original horizontal diameter. The mechanics of the jointing of igneous rocks forbids such a supposition, and we must believe that it represents only a still uneroded fragment whose vertical walls are produced by the columnar structure of a mass which formerly was of much greater lateral extension and possibly of laccolithic form."

IRVING.

A valuable paper by J. D. Irving[1] has recently been published, in which the conclusion is reached that the most important influence on the form of an intrusive body is the character of the sedimentary rocks invaded. With the following conclusions by Dr. Irving, the present writer is heartily in accord:

> In the Algonkian areas, where the schists and slates are tilted on end, the lines of least resistance lie in an approximately vertical direction, and we have a great profusion of dikes, conforming * * * to the strike and dip of the slates. So soon, however, as the eruptives reach the Cambrian formation * * * the lines of least resistance lie in a horizontal direction, and eruptives on encountering the heavier members of this formation have found it easier to insinuate themselves between the easily cleavable shales and sandstones than to break through the heavy overlying rocks. Therefore we find the predominant type of intrusion in the Cambrian formation to be the intruded sheet. * * * If the intruded mass has been large and the force of intrusion great, not only has the rock spread out between the sediments, but it has domed up those which overlay it, producing a laccolite.

Irving notes, further, that higher intrusions, doming up and breaking through the massive limestones of the Carboniferous, have "small thick-set" forms. He believes that Professor Russell "would have modified his views very much had he been able to see the eruptive region of Terry Peak."

It will be seen by the foregoing brief summary of what has been written on the younger igneous rocks of the Black Hills that there is some diversity of opinion concerning the form of the eruptive bodies and the dynamic conditions by which they originated. They have been variously described as volcanic and plutonic plugs, extrusions, sheets, overflows, laccolites, pustular eruptions, protrusions, and outbursts. One writer,[2] who visited only outlying subordinate laccoliths, remarked on the absence of dikes, finding no evidence as to "how the stratified beds below the domes that covered the plugs were displaced, *or perhaps fused*, so as to furnish room for the passage of the intruded material." In the mining districts, one continually hears mention of flows and overflows—the error arising from reverse conditions to those of the outlying districts—the region being characterized by

[1]A contribution to the geology of the northern Black Hills, by John Duer Irving: Ann. New York Acad. Sci., Vol. XII, No. 9, p. 187 et seq.
[2]I. C. Russell, loc. cit.

dikes which bend into uncovered sills and by irregular cross-cutting lower contacts of laccolithic bodies. The natural inference from narrow and localized experience here is that these rhyolites welled up and overflowed an eroded surface, no cover being now visible.

All the intrusions hitherto described and a number of others not recorded have been visited with a view to the preparation of this paper, and in this chapter the facts of observation are presented. As far as possible the theoretical conclusions deduced from these observations are reserved for a later chapter.

LACCOLITHIC INTRUSIVES OF DEADWOOD DISTRICT.

GEOLOGICAL MAP.

The accompanying geological map (Pl. XX) is of a portion of the Sturgis quadrangle (see Pl. XVIII) showing the Two Bit mining district in the region east of Deadwood and the intrusive masses northwest of the town of Runkel. These two districts are separated by a synclinal valley, the syncline being formed by the depression between the domical uplifts occasioned by the greater intrusions. Detailed study in these districts has thrown much light upon the dynamics of intrusion characteristic of the younger porphyries in the Black Hills, and it will be well to describe in some detail the laccoliths here as types from which may be drawn general conclusions that find confirmation in other localities.

The southern part of the map (Pl. XX) shows, in Two Bit Valley and on the hills east and west of it, a complication of intrusive sills and dikes in Cambrian dolomitic flagstones and shales, which can not be adequately represented on a map of this small scale. The most conspicuous feature in the field is the large number of sills, varying in thickness from 2 to 30 feet or more, and at a number of localities these are cut across by dikes, or themselves break upward obliquely across the strata, merging into other masses at higher horizons (Section D–E, Pl. XXI). In Two Bit Canyon good sections are exposed, but in the upper part of the valley the rounded hills covered with débris frequently show these alternations of porphyry and shale only by lines of surface float or in artificial diggings.

On the southwestern border of this map, and along Strawberry Creek on the extreme southern border, the Algonkian rocks are shown cut by numerous dikes, which pass up into the Cambrian series and form the conduits through which many of the higher sills and laccolithic masses were intruded. The base of the Cambrian, for a distance of about 5 miles south-southwest from Deadwood, forms a continuous escarpment, through which the porphyries have broken at many points, the quartzite dipping gently to the northeast, forming a wall along the crest of Strawberry Ridge, through which here and there a deep chasm marks the presence of a dike. On the northwestern dip slope of this ridge is usually found a cap of porphyry, frequently eroded away from the immediate summit of the escarpment, but leaving traces of its lower contact with the quartzite in the shape of irregular nodules of white quartz, which are characteristic of the contact zone where the porphyry sill and quartzite are seen together, as on the spur just south of Deadwood. At a higher point of the escarpment, near the head of West Strawberry Creek, there is some appearance of faulting, the Cambrian strata being broken across obliquely by the porphyry, and the basal beds of the Cambrian lying at a much lower level on the southwestern side of the valley than on the northeastern, where they appear to have been pushed up by the porphyry. In this case, as in others to be mentioned, the trend of the fault plane is NW.-SE., and the faulting appears to have been contemporaneous with the intrusion. This trend conforms with the general strike of the sediments here on the northeastern side of the Black Hills uplift. Mention has been made of the northeast dip shown by the quartzite. This dip is enhanced by the intrusives at many points; but far to the southeast, where intrusives are absent, a uniform dip toward the east is observed on the Algonkian slope, indicating that orogenic forces had produced the monoclinal structure as a whole, quite independently of the intrusive forces.

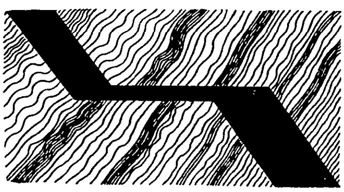
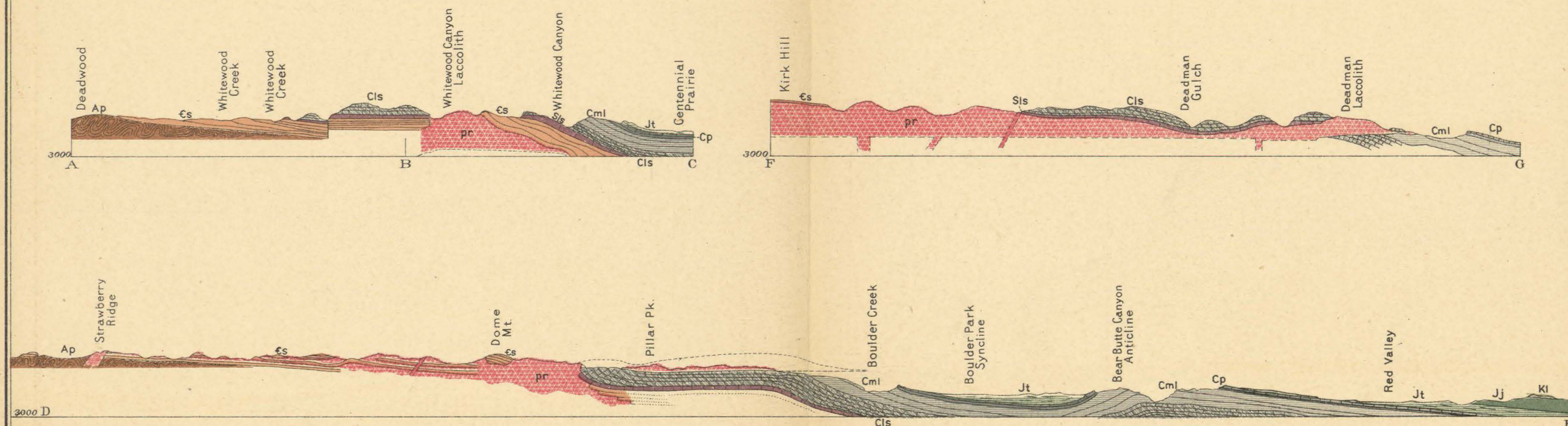


FIG. 68.—Crooked dike in schist, Deadwood.

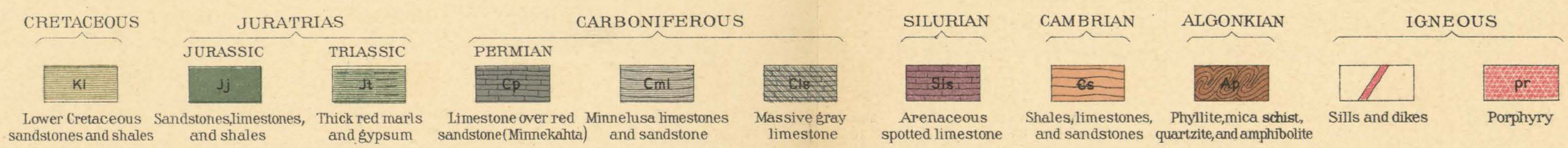
DIKES IN SCHIST.

In the wall of Algonkian schist opposite the Burlington station at Deadwood several small dikes, varying in thickness from 6 inches to 2 feet, follow very irregular fissures. In fig. 68 is shown one of these that illustrates the manner in which the rock gaped apart at the time of intrusion. It will be seen that the dike followed a crook or bend in a pair of matched joint surfaces, and had the movement of gaping been normal to the course of the joint as a whole the thickness of the dike would have been the same at the crook as elsewhere. Instead, the dike is thinner between the bends, showing that the rock moved apart to permit the injection (or was forced apart by it?) more readily in a horizontal than in a vertical direction. On the hill slopes east and southeast of Deadwood are shown good examples of the transition from the zone of dikes to that of sills in the Cambrian, and in these places there is considerable faulting on a small scale, which is one of the striking features of the mining district. In many places there is evidence of small dislocation in the Lower Cambrian beds, caused by movements of slipping on the laminæ or joints of the Algonkian schists beneath.

In a small open cut on the west side of Whitewood Creek, on the



LEGEND



STRUCTURE SECTIONS ON LINES A-B-C, D-E, AND F-G, PLATE XX

By T. A. Jaggar Jr., assisted by J. M. Boutwell

Horizontal and vertical scale

1 ½ 0 1 2 3 4 MILES

1900

JULIUS BIEN & CO. LITH. N.Y.

spur just south of Deadwood, occurs the curious mixture of beds, due largely to faulting, shown in the accompanying diagram (fig. 69). A sill of porphyry some 5 feet thick, similar to others that are conspicuous in the cliffs above, caps the spur in the section exposed, and both over and under this are a few feet of glauconitic shaly beds of the Cambrian carrying *Obolus*. These dip northeasterly at a low angle, and rest directly upon the upturned edges of the Algonkian beds, which show some crumpling and confusion at the contact. This indicates that there has been movement directly along the base of the Cambrian, and the entire absence of quartzitic or pebbly layers, elsewhere characteristic of this horizon, indicates that this contact is not the normal unconformity. Such horizontal slipping parallel to the Cambrian contact is probably a result of movements of lateral extension in the schists when they were invaded by dikes, which necessarily forced

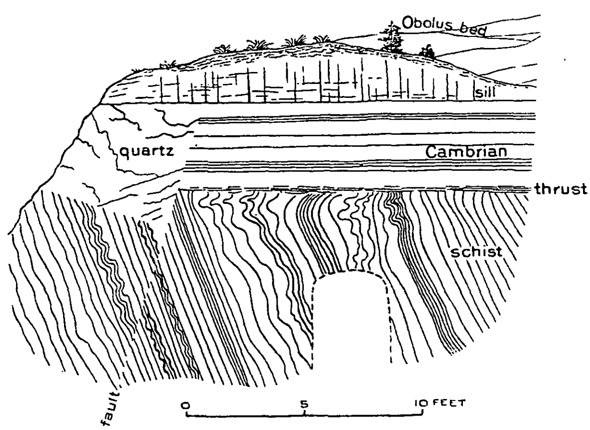


FIG. 69.—Outcrop showing faults, spur south of Deadwood.

apart and thickened the whole Algonkian series. On the western side of the outcrop, separated from the shales and the Algonkian alike by a "vertical"[1] (here a small upright fault plane), is a huge triangular mass of white quartz some 12 feet in diameter, apparently faulted into place as a solid block. In this case the slipping plane does not conform with the Algonkian laminæ, but intersects these on a transverse joint. There is no evidence in this place that the fault dislocated the porphyry above; the latter would seem rather to be younger than, or contemporaneous with, the movements in the rocks below.

Higher on this hill, to the eastward, other porphyry sills occur, and these sills may be differentiated megascopically by the occurrence or absence of large phenocrysts of quartz. In the lower sill these phenocrysts are absent, but in the sill next above they are visible. On following the hill along its south side, the lower sill, 5 feet thick at

[1] A local mining term.

the point of the spur, was found thickening eastward, 20 or 30 feet of the fine-grained rock being exposed under the Obolus shale horizon. The beds here dip to the northeast, but show a tendency to curve downward to the northwest along the general strike over the porphyry. This lends additional confirmation to the supposed identity of this sill and the one first mentioned, and the evidence shows that in a distance of a few hundred feet a 30-foot sill thins to one whose maximum thickness is not greater than 6 feet. In such a case as this the inspection of a single outcrop would give but slight evidence of thinning; many cases studied indicate that such thinning in short distances is very common (cf. fig. 76). On the northern side of this spur the Obolus sandstone is found resting on the Algonkian schist, without any porphyry visible, presenting evidence that the sill has completely thinned out to the northward.

In an open cut opposite the Hoodoo shaft on Strawberry Creek a fault cutting Algonkian and porphyry alike is exposed (fig. 70). The northwest wall of the cut shows a triangular mass of porphyry bounded on one side by an oblique thrust plane that cuts across the schistosity. The latter here trends northwest and dips 50° to the southwest. A second lenticular tongue of porphyry is seen to thin out downward. The igneous contacts of both porphyry masses conform to the schistosity, and in this respect are like the greater number of dikes in the Algonkian. Similar contacts are exposed in the tunnel of the Dakota Maid, on the north side of Strawberry Gulch. These dikes are direct feeders of the large laccolithic mass of Union Hill, hence the 50° W. dip of their walls is significant (see Experiment IV, p. 298). The southern wall of this open cut shows two sets of joints in the schists, crossing each other, each making an angle of 60° with the horizon, one trending N.-S., the other S. 30° W. In the eastern end of the cut there is an upright lenticular mass of porphyry 18 feet thick in the middle and tapering rapidly, with northerly trend across the schistosity. These porphyries are of the older rhyolite series.

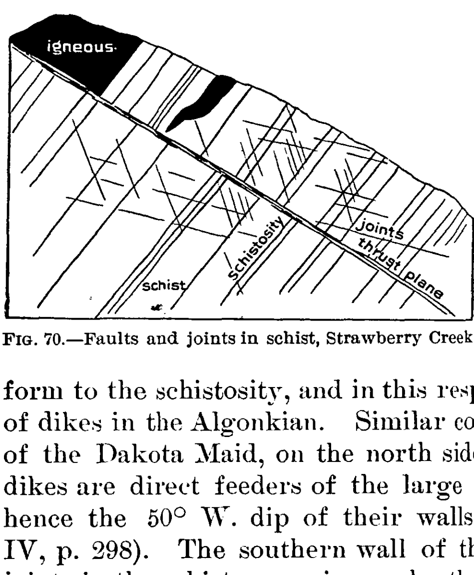
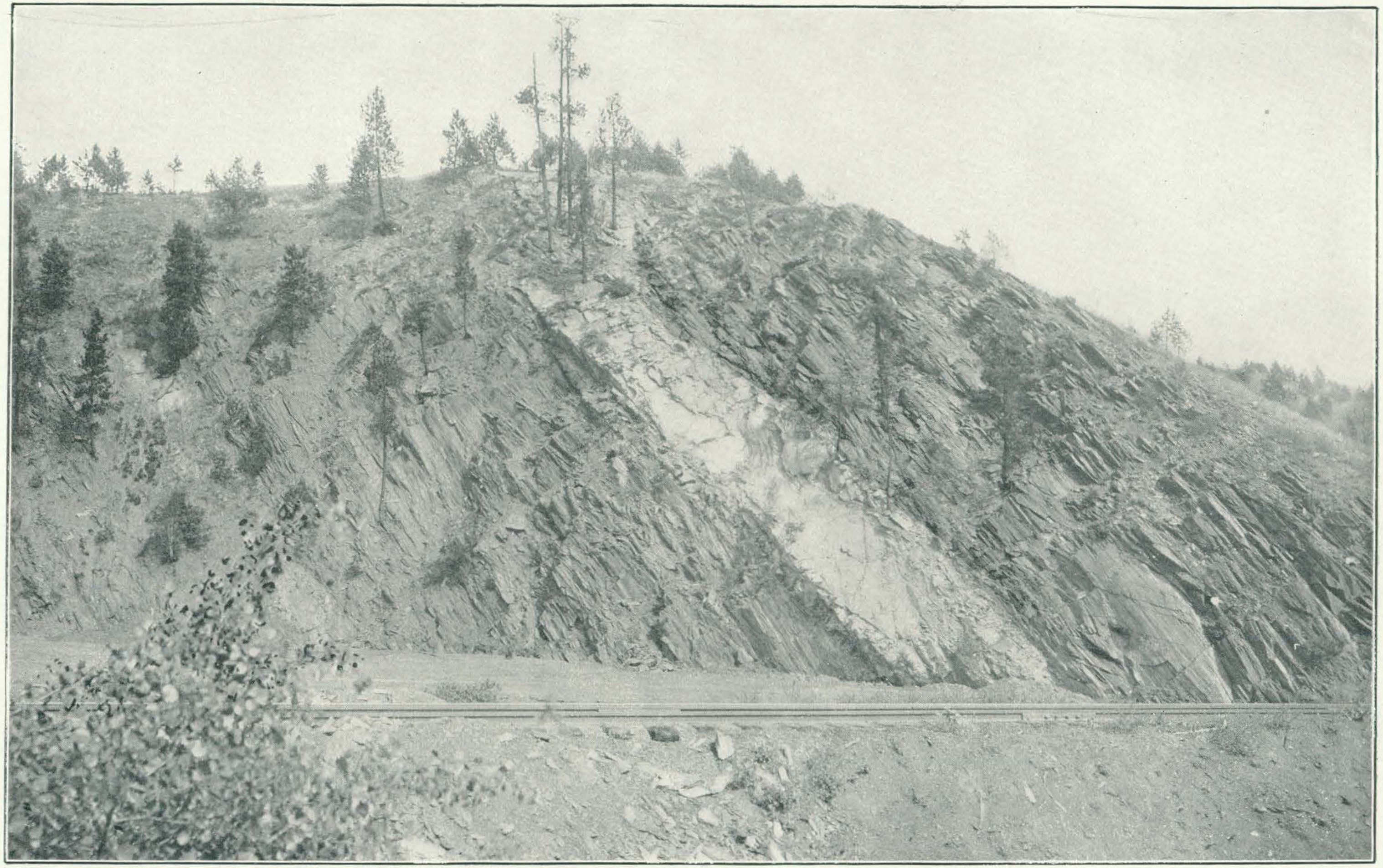


FIG. 70.—Faults and joints in schist, Strawberry Creek.

TRANSITION FROM DIKES TO SILLS.

The dikes filling fissures in the schist on planes of schistosity have in general a trend west of north, to correspond with the Algonkian strike. The inclination of the schistosity varies at angles between 45° and the vertical, being sometimes to the east and sometimes to the



RHYOLITE DIKE IN SCHIST, NEAR DEADWOOD.

west. Throughout the schist area west of Lead the Algonkian dip is westerly as a whole. Between Lead and Deadwood it is easterly, and a sharp fold, accompanied by fracture, is indicated by the change in dip about the region of the Homestake ore body. A dike in easterly dipping schist on the line of the Burlington Railroad near Deadwood is shown in Pl. XXII. This dike shows a slight tendency to develop short columns on the border, with a wide, massive medial portion. It will be readily understood that an igneous mass rising through an inclined fissure to the Cambrian unconformity would spread, on reaching the thin-bedded shales, in the direction of its inclination from the vertical. Some such inclination of the conduits upward and eastward, in the region east of Deadwood, where there is a recurrence of west-dipping schist (sections, Pl. XXI), accounts for the prevalent tendency of the porphyries to spread to the northeast (Experiment IV). In a railroad cut near the cemetery south of Lead, on the divide between Lead and Whitetail Gulch, is an exposure of reddish schist under

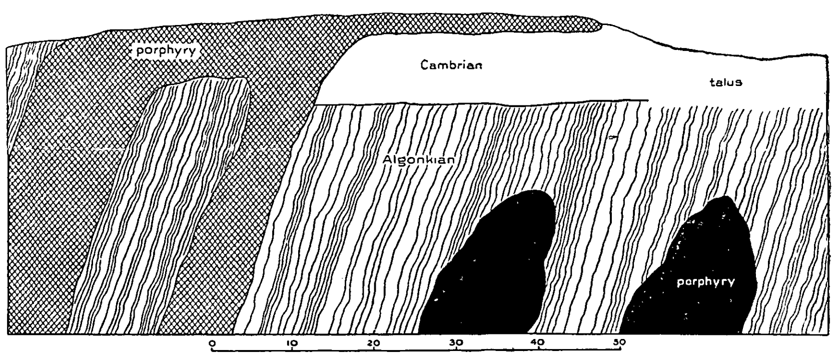


FIG. 71.—Section near cemetery, Lead.

Cambrian beds (fig. 71). Looking south in the cut, the dip of schist laminæ is seen to be eastward, and two dikes of fine-grained white rhyolite, in general parallel to the schistosity, pass up into the Cambrian, where they merge into a sheet extending to the west, the upper portion of which is eroded away. As shown in the figure, some faulting of the schist concomitant with intrusion is suggested by the progressive elevation of the upper schist surface eastward from the dikes. This may, however, be due simply to the lifting effect of the intrusions on the side of the hanging walls. On the east two dikes of dark green phonolite end in irregular bosses without reaching the Cambrian beds. These are lithologically identical with a sill and other dikes on the south side of the same hill (above Whitetail Gulch), and with the tabular columnar cap of the spur across Whitetail Gulch to the south. The rhyolite is the same as that which caps all the hills about the Homestake workings, and elsewhere on this same hill it is seen as a cap of some size. The structure is the same as that of the dikes in the Homestake open cut, where, looking north, they are seen to bend into sills which spread to the west (Pl. XXIII and fig. 72).

At the northwest end of Strawberry Ridge an interesting series of dikes passing directly from the Algonkian into the Cambrian is exposed. A 40-foot dike trending north cuts the quartzite obliquely across its strike. There is some slight suggestion of faulting locally in the quartzite on opposite sides of these dike fissures, but it is slight. The downthrow is to the north. Farther along to the northwest a break of 250 feet occurs in the quartzite ledge, occupied by a complex of dikes, and still others are seen beyond. In this case the composition of the rock varies, after the fashion of a composite dike; for a thickness of 75 feet on either side the rock is rhyolitic, while the middle 100 feet is coarser, showing large white feldspar laths.

A remarkable feature of the sandstone in contact with these dikes, also characteristic of the upper surface of the quartzite escarpment, is the occurrence of milky quartz in the form of infiltrations of irregular outline, sometimes filling cavities in the surface of the rock, but not in the form of veins.

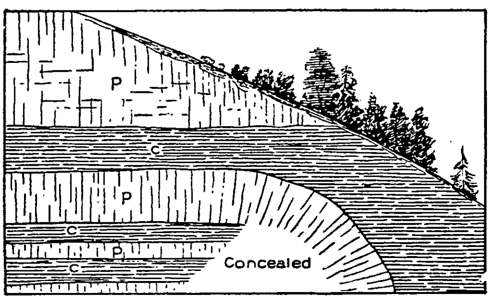
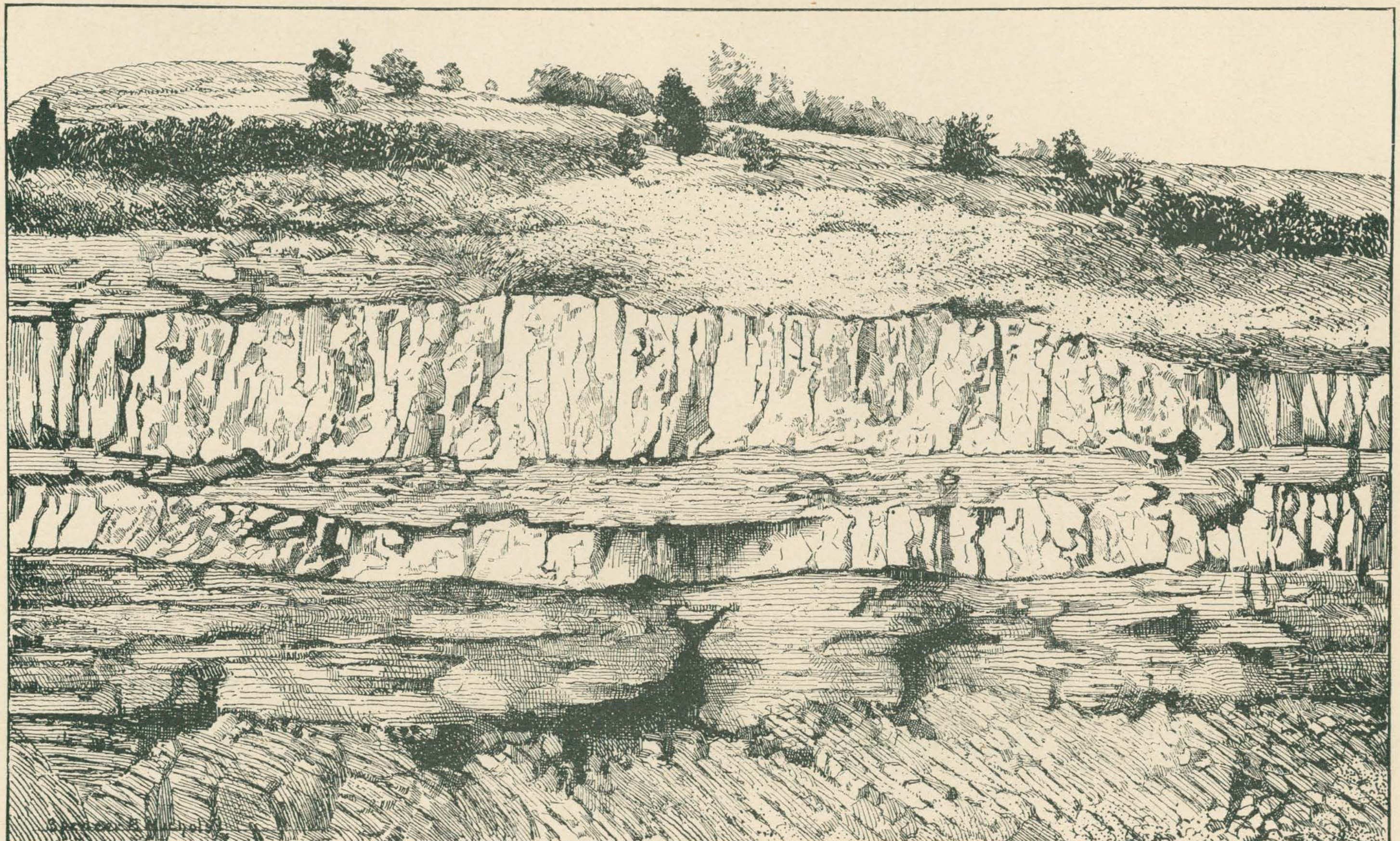


FIG. 72.—Dike curving into sill, Homestake open cut.

South of the main quartzite escarpment of Strawberry Ridge occurs a lower bench of massive white quartzite, forming cliffs 40 feet high capped by reddish shales which carry the usual white shell fragments (*Obolus*); above this, on the slope between the two quartzite outcrops, porphyry occurs. The thickness of the Cambrian quartzite would be so abnormally great were this porphyry a sill, that it seems probable it is a mass filling a strike fault fissure and that the upper quartzite bench is faulted up by the porphyry. This is the more probable, as the base of the Cambrian occurs at much lower levels across the valley on the south side of West Strawberry Creek. Under the lower bench of quartzite the mica-schist is found, and farther east an extremely complex structure of dikes and faults gives evidence that the conduit region at the time of intrusion was a zone of faulting and deformation, communicated from the schists to the hard beds at the base of the Cambrian. The schists here, as in the case described on page 201, contain large masses of white quartz. The hills a short distance west—i. e., farther within the Algonkian area—consist of slate capped with porphyry. The porphyry extends down the schist slopes in places and runs out into dikes in such fashion as to indicate that these seeming caps are in some cases stocks or conduits of irregular shape (Pl. XIX).



HOMESTAKE OPEN CUT, SILLS IN CAMBRIAN, SHOWING ALGONKIAN SCHIST BELOW.

SUMMARY OF DIKES IN SCHIST.

The exposed schist area southwest of Two Bit is a region of conduits which fed sills and laccoliths whose remnants still persist in the eroded monoclinal structure to the northeast. The dikes have northwesterly trend and east or west dip, with the schist lamination. Sills fed by such inclined dikes spread in the direction of the dikes' inclination from the vertical. Dikes in the Cambrian strata retain the northwesterly trend imparted to them by the schist below (Pl. XX). Deformation of the schist by faulting accompanied intrusion, and was transmitted to the Cambrian quartzite. Other faulting of later date intersects schist and rhyolite alike. Faulting on the plane of contact between Cambrian and Algonkian indicates movements of extension in the latter. The quartzite escarpment of Strawberry Ridge, representing the basal contact of Cambrian on schist, is faulted and broken through by many feeding dikes.

TWO BIT REGION OF SILLS AND LACCOLITHS.

WHITEWOOD GULCH.

The Two Bit sill district is limited on the southwest by the Strawberry Ridge escarpment, and this escarpment is practically continuous

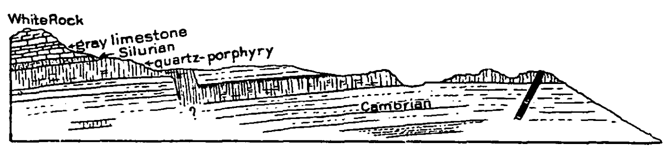


FIG. 73.—Section of east slope of Whitewood Gulch, Deadwood.

to the northwest as far as White Rock, above Deadwood. On the western slope of the ridge between Whitewood Creek and Spruce Gulch above Deadwood the complex of dikes and sheets begins. Fig. 73 shows diagramatically a section of the White Rock slope above Deadwood. The shales and sandstones of the Cambrian here dip 22° north-northeast, and a large dike of quartz-porphyry apparently feeds sills in the Cambrian flags and in the thick shale bed that lies immediately under the Silurian limestone at the base of White Rock. In the southernmost spur figured is shown a 3-foot dike of phonolite, which is younger than the quartz-porphyry that caps the ridge. The sill shows distinctly its intrusive character by the selvage at its upper contact, which is finer grained and of darker color than the rest of the mass. The upright contact, where the porphyry truncates the shale beds, shows in the igneous rock a lamination parallel to the contact.

TWO BIT CANYON.

Fig. 74 shows the eastern wall of Two Bit Canyon formed by the northwest spur of Dome Mountain. This illustrates the transition from large, irregular laccolithic masses to fingering sills about their periphery, and is closely similar to the structure figured by Holmes in the Carriso and La Plata mountains (fig. 75). Two distinct varieties of eruptive are here present (fig. 74), and the lower hornblende - diorite-porphyry is probably the younger. The greater thickening of the laccolithic masses occurs at the base of the Silurian, where the porphyry in its upward progress met heavy resistant limestones, and the soft, thick shale bed at the top of the Cambrian offered an easier passage for spreading horizontally than was possible by continuing upward. Upward movement, or doming, eventually took place, when with continued inflow the mass and viscosity of the porphyry, as the result of lateral spread and cooling, were sufficient to flex

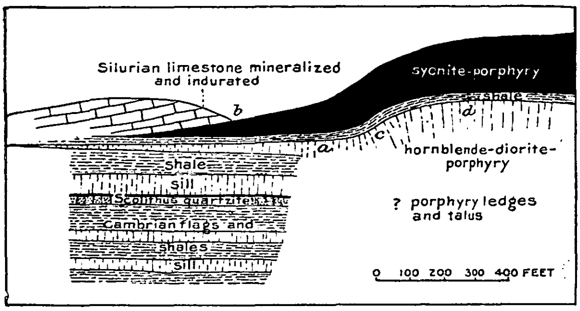


FIG. 74.—East wall of Two Bit Canyon.

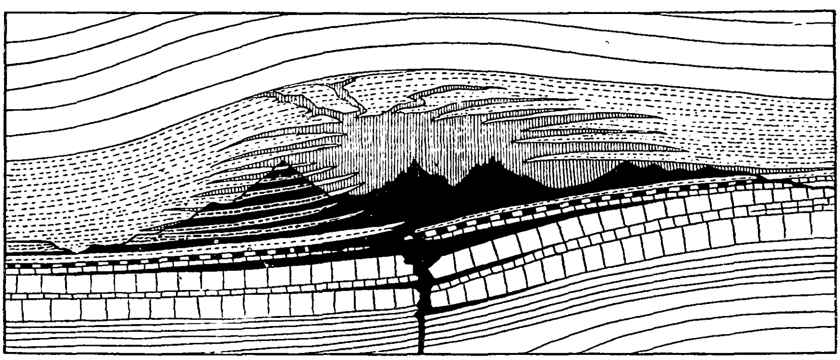


FIG. 75.—Section of La Plata Mountains (Holmes).

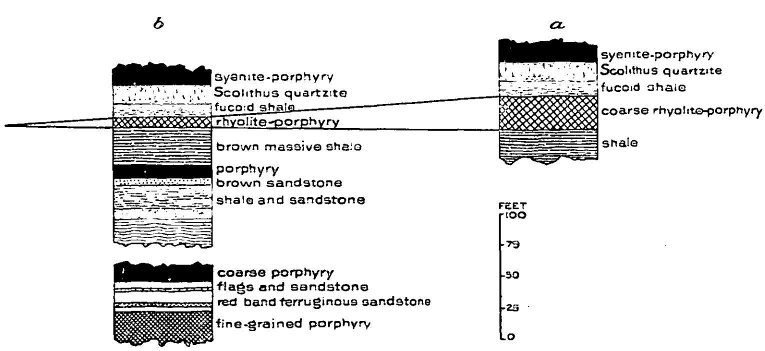


FIG. 76.—Sections showing thinning of Two Bit sills. *a*, Southeast side of Two Bit Canyon; *b*, Northwest side of Two Bit Canyon.

the thick limestones. In the figure the diorite-porphyry at the right is probably made up of a number of sills, though porphyry talus covers the whole hill slope, and if Cambrian beds occur there they are completely masked by the slide rock. In the uppermost bed, *a*, there are at least 250 feet of diorite-porphyry exposed, and apparently this mass lifted the syenite-porphyry above. That the upper laccolith ends rather abruptly to the northwest (Pl. XX) is proved by the fact that the walls of Two Bit Canyon opposite to the slope figured in the section (fig. 74) show none of the upper porphyry, and only one diorite-porphyry bench conforming to the bench in the figure. At the contact *b* the Silurian limestone is highly mineralized and silicified. At *c* the columns in the phonolite have a southerly inclination of 40°. At *d* they are nearly vertical. In each case, in other words, the columns are normal to the upper contact, and in a number of cases this variation in the inclination of columns was found to be a useful guide to the original curvature of a laccolithic mass where the covering strata had been eroded away.

The two columnar sections in fig. 76, constructed from outcrops in Two Bit Valley, illustrate the thickening of porphyry sills eastward across Two Bit Canyon, and show various members of the Cambrian, which may be used as horizon markers for identifying contiguous sills; *a* is from an outcrop on the east side of the valley; *b*, from one on the west.

In the Monarch shaft it is stated that the quartzite is faulted in steps, the ore occurring along the fault planes.

Cross-cutting sills.—The cases cited show that laccoliths under the great limestone thin out into sills, that sills thin rapidly (fig. 76), and that the region of sills is one where the alternation of shales and thin-bedded limestones through unusually thick series (Pl. XIX) affords innumerable splitting planes. The earlier rhyolitic porphyry in general spread through the Cambrian beds as sills, and the connection of one sill with the next at a higher horizon is usually an irregular dike or an oblique split corresponding to the more pronounced peripheral fractures about a laccolithic dome (Experiments III and IV; also p. 231). In a tunnel extending 375 feet eastward from the roadside in upper Two Bit Valley, Cambrian limestone flags and shales dip 6° N. 30° E. Three feet above the mouth of the tunnel a 6-foot sill occurs, and just within the tunnel is a very ragged dike (fig. 77). Some 50 paces within, a porphyry mass 40 feet thick, dipping 11° W., is seen to rise from the floor

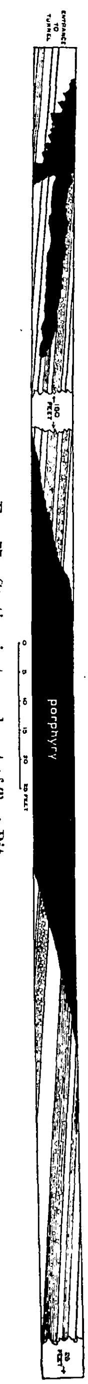


Fig. 77.—Section in tunnel east of Two Bit.

of the tunnel and cross the strata obliquely upward to the northeast. This may be taken as a type of the cross-cutting sill. The floor of the mass does not conform to the bedding, but is guided by it. The tendency of the porphyry to spread onward and resist the downward pull of dipping strata causes it to cut them transversely. This transverse cutting of beds is not confined to small sills. The rhyolite capping of the hill above the southern Terra open cut, probably a laccolith rem-

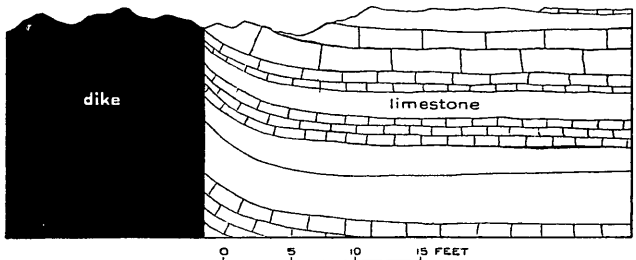


FIG. 78.—Dike crossing spur west of Peedee Gulch.

nant, obliquely cuts across the Cambrian bedding only a few feet above the contact of the latter with the schists (Pl. XXIV). On the west side of Spearfish Canyon, high up on the summit of the limestone cliff below the mouth of Rubicon Gulch, a fine columnar sheet may be seen lying obliquely across the bedding of the limestone.

Dikes in Cambrian.—The later dikes probably found the Cambrian as a whole indurated by the earlier porphyry and rigid, hence more capable of breaking on smooth vertical joints. These dikes cross the country for miles in Two Bit, but are not very numerous. In fig. 78 is shown a dike 16 feet wide which cuts gray limestone on the hill west of Peedee

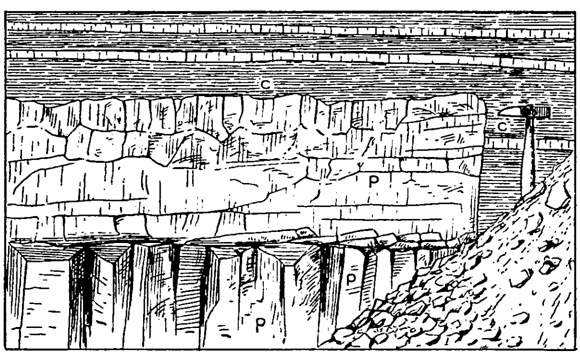


FIG. 79.—Abrupt termination of sill, east wall of Bear Butte Canyon, near Galena. The hammer rests on Cambrian beds.

Gulch. The massive limestone is bent up on the eastern side of the dike, showing that there was considerable upward thrust exerted by the magma after its first solidification on the wall. The dike trends N. 30° W., and hence is one of the numerous strike-fissure dikes which probably fed higher laccolithic bodies. If the magma which filled this fissure rose through west-dipping schists below, as usual, it is natural that it should tend to produce maximum deformation on the east.

SOUTHERN TERRA OPEN CUT, PORPHYRY ABOVE OBLIQUELY TRUNCATING CAMBRIAN BEDS, WITH SCHIST BELOW.

The transition from dike to sill is shown in a sill above the Hayes mine, on the east side of Bear Butte Creek, at Galena. The sheet is 12 feet thick, columnar below, with an upper selvage of finer grain from 12 to 18 inches thick. This upper portion resembles a separate sill, showing a sharp contact bench made by its lower surface with the columnar porphyry. The contact of the upper portion with the Cambrian limestones is irregular and comes to an abrupt angular termination, the contact bending to a vertical position, as shown in fig. 79. The sill apparently abuts against a smooth upright joint plane, and probably a feeding dike follows this plane below the talus.

DOME MOUNTAIN AND SUBORDINATE LACCOLITHS.

East of the Two Bit Valley complexities the marked simplicity of the laccolithic masses of Pillar Peak, Dome Mountain, and Bear Den Mountain is conspicuous. Concomitant with this change is a change in the horizon of intrusion, the lowest of the greater laccoliths, Dome Mountain, being intruded in soft green shales under the Silurian limestone and at the upper limit of the Cambrian. Pillar Peak and Bear Den Mountain are laccolithic masses that have broken up to still higher horizons, the former resting in part upon the gray limestone (Carboniferous) and in part overlapping the lower sandstone member of the Minnelusa formation. Bear Den Mountain reaches a still higher horizon, the purple Minnekahta limestone. The northern spur of the mountain thus is intruded on the horizon of the thicker Red Beds of the Trias. In both Pillar Peak and Bear Den Mountain it will be seen that the laccolithic floor is not a single stratum, but rather represents a plane approximately horizontal, which cuts across the initial northwest dip of the beds and so permits the intrusion to penetrate progressively to higher horizons. It is this progressive truncation of dipping strata on a horizontal plane that has given to these masses the local name of "overflows" among the prospectors and miners. If no evidence were present other than this lower contact, an extrusive flow on an old topography might be suspected in these cases; but the presence of upper contacts, the coarse-grained character of the rock, and the entire absence of true extrusives in the region, combined with the evidence presented here and elsewhere of deep denudation and former extension of laccolithic masses, as indicated by present drainage and by similar intrusive masses, still partially covered by a sedimentary mantle—all of these data make it clear that these are remnants of unsymmetrical laccolithic intrusions. The Dome Mountain mass extended laterally on the soft shales and swelled vertically, its greater mass spreading on a single horizon. Its extension on this horizon in a northeast direction was impeded by the initial dip encountered, which compelled the intrusive to plunge downward if it would remain between the same stratigraphic planes. In other words, when the steeper northeast dips were encountered, the force of wedging apart horizontal rocks was converted into a thrust against upturned rocks. The result was more violent deformation of the initially dipping beds to form an unsymmetrical laccolith with steep northeasterly dip. In Chapter V it is shown by experiment that the fractures of a dome are radial on the crest, gaping upward and closed below; they are concentric on the periphery, gaping downward. These peripheral strike fractures open toward the porphyry core. If the dome is unsymmetrical, the rupture occurs first on the side of most intense flexure. In Dome Mountain, after the limit of flexure was reached on the northeast, the beds fractured and gaped open to admit the porphyry to higher hor-

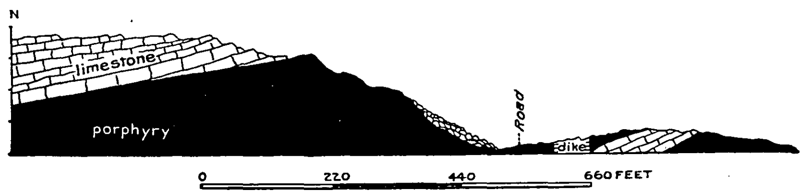


FIG. 80.—Section of divide, head of Lost Gulch.

izons. In Lost Gulch, on the eastern flanks of Dome Mountain, the upper contact of this laccolithic mass with Silurian limestone is well shown. Here the limestone is seen dipping at an angle of 40°, so violently strained and contorted at its contact with the porphyry that it is infolded in a small pinched syncline plunging northeast between two lobes of the laccolith. A few hundred paces to the north the porphyry may be followed continuously, crossing Silurian, Carboniferous, and Minnelusa beds; here the flexure has passed into rupture. The phenomenon is the same as that represented by the cross-cutting sill in fig. 77, the only difference being that in this case large lacco-

FIG. 81.—Section of Carriso Mountains (Holmes).

lithic masses are involved (Experiment IV, p. 298). A short distance farther northeast from Pillar Peak deformation of the sediments on a grand scale, probably due in part to the porphyries, may be seen in the canyon of Bear Butte Creek and in the synclinal basin of Boulder Park, this spoon being inclosed between three laccolithic uplifts of flexed strata (Pl. XXI, section D–E).

The southeastern border of the Dome Mountain mass shows less abrupt flank contacts, but is complicated with the conduits that fed the Bear Den Mountain laccolith. From the nature of the rock there is evidence that the later dikes were the feeders for Bear Den. In fig. 80 is shown a N.-S. section on the road which crosses the divide between Bear Butte Creek and Lost Gulch. In the cliff above the road on the north side shaly limestone overlies massive coarse columnar porphyry, the columns being perpendicular to the limestone contact. The limestone dips to the north and the upper surface of the porphyry shows some slickensides or rough grooving, which indicates movement parallel to bedding planes, of later date than the intrusion. Possibly such movement may be correlated with the intrusion of the later dikes. A conspicuous dike ridge crosses the saddle for a distance of one-quarter mile, trending variously from northeast to east. Above it to the north rises the talus slope of coarse porphyry, and similar float on either side of the trail of dike rock indicates that the larger igneous mass is cut by the dike. South of the dike occurs Silu-

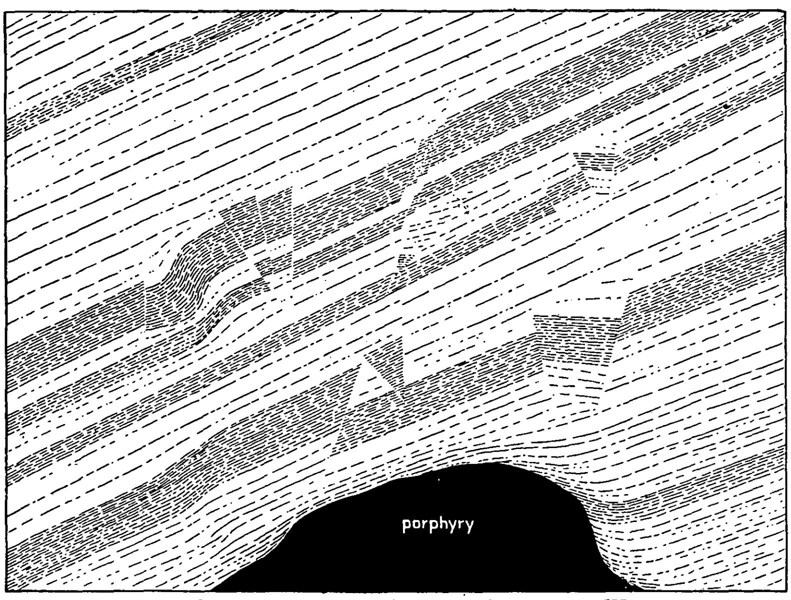


FIG. 82.—Section in shaft, summit of Dome Mountain.

rian limestone over sills and Cambrian beds in the slope below to the south. The sequence here, then, is the usual one—sills in Cambrian, thicker lenses at the base of the limestone, columns normal to the cooling surface, and porphyry of two ages. As shown on the map, Pl. XX, this section immediately north of Galena is a complication of dikes and irregular bodies, marking fractures in the limestone through which the Bear Den laccolith was intruded. This mass breaks northeastward across the whole thickness of Carboniferous and Permian to the horizon of thick Red Beds, the wall of porphyry over Lost Gulch being underlain by a white bench of brecciated Minnekahta limestone.

On the summit of Dome Mountain, in several places, occur isolated Cambrian outcrops completely surrounded by porphyry. These appear to be large included bodies, mostly lying flat, carried up in the magma as a result of excessive doming. The arched strata, unable to stretch, fractured in many places, and the fractures filled with igneous matter; increased swelling separated the fractured pieces and erosion has revealed some of them. The same phenomenon is figured by Holmes in the Carriso Mountains (fig. 81). In a shaft 30 feet deep, through one of these masses on the summit of Dome Mountain, 24 feet of Cambrian shale is shown above, and 6 feet of porphyry in the bottom of the shaft. The porphyry surface curves downward to the south, showing dome shape, conformable at the top to the overlying shales, but breaking across them on the slope of the dome. The shales above are crumpled and their bedding is interrupted by very numerous small V-shaped faults (fig. 82). The shales dip to the northeast. Phenomena like this are abundant, and illustrate the way in which stresses due to intrusion are absorbed upward in incompetent strata.

SUMMARY OF TWO BIT REGION.

The Two Bit district contains a progressive series of intrusive types from southwest to northeast, this direction at the same time marking a progression from older to younger strata and a transition from approximate horizontality in the extreme southwest to pronounced dips and folds on the northeast. Dikes of trend mostly northerly, conformable to the lamination of the Algonkian, penetrate the base of the Cambrian, where a series of separation planes in thin-bedded limestones and shales offers the necessary conditions for the eruptive to spread horizontally in many thin sills. About the base of the massive limestones of the Middle Paleozoic, swelling en masse was easier than continued fracturing and horizontal splitting to form sills. At this horizon, where also a thick series of soft green shales under the great limestone offered easy material for crushing and opportunity for lateral extension, there followed a thickening of the uppermost sills into the irregular laccoliths of Dome Mountain and the adjacent masses which thin out across Two Bit Canyon to the northwest and across Bear Butte Canyon to the southeast.

The tendency to spread northeast is indicated by more violent deformation of sediments whose initial dips oppose extension in that direction, and by the igneous rock shown breaking across these sediments to produce at higher horizons the subordinate laccoliths of Pillar Peak and Bear Den Mountain. The whole series of eruptives of the Two Bit district may represent the peripheral intrusions of magmas that are most conspicuous in the more deeply eroded porphyry complex of Terry Peak (Pl. XIX). Evidence of strike faults in association with intrusion is well marked locally, the downthrow being on the southwest, the intrusive itself using the fault plane as a conduit and adding to the effect of dislocation by arching up and intruding into the strata on the northeast side of the fissure through which it came. Tyyes of these faults are seen at Strawberry Ridge and in the subordinate laccoliths of Deadman and Whitewood canyons (pp. 204, 217, 218).

VANOCKER LACCOLITH.

East of Bear Butte Creek (Pl. XX) is shown a large igneous mass occupying as a whole only the upper horizons invaded by the Two Bit series of intrusions. Separated from the latter by a synclinal valley, there is no evidence that the conduits which feed the Vanocker mass were immediately connected with those of the Two Bit district. Schists underlying the Cambrian escarpment south of Elk Creek show almost no dikes, and apparently the dip of the Paleozoic rocks is here the normal monocline of the Black Hills uplift. The lowest beds exposed in contact with porphyry in the Runkel district (see Pl. XIX) are the shales and sandstones of the Cambrian, and chiefly its upper members. These Cambrian beds cap the laccolith of Kirk Hill, which is separated by a synclinal sag on the southeast from a very large mass which extends northeast to Vanocker Creek and forms a great irregular range of hills composed almost exclusively of igneous rocks. Perhaps it would be better to call the whole mass a single great laccolithic intrusion with local irregularities of the upper surface. Here and there occur tabular cappings of stratified rock, the lower horizon, in contact with porphyry, being either the Silurian limestone or shales which are the uppermost beds of the Cambrian. If any trace of conduits is present it is in the immediate vicinity of the town of Runkel, where the gray limestone is irregularly fractured by the eruptive; and rising through an oblique fissure in the limestone a great dike is seen, inclined to the eastward on the hill slope north of the village. To the east a large sill follows a separation plane within the limestone series, which here has a thickness of from 600 to 700 feet, greatly in excess of the same formation north of the Two Bit region. The border of the laccolithic mass as a whole is marked by dips away from the hills of porphyry on all sides, and in this respect a southern extension of the intrusive from its conduit differs from the conditions observed in the Two Bit masses at the same horizon, where upper contacts on the southern side have in all cases been eroded away. This difference may be due in part to an easterly dip recurring in the Algonkian, and hence in the conduits, under the Vanocker laccolith.

Except where the Cambrian occurs on the southwest the upper contact in the Vanocker mass is with the base of the Silurian limestone, as in the case of Dome Mountain. At several points this limestone or the subjacent shales could not be identified at the contact, and apparently the intrusive had broken across and buried or else torn away this member, so that the contact appears to be directly with the gray limestone. On the north side of the Vanocker mass dikes varying in thickness from 30 to 80 feet cut both porphyry and sediments, and two big dikes may be seen upon the Fort Meade Reservation road northwest of Deadman Gulch. There is thus a tendency on this northern side to break across strata to higher horizons, and there is evidence of a younger porphyry which cuts the older and greater

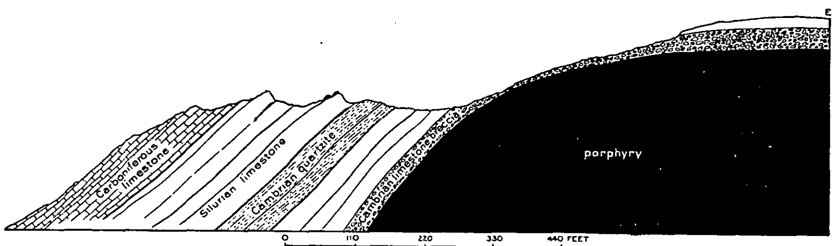


FIG. 83.—Section on west flank of Kirk Hill laccolith.

mass. The northern border of the Vanocker porphyry mass between Alkali Creek on the east and the eastern fork of Park Creek on the west, including the basin at the head of Deadman Gulch, is a different rock from the rest of the mass, being a fine-grained rhyolite, while the greater portion is a coarse syenite-porphyry. The contact between

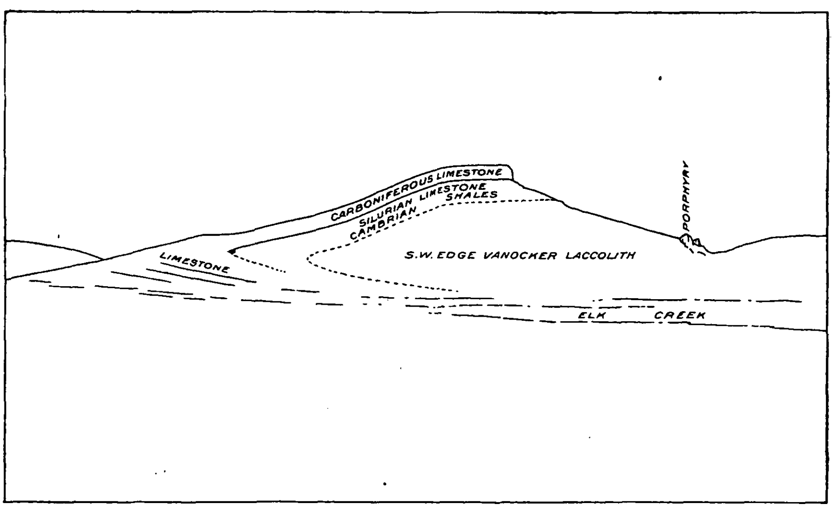
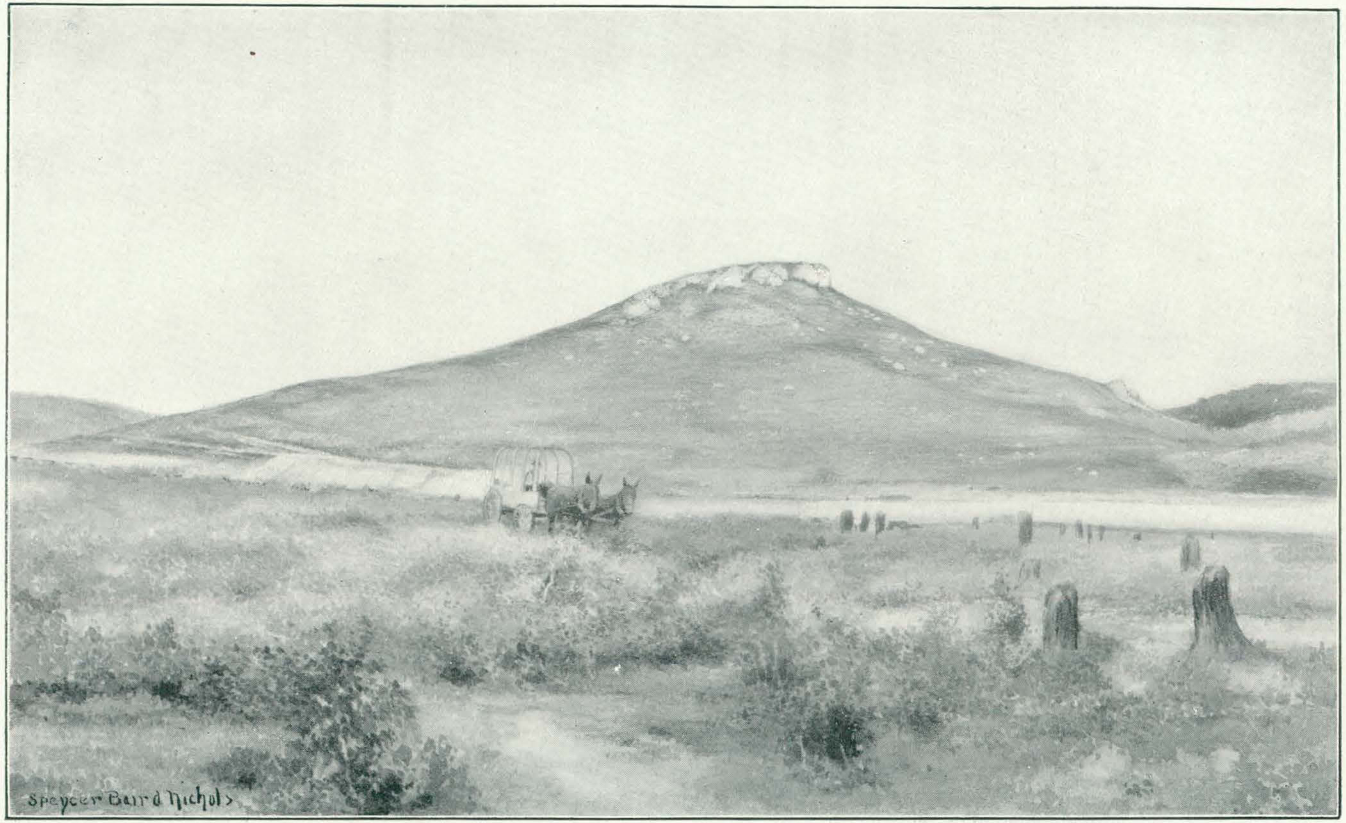


FIG. 84.—Southwest border of Vanocker laccolith, Elk Creek, showing surrounding rock formations.

these two rocks follows roughly the divide at the head of Deadman Gulch and the northern slopes of the valleys of the two creeks mentioned, but a definite contact was nowhere found; possibly the finer-grained northeastern portion was more rapidly cooled against the sedimentary cover, and is a differentiated facies of the larger mass.



SOUTHWEST BORDER OF VANOCKER LACCOLITH, ELK CREEK.

KIRK HILL DOME.

Kirk Hill, the western extremity of the Vanocker laccolith (Pl. XXI, section F–G.; Pl. XLI, iv), is remarkable chiefly for its complete cap of Cambrian limestones and sandstones. The porphyry is seen to plunge under the eastern limb of the syncline of Park Creek; and where the small radial streams have breached the Cambrian cover well-formed columns are shown, normal to the contact. Immediately at the contact limestone breccias occur with the usual green shales; and higher, in crescentic scarps that revet the base of the hill, the Scolithus quartzite, which is white near Deadwood, is here replaced by massive cross-bedded, rusty sandstones, showing some *Scolithus* borings. Above are the upturned edges of Silurian and Carboniferous limestone (fig. 83). In places the Cambrian veneer may be followed from crest to flank continuously in contact with the surface of the porphyry dome. On the walls of the little canyons the actual dome curvature at the contact may be seen in cross section. The old synclinal valley to the west still retains remnants of coarse Pleistocene gravels, which have their greatest development at the present head of the valley, where they form a portion of the divide between Park and Elk creeks.

BORDER OF VANOCKER LACCOLITH.

An exposure of other portions of the extreme rim of the Vanocker laccolith occurs three-fourths of a mile northeast of the town of Elk Creek, where a revet hill, flanked with gray limestone, exposes porphyry on its northeastern face (Pl. XXV and fig. 84), and débris in the slope above shows that the igneous rock was intruded on the usual horizon of green shales under Silurian limestone. A section just above the railroad at the foot of the western slope exposes the limestone with its dip apparently reversed. At first sight this section suggests the miniature lens at Galena (fig. 65), with its inward-dipping basement beds. Obviously, however, the basement beds of this border of the Vanocker laccolith are Cambrian, so that the Carboniferous limestone could be thrown into this position only by faulting or by a cross-cutting tongue of porphyry not shown. A simpler explanation of the reversal in dip is that the reversal shown is not real but only apparent. In the landscape figured (Pl. XXV) the limestone scarp curves around toward the observer, and the section exposed is probably an oblique truncation of beds dipping toward the foreground.

SUMMARY OF VANOCKER LACCOLITH.

The Vanocker laccolith is intrusive about the horizon of the base of the Silurian and shows no conduits, but breaks across the gray limestone irregularly in the vicinity of Runkel. The laccolith uplifted the strata above it, and arched them so that they now dip away both north and south, the southern dip produced being an inversion of the normal monoclinal tilt to the northeast, and hence there was produced a syncline in which now flows a portion of Elk Creek and one of its branches. Drainage from this great laccolithic mass follows in general radial courses in the case of the smaller streams, the larger ones encircling the mass to follow the contact zone on its periphery. The southwestern portion is still capped with sediments of Cambrian, Silurian, and Carboniferous age. To the north dikes break through the sediments, and in one case a northern extension of the larger intrusive mass breaks upward to form the subordinate Deadman laccolith at a higher horizon (Pl. XX). This laccolith is now largely uncovered by erosion, the only covered portion being the region above its conduit, which, however, is exposed in a canyon cross section.

SUBORDINATE LACCOLITHS.

Dome Mountain and the Vanocker laccolith represent the thickest porphyry masses of the two eruptive centers on opposite sides of the Park Creek syncline. Pillar Peak and Bear Den Mountain have been mentioned as offshoots from the thicker Two Bit complex, breaking to higher horizons. Somewhat more remote from the greater porphyry mass is a small laccolith east of Whitewood Canyon below Deadwood, injected through a fault fissure and doming up Cambrian, Silurian, and Carboniferous beds on its northern side. This Whitewood Canyon laccolith is rather a subordinate offshoot of the Polo Peak mass west of it (Pl. XIX). Remnants of a subordinate laccolith similar to Pillar Peak occur on the east side of Peedee Gulch, and again on the opposite side of the wide Pleistocene gravel area filling the head of Boulder Creek, where a small porphyry body lies next to a well-marked E.-W. fault. These two small masses are of the same rock—a phonolite—and were probably once continuous. As the northern mass rests on Minnelusa and the southern one on gray limestone, the progressive truncation northward of dipping beds is the same as in Pillar Peak and Bear Den Mountain. The two Whitewood Canyon faults (section A-B-C, Pl. XXI) have upthrow on the north in both cases and slight northerly hade. They fade out east and west, and are unquestionably occasioned by uplift due to the subterranean portion of the Whitewood Canyon laccolith. There is therefore no necessity for supposing that the phonolite adjacent to the southern fault is in any way genetically associated with it.

Tilford and Dead Man laccoliths (Pl. XIX), and remotely Bear Butte, are subordinate to the Vanocker mass, the last occurring 8 miles to the northeast. Bear Butte shows structure that indicates a subterranean conduit from the direction of the hills, as in the case of the others. Crook Mountain and Elkhorn Peak undoubtedly have similar structure, but erosion has not revealed the porphyry.

WHITEWOOD CANYON LACCOLITH.

In Whitewood Canyon immediately west of Whitewood Mountain is shown a small laccolithic mass of rhyolite which in cross section resembles Black Butte in the Judith Mountains, described by Weed and Pirsson.[1] The orifice of intrusion appears to have been a fault with upthrow on the north, and a second fault of similar character appears 1 mile farther south, up the canyon. These faults die out within a short distance of the porphyries east and west, and thus appear to be genetically associated with the deformation occasioned by intrusion. The laccolith is quite unsymmetrical, the Silurian and Carboniferous limestones on the southern side showing no marked deformation except a sharp backward bend at the porphyry contact, while on the northern side the whole Paleozoic series from the lower beds of the Cambrian to the Upper Carboniferous inclusive are upturned at a high angle, overlie the porphyry, and are locally faulted. (Section B–C, Pl. XXI.)

Topographically, Whitewood Canyon laccolith is inconspicuous. The traveler on the Fremont Railroad in Whitewood Canyon below Deadwood would not suspect its presence. In going down the canyon the most striking features seen are the brown Cambrian and white limestone cliffs that rise almost vertically 600 to 700 feet above the bed of the muddy torrent. At the bridge the line of the railway crosses the southern fault, marked in the cliffs by an abrupt transition from limestone on the south to steep walls of brown Cambrian flags, limestone breccias, and shales, which at the fault are indurated to a gray and black horny rock of chalcedonic aspect. Three-quarters of a mile below, a gulch is seen on the east side of the canyon that has been eroded out on the fault or conduit side of the laccolith. Curious revetting scarps of porphyry that at first sight resemble sediments curve up over the spur on the north side of the small gulch, while on the south side porphyry forms the lower portion of the slope, and above it the contact with dragged limestones forms a small bench. The summit of the porphyry hill on the north side is Cambrian Obolus sandstone, containing a small sill that outcrops in a ring about the crest. More conspicuous than this summit are the monoclinal ridges of Paleozoic limestone north and northeast, the second being Whitewood Peak; at one place the broad yellow bench of Silurian spotted limestone shows a bare rock face with small faults displacing the beds. This escarpment is a conspicuous landmark from the summits about, and may be seen dipping off the eruptive from the bend of Whitewood Creek, where, at a sharp elbow of stream capture, the railway leaves the canyon by a tunnel through the Minnelusa ridge. The Whitewood Canyon laccolith differs from the Judith Mountains type of

[1] Loc. cit., p. 555.

unsymmetrical laccolith mountain, Black Butte, in that erosion, by monoclinal shifting, has not progressed far enough to give the porphyry relief above the limestones which encompass it.

CROOK MOUNTAIN.

Crook Mountain, adjacent to the Whitewood laccolith on the northwest and separated from it by the synclinal valley of Sandy Creek, is the type of a laccolithic dome in which as yet the porphyry core has not been revealed by erosion. The Minnelusa sandstone and limestone dip away from the summit uniformly in all directions, and the purple Permian limestone is interrupted at only two points in its encircling escarpment. Through this escarpment the radial drainage cuts characteristic V-shaped gateways, the dips being steepest on the northeast side, where the Boulder Park syncline narrows to its region of maximum appression, confined between a plunging anticline on the east and the abrupt dome of Crook Mountain. On the northwest flank of the mountain Whitewood Creek has cut a deep canyon, revealing the underlying gray limestone, but not reaching the porphyry, which probably is intruded at the base of the Silurian. (Pl. XLI, II, geologic map of Crook Mountain.)

DEADMAN LACCOLITH.

The strata dipping to the north from the Vanocker laccolith form a syncline in Deadman Mountain (Pl. XXI, Section F–G), and in lower Deadman Gulch rhyolite again rises in a long, low dome which outcrops in the bottom of the deepest part of Deadman Canyon. At the point where this somber canyon opens on the north a cliff wall exposes the porphyry, filling a fault fissure which terminates this low dome on its northern side and permits the eruptive to break upward and outward to the northeast into the Minnelusa beds. There is thus exposed in cross section, for a distance of a mile, the upper laccolith, its conduit, and its source in the lower mass. On the western side a dike follows the fault fissure for a short distance along the contact between the faulted gray limestone and Minnelusa sandstone; in the bottom of the canyon the dike breaks across Silurian limestone and underlying shales. This dike fissure marks the fading out of one of the concentric fractures made by the lower dome in the limestones on its northern side, the middle portion of the fracture being occupied by the greater conduit. Four hundred feet higher, on the northeastern side of the canyon, the same Silurian limestone overlying the porphyry recurs, forced upward by the magma as it broke across the strata, while far below, on the northern side of the conduit, there are exposed, under the newer laccolith, beds of gray limestone that originally were continuous with those capping the uplifted mass shown on the same (eastern) side of the creek. (Pl. XXVI and fig. 85.)

A comparison of this Deadman laccolith with the one in Whitewood Canyon shows similar structure, the cross section revealed by erosion in this case making visible the conduit. This occurrence, and the dikes breaking through the upper Paleozoic strata a few miles to the southwest, show a repetition of the same phenomena that were observed in the cases of Bear Den Mountain, Pillar Peak, Whitewood Canyon, and Crook Mountain, where the greater eruptive masses show tendency to throw out offshoots northeast that mark the limits reached by intrusion in each district. The photograph of Deadman laccolith (Pl. XXVI) shows an abrupt break in the sky line occasioned by Bear Butte, another igneous intrusion far out in the plains, almost in the line drawn through Deadman laccolith from the greater interior porphyry mass of Custer Peak. Coincident with its greater remoteness from the seat of greatest igneous activity, the porphyry of Bear Butte has reached a higher horizon stratigraphically than that in contact with any of the other igneous masses of the northeast border of the Black Hills, and yet it shows the same structure.

The section from southwest to northeast, shown in Pl. XXI (F–G), is repeated in the sketch (fig. 85), but seen from the opposite side. Here is shown the eastern wall of Deadman Canyon, with the upraised limestones resting above the conduit and the laccolith extending to the northeast; the direction of its irruption seems to point toward distant Bear Butte as to another outbreak on the same line of igneous activity. Gray limestone occurs under the laccolith on the east side of the canyon, and a small remnant cap of limestone still rests upon the porphyry flank at one point.

Topographically in the Deadman as in the Whitewood laccolith, the limestones above the conduit region dominate the porphyry and occupy the highest summits. Intrusion at a higher horizon, however (Minnelusa instead of Cambrian), has permitted erosion to go deeper into the laccolith on the east and west flanks, and in consequence the basement strata and conduit are revealed. The flanking sediments, while still forming an encircling escarpment, do not lap over the edge of the lens of igneous rock, which has been eroded almost bare.

TILFORD LACCOLITH.

An eastern offshoot of the Vanocker porphyry mass occurs 2 miles west of Tilford. In structure this is an unsymmetrical laccolith, essentially like the one at Deadman Gulch, intruded in the Minnelusa shales and sandstones. From a road in the canyon west of Tilford the dome surface curving down to the east is seen to dip under a Minnelusa escarpment. Continuing westward, the road enters a narrow glen with vertical porphyry walls which show a remarkable massive platy parting. Finally the western contact of porphyry and limestone is seen, showing the limestone bed with gentle dip eastward, cut across by porphyry, which curves upward to the east and shows well-developed columns perpendicular to the contact. The limestone here seems but little deformed (Pl. XXVII). This again illustrates the invariable

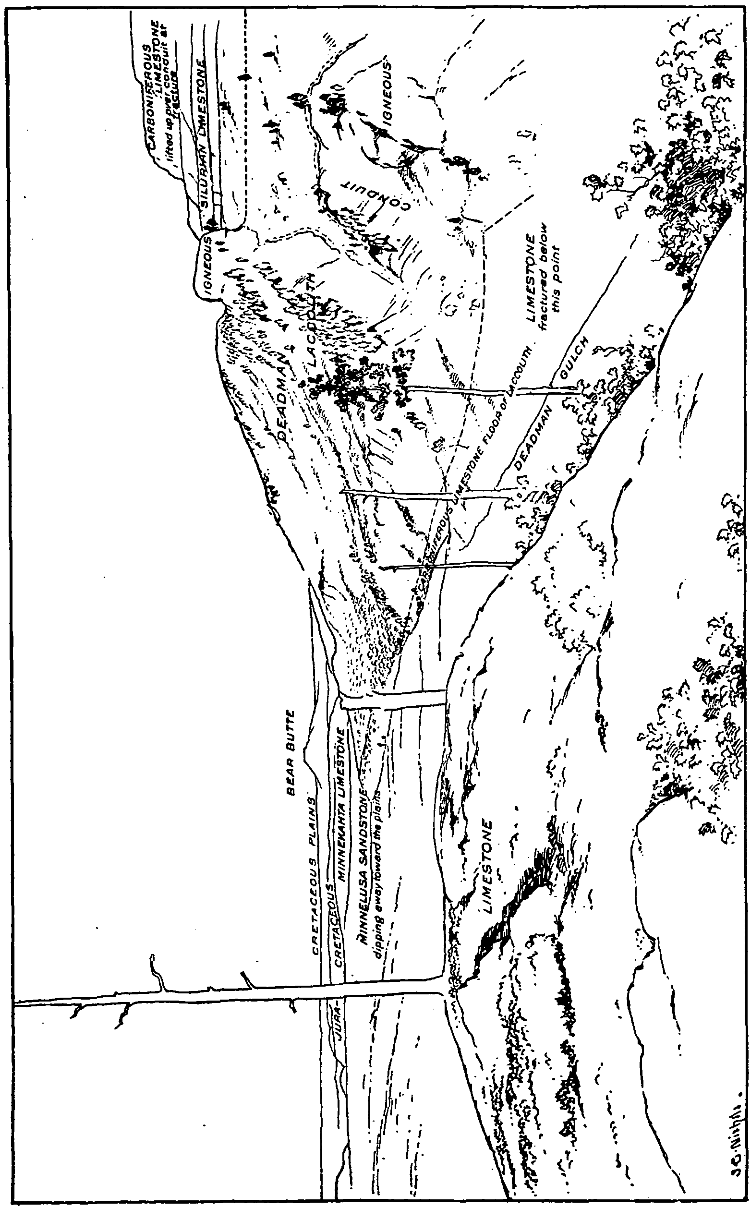
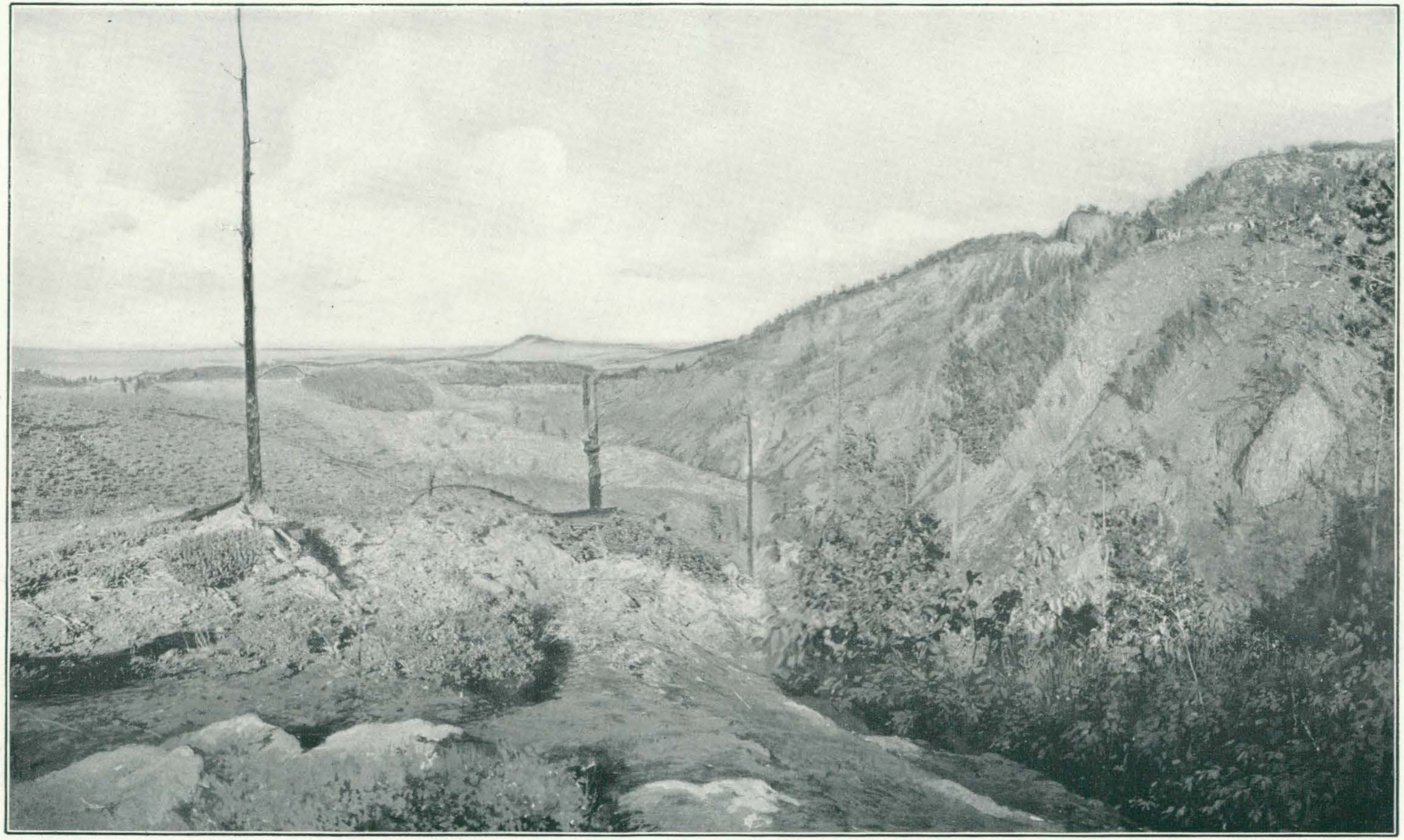


FIG. 85.—Deadman laccolith, looking east across Deadman Gulch.

relation of subordinate laccolith to main mass, the conduit of the former being a peripheral strike fracture in the sedimentary cover of the larger igneous body.



DEADMAN LACCOLITH, LOOKING EAST ACROSS DEADMAN GULCH.

BEAR BUTTE.

Bear Butte is an isolated, steep intrusive mass 6 miles northeast from Sturgis, a town situated in the Red Valley, on the northeastern border of the Black Hills (Pl. XVIII). Bear Butte is about 5 miles from the nearest hills of Cretaceous strata that represent the periphery of the Black Hills uplift, being thus wholly within the area of the Great Plains, which are here made up chiefly of dark shales of the Benton horizon. While somewhat less abrupt than Mato Teepee, this lonely monolith in the midst of flat and arid land is quite as impressive, and for the geologist more interesting, on account of the exposures about its base of upturned strata that show clearly the manner of its intrusion. In a previous paragraph mention has been made of the fact that Bear Butte lies in a direct line connecting the Deadman laccolith with Custer Peak, and the nature of the rock as well as the method of its intrusion indicates a laccolithic structure which differs from that of the Deadman laccolith only as it affects beds stratigraphically higher, and has a greater thickness in proportion to its lateral extent (Pl. XXVIII).

The accompanying sketch map and cross section show the structure of Bear Butte (Pl. XXX), the strata affected ranging from the base of the Carboniferous gray limestone to Benton shales, above which the eruptive mass now protrudes. In form the mountain is elliptical, its longer axis trending east and west, the greater mass forming an elongate western dome, which is separated on the east by deep chasms from a series of upturned eroded shells of Carboniferous limestone that now forms a steep pinnacled secondary mass from which extend spurs north and south. The summit of Bear Butte is 4,422 feet above the sea, or about 1,300 feet above the surrounding plains. Upturned sediments occur at the western base of the mountain, these being Juratrias and Cretaceous, while at the eastern end is exposed a section from the gray limestone to the Benton, complicated with some faulting and imperfectly exposed. The gray limestone and Minnelusa beds are fractured and somewhat silicified, and there is evidence that the Minnelusa is all very calcareous at this distance from the hills. The two formations are not clearly distinguishable. The faults mapped are only approximate in their position and trend.

To one approaching the mountain from the west, a conspicuous feature shown at the southwestern corner of the mass is a series of low escarpments extending from one-half to three-quarters of a mile from the base of the porphyry cliffs. These ridges are composed of dipping strata of limonitic Dakota sandstone and shales, having a dip which changes from the base of the mountain, where it is due east, to east-southeast, southeast, south-southeast, and south in a distance of half a mile to the southwest. In other words, the escarpment shows a curve along its strike, and when viewed from a higher point at the western base of the mountain this curve is seen to continue in an elliptical wall inclosing an area which shows inner escarpments of similar trend that indicate a doming up of the strata immediately east-southeast of the mountain. The central portion of the inclosure thus encircled with curving dip scarps, Circus Flats, is a basin eroded out of the soft red beds, and the diameters of that portion of the swell which affects the beds now exposed are about 1½ miles east and west by 1 mile north and south (Pl. XXX). The inclosing escarpments are less clearly shown on the northwest, where erosion by Spring Creek and its tributaries has destroyed them. The encircling escarpments, however, northeast, east, south, and west, are sufficiently pro-

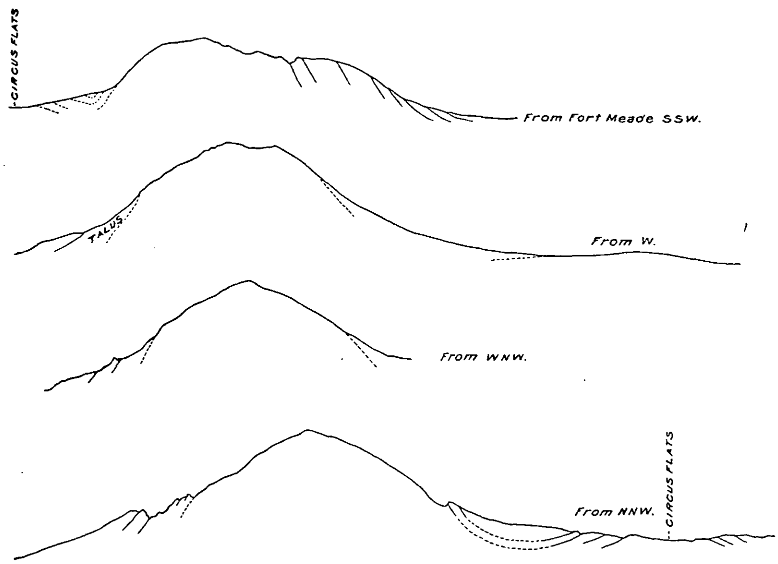
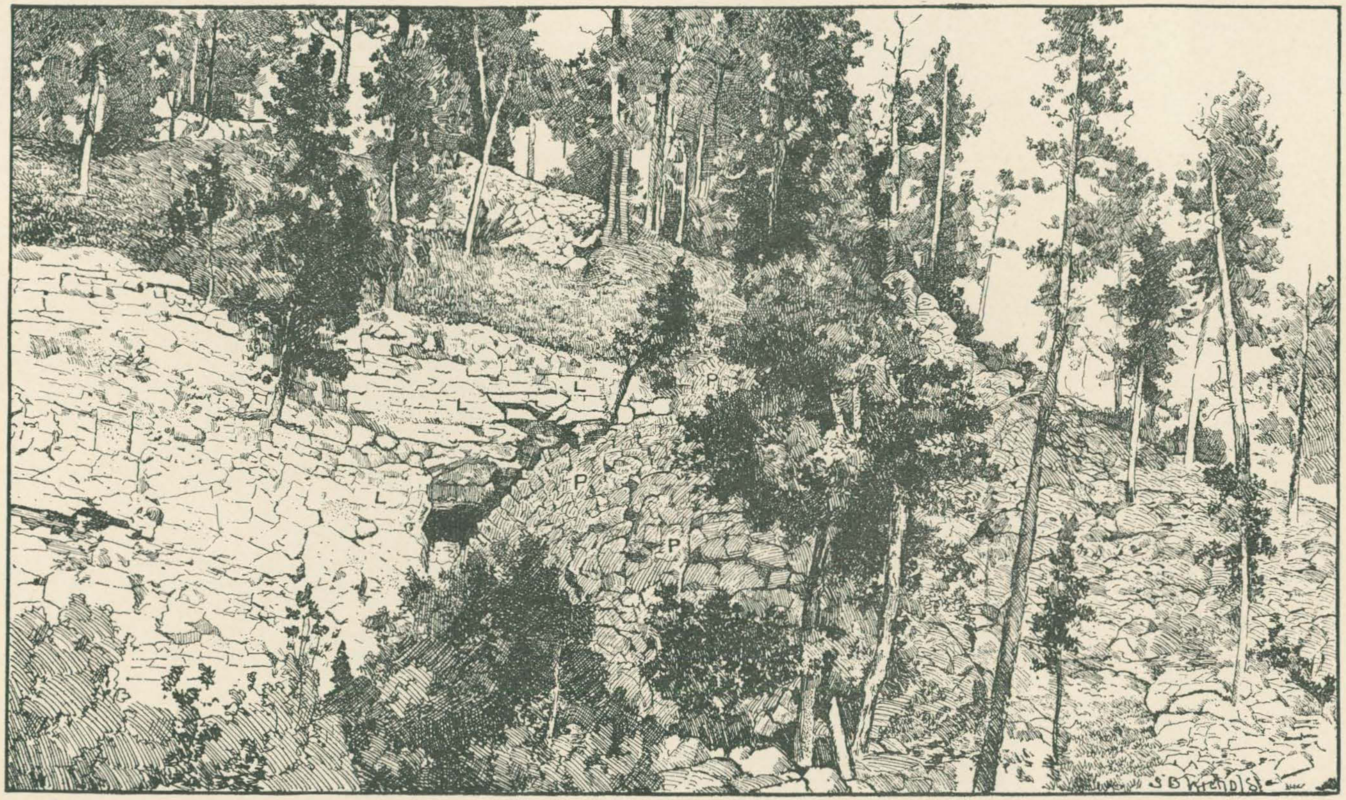


FIG. 86.—Profile sections of Bear Butte.

nounced to leave no question that we have here a true quaquaversal, which differs from such domes as Elkhorn and Crook Mountain only by reason of the fact that erosion has not yet reached the resistant purple limestone and Minnelusa sandstone, but is still at work on the soft red beds, and accordingly produces a basin instead of a dome. The resemblance of this basin to a circus ring or race course is most remarkable, and on this account it has been named Circus Flats. Lying east-southeast of Bear Butte—that is, in a similar direction, relative to the greater mass, to that of the feeding reservoirs of Deadman or Whitewood laccolith—there is good reason for the assumption that this doming up of strata to the southeast indicates a subterranean laccolithic swelling that marks the first effort of the Bear Butte magma prior to the production of the fissure through which was forced upward the mass which now makes the mountain.



CONDUIT OF TILFORD LACCOLITH, SHOWING PORPHYRY (P) BREAKING ACROSS LIMESTONE (L).

The deformation of the sediments at the western base of the mountain indicates a sharp synclinal bend between the east-dipping members of the Circus Flat series and the beds upturned by the Bear Butte irruption. The section here exposed is shown in Pl. XXX. Immediately at the base of the mountain, dipping 60° to the westward, is a dense gray quartzite overlain by red and buff sandstones and white sandstone. Intercalated among these sandstone beds are sills of rhyolite 30 and 50 feet thick, representing that portion of the magma which breaks through the bends, as indicated in the original type sections in the Henry Mountains.

The topographic expression of this section is shown in the several profiles (fig. 86) and in the sketches (Pls. XXXI, XXXII). Especially striking is the drainage of Circus Flats, illustrating many features of stream capture, and the development of subsequent drainage, in a fashion that makes this locality a type and model for the study of physiography. The stream in the foreground (Pl. XXXII) is the master of the several radial streams that at one time flowed off the dome of Dakota sandstone. Outside of the Dakota rim these radial streams may still be seen, while Spring Creek circles around and avoids the dome on its western and northern sides. By reason of its advantage in fall, being the stream that enters Spring Creek at the lowest point, and the first to reach the soft Red Beds, the northward-flowing master radial stream has gradually reversed the drainage of the central portion of Circus Flats from radiation outward to radiation inward.

A comparison of the cross sections of Bear Butte with those of Whitewood Canyon, Deadman Gulch, and Pillar Peak (Pl. XXI) will show the writer's reason for reconstruction of the subterranean conduit on the western side of the butte. Erode away the section as figured (Pl. XXX) and remove the greater part of the eastern flanking sediments, and there will be left the Deadman laccolith section. There is some resemblance, too, to Black Butte in the Judith Mountains, but no surface indication of the subterranean feeding mass equivalent to the Circus Flats dome is there indicated. To this underground dome, which is probably much larger than the surface quaquaversal (see p. 268), Bear Butte is but a peripheral offshoot. In Oyster Mountain, north of Sturgis, there is a faint quaquaversal structure, and it is very probable that in the buried Cambrian beds between Deadman Gulch on the west and Bear Butte on the east there are large masses of igneous rock.

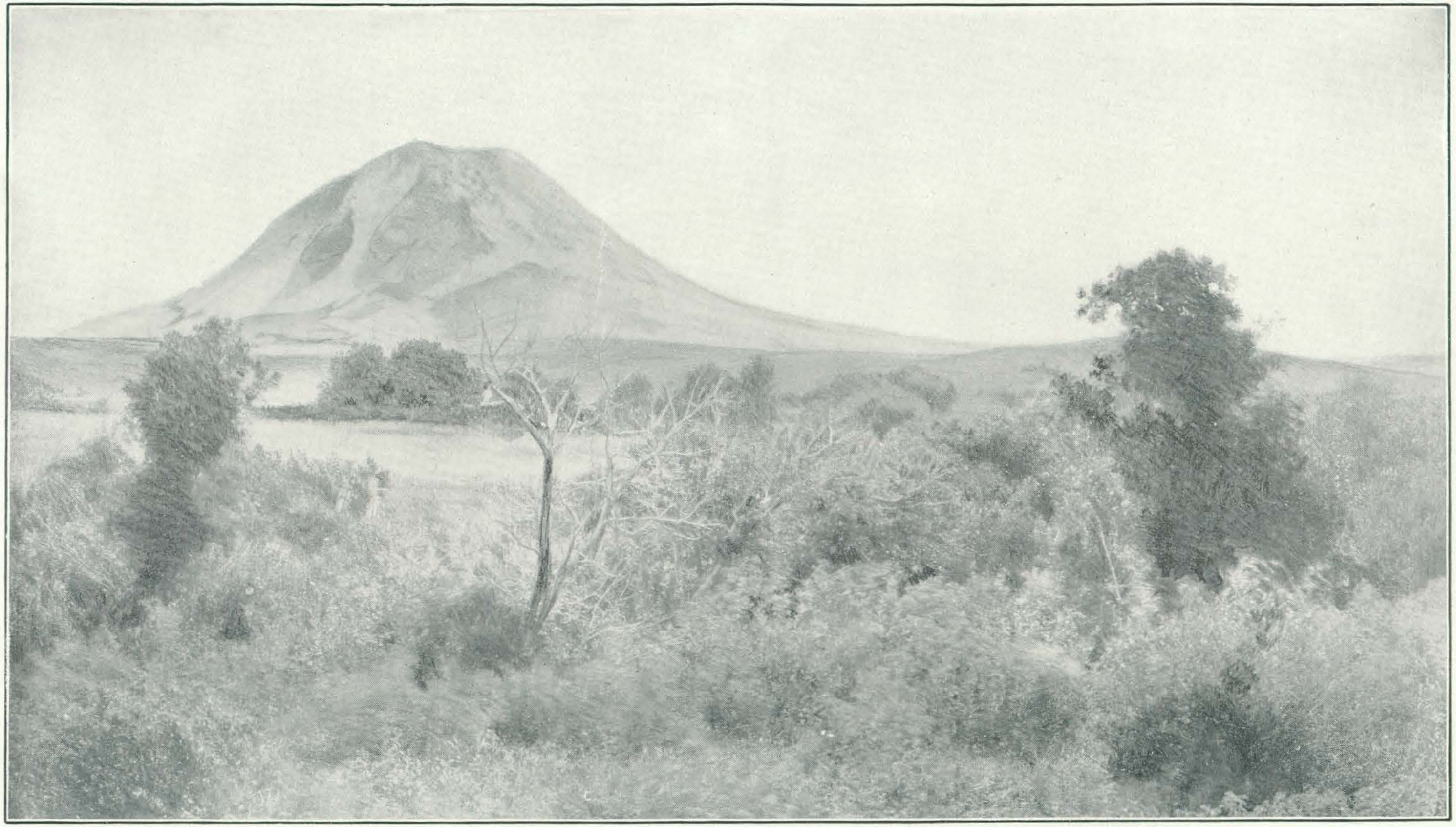
DEFORMATION DUE TO INTRUSION.

In the Whitewood Canyon intrusive body a cap of Cambrian sandstone still remains, and the flanking strata are shown in great completeness, the greater part of the porphyry dome being perhaps still masked by the mantling strata. In Crook Mountain, recognizable as laccolithic in character by its perfect dome structure, the porphyry is still unrevealed and the drainage radiates on the Minnelusa sandstone cover in all directions to supply the encircling greater streams which outline the periphery of the uplift. Finally, between those masses whose capping strata still persist, as between Crook Mountain and the Whitewood Canyon laccolith, synclinal depressions are observed, and to the east of the Pillar Peak, Bear Den Mountain, and Dome Mountain laccoliths, occurs a similar syncline, separating these from the Vanocker district. Inclosed by the whole group of intrusions is the Boulder Park Basin, which is bounded on the northeast by a great anticline that originated over the elongate intrusions that extend from lower Deadman Creek many miles to the southeast. The intrusives of this region, therefore, may be in part considered as sources of deformation with reference to the sediments, capable of exerting lateral as well as vertical pressure, and the strata yielded to the stresses applied by this agent in the same fashion and following the same laws of competent structure with reference to applied force that are observed in the greater plications of the Appalachians.

OROGENIC DEFORMATION.

It can not be asserted, however, that the Bear Butte Canyon anticline and the Boulder Park syncline were wholly induced by the intrusives. Similar folds occur along the eastern border of the Hills where porphyry is absent, as at Hot Springs, where the lower Mesozoic rocks are warped into massive folds of Appalachian type with axes following the general strike on the curve of the Black Hills ellipse. Such folds may be regarded as due to a settling back or overturning of the greater dome of the Hills, or to movements of actual extension, perhaps accompanied by fracture and faulting locally. Such greater movements gave passage to the eruptives; and the latter have been shown to produce great horizontal extension by filling the upturned Algonkian strata with dikes. This extensional movement, transferred to the flat Paleozoic sediments resting across the Algonkian beds, was transmitted horizontally by the competent Siluro-Carboniferous limestone, and was accommodated by folding.

Concomitantly the intrusive filled every weak place where the arches tended to open and where the incompetent Cambrian strata were thickest, avoiding the synclinal axial regions of appression; given impetus locally they wrinkled and ruptured the strata; in greater masses they transformed an initiated anticline into an irregular dome; they filled anticlinal elevations and accentuated the intervening synclines, buckling and warping the folds and destroying any original tendency to axial alignment. The Bear Butte Canyon anticline may be considered one of the original folds; it is distorted into the Vanocker-Deadman dome in its southeastern extremity, and it pitches northwest at Whitewood and flattens out. At Bear Butte Canyon it has the profile of a



BEAR BUTTE, FROM THE WEST.

step fold with its steeper limb toward the Algonkian region of conduits on the west—i. e., toward the applied force.[1]

The Boulder Park spoon is a remnant of the original syncline. At the southeastern end it doubles, forming the synclines of Deadman Mountain and Park Creek, both separating porphyry masses. At its northwestern end it is divided in two by Crook Mountain dome, which pinches it on the northeast side against the aforementioned anticline, and on the southwest side against the Whitewood Canyon laccolith. Beyond, to the northwest, the broad syncline continues, flattening out in the Jura-Cretaceous hills west of Whitewood, where it is again interrupted by Elkhorn dome. The next fold to the southwest was a great anticline over the whole Terry Peak district (Pl. XIX). Its crest is entirely eroded away; it was scalloped on its northern side into transverse folds of northerly and northeasterly pitch, with the anticlines domed up by the Spearfish Peak, Polo Peak, and Dome Mountain laccoliths. Along the synclines flowed the ancient Pleistocene streams (Pl. XX), and the history of the development from them of the present drainage forms one of the most interesting chapters in the evolution of the region.

SUMMARY OF SUBORDINATE LACCOLITHS.

The Whitewood Canyon laccolith was fed from a subterranean mass, which, in its first effort to dome the massive limestones, fractured them and arched them up north of the southern fault. Through a second fault gash the magma swelled to the northward and arched the Paleozoic beds into an unsymmetrical dome. Probably the fault died out upward, as it is seen to do laterally. In Crook Mountain the dome is preserved, with no conspicuous faults shown. In the Deadman laccolith the southern fault is replaced by a monoclinal fold; the representative of the northern one persists, and, since the magma was intruded at a higher horizon, erosion has removed most of the covering strata and revealed in cross section the conduit. Another stage is shown in the case of the Tilford laccolith, where the same kind of conduit section is revealed in part and the eastern upper flank contact is still preserved. All of these are unsymmetrical laccoliths, producing maximum deformation of sediments on the side remote from the Black Hills, and fed from inclined conduits.

Precisely the same structure is indicated by the evidence at Bear Butte, where the backward flexure of the limestone on the side remote from the Hills is still more intense, and the eastern subterranean dome indicates the direction from which the mass was fed. In all of these stages there are various sizes of laccoliths at the same horizon, and laccoliths of similar size at different horizons, though in no case can positive measurements be given, owing to the concealment in most cases of the extreme rim or wedge at the border. It may, however,

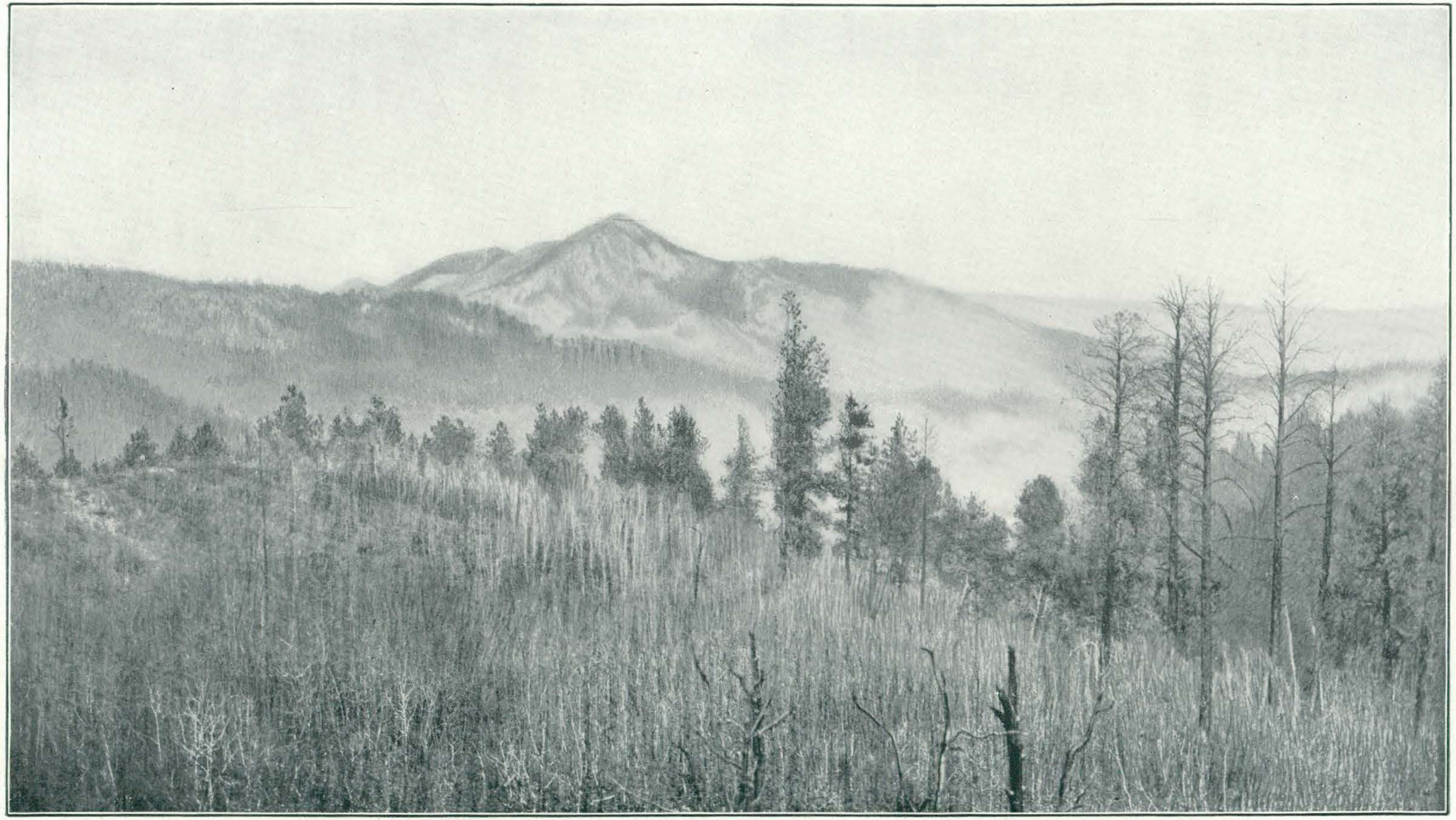
[1] Mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey.

be stated with some assurance that the ratio of breadth to height diminishes in the subordinate laccoliths, and that the higher the beds deformed by the porphyry the greater the steepness of the dome and the smaller the ground plan. All of these laccoliths are intruded among folds, through conduits which are in some cases demonstrably faults. Similar deformation occurring elsewhere, the preponderance of evidence shows that the intrusives were contemporaneous with or subsequent to orogenic deformation.

LACCOLITHIC INTRUSIVES OF TERRY DISTRICT.

The several groups of intrusive bodies may be individually described under the name "complex." Five such complexes are distinct, and show evidence of being separated from one another by what were originally synclinal depressions in the covering strata. These are, from east to west, the Vanocker, Two Bit, Terry-Polo, Cement Ridge, and Bearlodge complexes. Of these the most conspicuous, by reason of its association with valuable ore in the most populous district of the northern hills, is the Terry-Polo complex.

The area of porphyries immediately associated with those which form the Deer Mountain Range, including Terry Peak, the highest point of the northern Black Hills, embraces about 80 square miles, naturally bounded by Spearfish Canyon on the west, that portion of the Red Valley known as Centennial Prairie on the north, and portions of Whitewood Canyon and Bear Butte Valley on the east, while to the southward Custer Peak forms the last porphyry remnant of importance in the schist region of maximum corrasion of the Black Hills dome (Pl. XIX). Genetically it is not improbable that Citadel Rock and Crow Peak, lying to the northwest, in the line connecting Custer Peak, the Woodville Hills, Terry Peak, and Ragged Top, may be related to this Terry group by reason of the fact that the greater number of known dikes in the Algonkian have a trend parallel to this one, and hence it is probable that great laccolithic bodies lying in a continuous line have a common conduit or group of conduits. Petrographically, however, they are composed of a variety of different rocks. The area of the Terry complex may be divided into three belts. The Deer Mountain belt includes Custer, Deer, Terry, Ragged Top, and Spearfish peaks, lying in general to the east of the exposed Algonkian. The second belt includes dikes and stocks in schist extending from False Bottom Creek southeastward to Bear Butte Creek. The third belt is made up of intrusives in dipping strata from Cambrian to Carboniferous, and includes the sills and laccoliths between Tetro and Whitewood creeks. The three belts are topographically distinct, the first being the edge of the great western limestone plateau, the second the Algonkian valley, and the third the Palæozoic escarpment, corresponding to the Two Bit and Vanocker districts southeast.



CROW PEAK, FROM THE SOUTHEAST.

STOCKS.

FALSE BOTTOM CONDUIT.

On the east side of False Bottom Creek, 1 mile above Garden, occurs a mass of phonolite of irregular form immediately in contact with schists. From this mass dikes run out to the southeast, and probably in other directions, though no actual junction has been observed. The mass as a whole forms a hill rising 400 feet above the creek, and the eastern and northern crests form a peculiar curved escarpment, made up apparently of coarse sheaflike joints or columns projecting obliquely upward and outward. In the bottom of False Bottom Creek, a few yards below the falls and immediately under this hill, the porphyry is seen in contact with schists, the contact being in general that of a dike parallel with the schistosity. There is no appearance of horizontal contacts with Cambrian beds in the hill slope. It seems probable that this is a true stock which represented the conduit of laccolithic bodies whose southern ends are now eroded away.

Exactly the same rock occurs in Cambrian strata on the spurs to the north, on both east and west sides of False Bottom Creek. These masses are dipping with the sediments, and form a series of lenticular bodies intruded in the northward-dipping Paleozoics on the several ridges between Spearfish and Miller creeks. On traversing any one of these ridges northward the edges of dipping strata and igneous lenses of varying composition form a series of steps or small transverse ridges, and the igneous bodies thus show signs of having formerly continued southward. Such southern continuation of the phonolite mentioned would pass over the False Bottom stock.

DEADWOOD CREEK CONDUIT.

A massive stock of diorite forms precipitous cliffs 1½ miles above Central, at a sharp bend in Deadwood Gulch, on the line of the Crown Hill branch of the Fremont Railway. This stock, as seen from the canyon, resembles more a huge dike, its contact walls being parallel with many other dikes exposed along this railroad between Central and Texana. The mass has, however, no considerable longitudinal extent, as it either forks into smaller dikes or thins out southward, and its northern continuation is obscure. This stock, as in the case of the False Bottom conduit, may be a feeder of laccolithic masses to the northeast, where, beginning along the eastern wall of Blacktail Gulch, a series of sills and laccoliths may be traced into the northeasterly dipping Paleozoic sediments; these form the Polo Peak group of hills, one of the most continuous and extensive porphyry masses in the region. In this is included the high porphyry hills between City Creek and Blacktail Gulch, and, farther north, the Miller Creek porphyry, Sheep Mountain, and Polo Peak. This is the region of greatest thinning in the Carboniferous limestone, and consequently the place where it was the most flexible to bend upward under pressure of porphyries below (see section on Pl. XIX.)

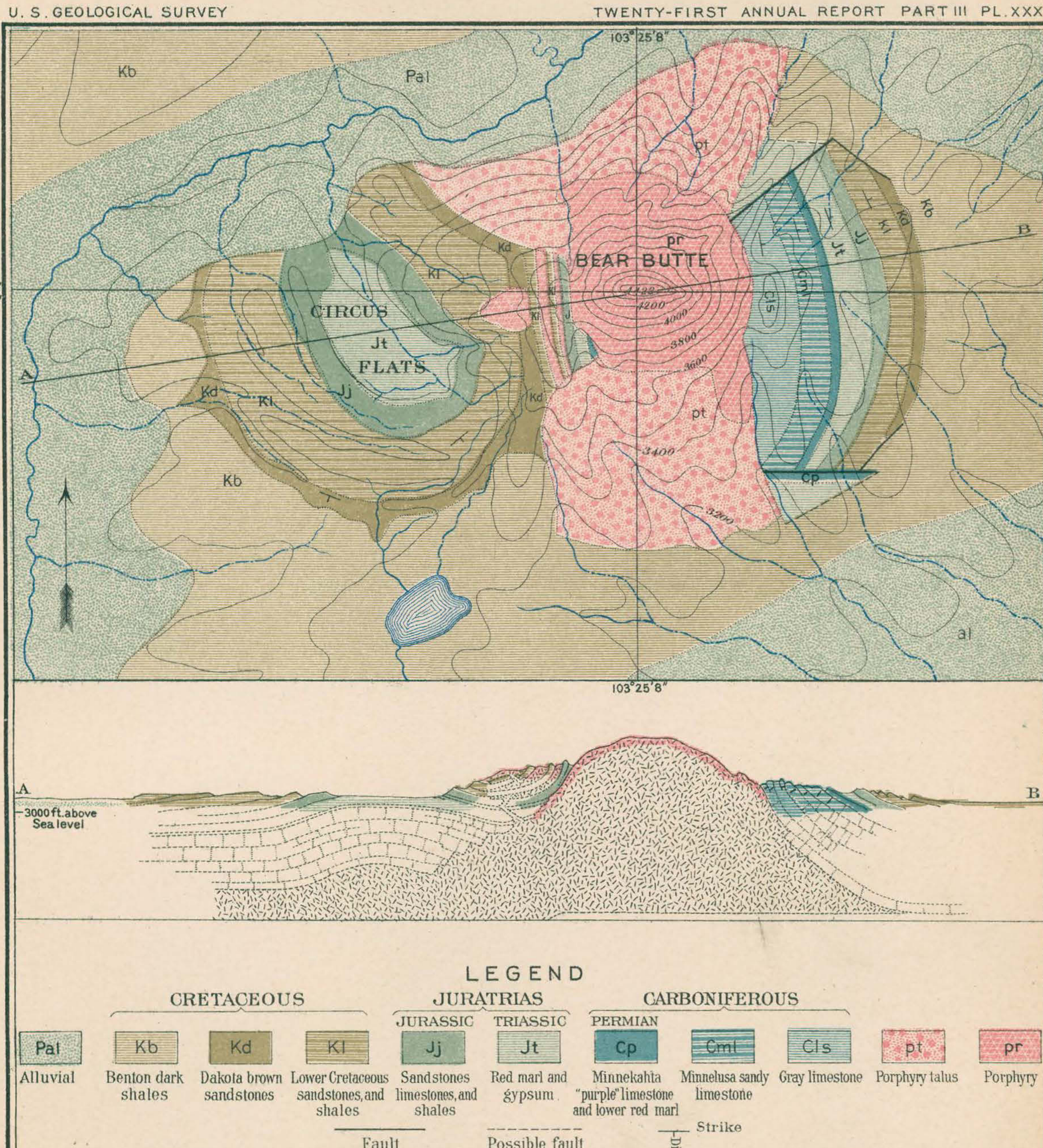
DIKES.

TEXANA DIKE DISTRICT.

The diorite stock, 1,500 feet thick, is only one of many conduits in Deadwood Gulch. West of it, along the railroad, there is an 1,800-foot section which shows chiefly porphyry dikes. Farther west two dikes, 630 and 10 feet thick respectively, cut the schist. In the spur south of Texana ten dikes are shown, ranging in thickness from 2 to 780 feet. Irving mentions twenty-two dikes from 10 to 100 feet in width between Texana and the great diorite mass. He states his belief that "were the whole of the Algonkian area carefully mapped, it is no exaggeration to say that at least one-third, if not more, would be igneous rock."[1] He refers to the diorite as a dike. The masses called stocks in this paper have usually an elongate trend parallel to the schistosity of the Algonkian, but their size and irregularity warrant separate mapping. The False Bottom and Deadwood Gulch stocks may occupy a common fissure, as they lie in a line parallel to most of the dikes. The dikes in Deadwood Gulch follow westward-dipping lamination planes and are very commonly associated with breccias on the walls, in zones from a few inches to a foot or more in thickness, made up of fragments of schist embedded in a muddy, siliceous, or carbonaceous matrix, the latter derived from graphitic schist. Sometimes the porphyry is charged with a jumble of fragments.

The most conspicuous of these dikes is the great Texana dike, locally 600 feet in thickness, which stands out on the wooded hill slope as a wall ledge, and may be seen as a prominent landmark from the high summits for miles around. This has been chosen as a type for naming a district which really involves all of the exposed Algonkian area east of Spearfish Canyon containing any porphyry. All of the railway sections in the Bald Mountain mining district show dikes and irregular intrusions of many shapes and sizes cutting the schist. Several of these are crossed by the branch railway in Gold Run Gulch, between Deadwood and Lead. A big dike forms the bottom of Whitewood Canyon just above Pluma and crops out on both sides of the canyon. This dike is so large and irregular as to be worthy of separate mapping as a stock (Pl. XIX). It is complicated with another crossing it at right angles, and apparently forks to the southward in the spur between West Strawberry Creek and Whitewood Creek. One of these forks may be seen in the elbow of Grizzly Gulch, the western branch of West Strawberry Creek. Another dike, readily observed

[1] Loc. cit. p. 209.



LEGEND

CRETACEOUS				JURATRIAS		CARBONIFEROUS				
				JURASSIC	TRIASSIC	PERMIAN				
Pal	Kb	Kd	Kl	Jj	Jt	Cp	Cml	Cls	pt	pr
Alluvial	Benton dark shales	Dakota brown sandstones	Lower Cretaceous sandstones, and shales	Sandstones limestones, and shales	Red marl and gypsum	Minnekahta "purple" limestone and lower red marl	Minnelusa sandy limestone	Gray limestone	Porphyry talus	Porphyry

Fault — Possible fault — Strike — Dip

GEOLOGICAL SKETCH MAP AND CROSS SECTION OF BEAR BUTTE AND CIRCUS FLATS

BLACK HILLS, SOUTH DAKOTA

BY T. A. JAGGAR JR.

1900

Horizontal and vertical scale

0 — ½ — 1 — 1½ — 2 MILES

Contour interval 100 feet

Colored portions of section indicate rocks exposed

JULIUS BIEN & CO. LITH. N.Y.

on the line of the Burlington Railway, is seen across the creek near a sharp bend half a mile above Deadwood. This dike (Pl. XXII) is very uniform in width and parallel with the Algonkian bedding.

HOMESTAKE DIKES.

A section from southwest to northeast through the Homestake and Caledonia open cuts (fig. 87) serves to illustrate the frequency and thickness of dikes in the schist area that were conduits for westward-spreading sills and laccoliths. Here the schist dips to the east and contains much quartz, which in places is distinctly quartzite, elsewhere is massive quartz. The schist is red and ferruginous in this region, but talcose, slaty, or graphitic where less altered. The dikes average 35 to 40 feet in thickness. Three dikes in the Homestake section are associated with breccias; in one case on the foot wall; in another the fragments of schist are embedded in the igneous rock; and in the third case, a small 4-foot dike high up on the eastern slope of the main cut, a breccia 6 inches thick occurs on the hanging wall. These breccias sometimes contain fragments of both schist and porphyry, and therefore might be the product of faulting subsequent to intrusion. In other cases they are unquestionably the product of brecciation concomitant with intrusion.

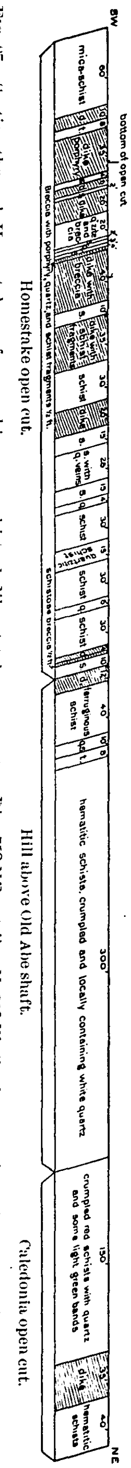


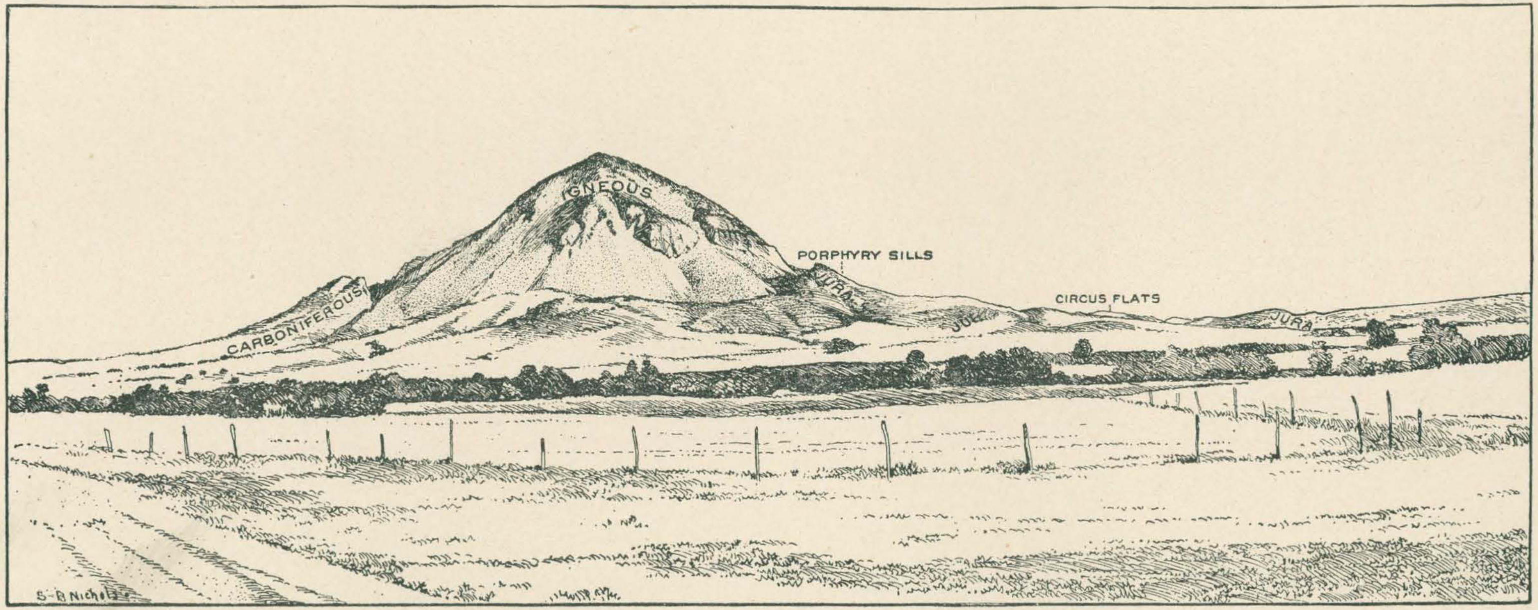
FIG. 87.—Section through Homestake surface workings. *s*, schist; *d*, dike; *t*, talus; *q*, quartz. Dip, 75° NE.; strike, N. 30° W. (both approximate). The sections probably overlap, making the error on the side of excess. Dikes do not always coincide with the lamination as shown, nor is the dip and strike uniform.

COLUMNAR STRUCTURE.

Two interesting dikes are shown in Pl. XXXIII, occurring on the west side of Whitetail Gulch. These are of fine-grained white rhyolitic porphyry cutting graphitic schist. In both cases the portion next to the walls is columnar, and a zone in the middle is massive and irregularly jointed. This arrangement of massive medial portion and columnar borders, while not invariable, is very common. The explanation of the phenomenon bears on important questions of interpretation in the case of isolated erosion forms like Mato Teepee, whose origin has been the subject of controversy. It is commonly understood that columnar structure is the product of contraction in a solidifying mass, comparable to similar phenomena in drying starch or mud. Polygonal cracking of a dried clay surface is due to differential contraction, greater in the superficial sun-heated stratum than in the moister depths. The upper stratum, forced to diminish in area while attached below to a stratum retaining more nearly its original extent, cracks uniformly under the uniform tensions developed. Polygonal parting is the form that results from a sort of natural economy of plane fractures.

In the case of a fissure filled with molten lava the walls act as cooling surfaces, and the first solidification takes place in that portion of the viscous mass which is in contact with those walls. This initial congelation is very rapid, producing a glassy selvage of lower specific gravity and consequently less subject to contraction than the crystalline forms of the rock; from the border inward crystallization goes on thereafter more slowly. Contraction will show its effects, as in the case of mud cracks, only in those directions where linear shortening is impeded by attachment to a surface tending to maintain its original areal extent. Such a surface is furnished by the dike walls when firmly cemented to the magma by the selvage. In any direction parallel to the walls, contraction being impeded by the failure of the attached wall surface to shrink with the rest of the material, parting planes are developed as the magma solidifies, these planes naturally lying normal to the tension that acts parallel with the walls. Thus, polygonal bodies with faces at right angles to the dike walls are formed from the walls inward as solidification proceeds. If a loose, porous, muddy breccia forms the walls, offering no rigid surface of attachment for the siliceous glass, contraction will not be impeded by the surface of attachment and regular columns will not form.

The size of polygonal columns is in some way a function of the extent and thickness of the intrusive body as a whole. The thickness of a dike or a sill and the size of the conduit probably have some influence on the length of the columns, for in some cases these will continue across the body from wall to wall. In other cases they extend into the dike for a foot or more, and are there replaced by a massive middle portion. The dynamic significance of this massive medial zone is probably somewhat as follows: The columnar parting being dependent upon differential shrinking of crystallizing magma relative to glassy selvage, the tendency to produce parting normal to the walls becomes less in the interior portions of a dike. As actual shrinkage is equal in all directions, as soon as the rock has solidified to such a distance from the wall that the drag of the latter is less felt, those components which act crosswise, as well as the lengthwise ones, begin to take effect. The first result will be recorded by curvature in the inner prolongations of columns already formed. Farther inward, in the heart of the dike, the drag ceases to have any effect and contraction takes place equally in all directions, producing irregular joints. If in this last stage fluid magma is still present in the region of the conduit or the depths, contraction may be compensated by movements in this magma, so that no parting is required. Good columns are seen



BEAR BUTTE, FROM THE NORTH.

at the head of the northern open cut at Terra, in the great headland capped by a laccolithic mass which projects from Dome Mountain into Two Bit Valley, in the Needles, and in Mato Teepee, hereafter to be described.

FEEDING DIKES.

The dikes of the Homestake open cut illustrate the great profusion of porphyry-filled crevices in the Algonkian (fig. 87). An interesting feature of the upper portion of the main open cut at Lead is the curvature of these dikes into sills in the Cambrian (fig. 72). A dike in the Caledonia open cut illustrates the formation of small columns on the walls. The occurrence of so many dikes and stocks in the small area of Algonkian schists exposed by erosion gives ample evidence of the mode of intrusion by which the porphyry reached the base of the Paleozoic series. There is, obviously, an equal number of dikes under any of the greater laccolithic masses, just as there is here ample evidence from the porphyry hill caps that laccolithic masses once extended over the area now occupied by dikes. There is no reason for supposing that independent laccolithic masses have single shaftlike conduits or "necks."

SILLS.

Sills occur in False Bottom Creek below Garden, in Squaw Creek, and in Annie Creek, showing phenomena similar in all respects to those of Two Bit Valley (p. 207). In the case of the sill conspicuous under the cliff north of Garden, truncation of Cambrian beds from southwest to northeast is shown at a very oblique angle, so that it is only by very close inspection that the departure of the plane of intrusion from that of bedding may be detected. Similar oblique truncation of bedding is shown in Squaw Creek, where the porphyry lenses reach a thickness of 50 feet in places, more than the height of spruce trees growing on a Cambrian bench below. These are in part the western extension of thicker porphyry masses at the head of Squaw Creek.

COMBINATION OF SILLS AND LACCOLITHS.

The porphyries in the schist area, representing laccolithic remnants, form domelike mountains which at first sight give the impression that the topographic domes are structural ones. Bald Mountain and Sheep Mountain are types of this, the dome shape being due to uniformly graded slopes on a hill made up of approximately horizontal sills and Cambrian strata, with a thicker remnant cap of porphyry forming a rounded talus of coarse blocks ("Felsenmeer") upon the summit. In Pl. XXXV, looking southwest from Polo Mountain toward Terry Peak, the schist area is seen to be an old lowland, Sheep Mountain on the left and Polo Peak in the foreground representing the base of the northern sedimentary rim of the Black Hills, thickened by porphyry. The straight divide seen in the middle distance is a mass of Tertiary and Pleistocene deposits.

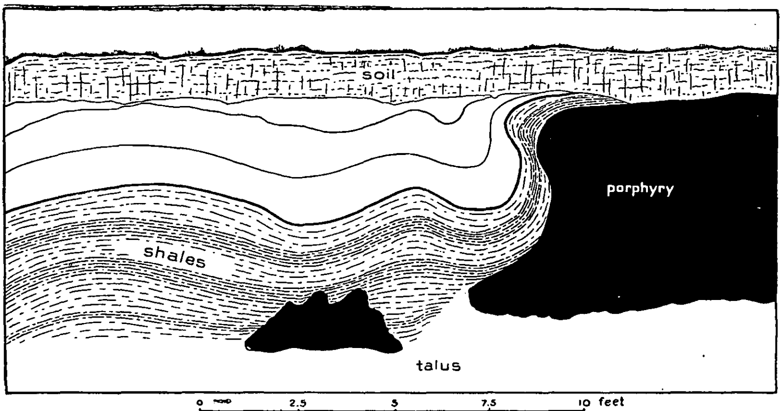


FIG. 88.—Deformation of shale by porphyry, Burlington Railroad, east of Whitetail Gulch.

TERRY PEAK.

Of the mountains made up of sills below, with a laccolithic remnant for cap, Terry Peak may be considered the type. None of these mountains can be called typical laccoliths, because the evidence for

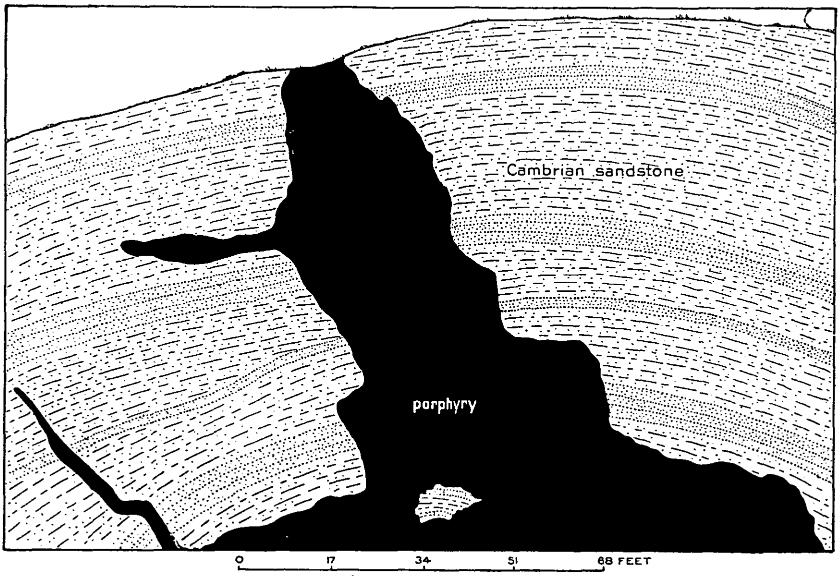


FIG. 89.—Irregular intrusions, north slope of Terry Peak.

their laccolithic structure based on flanking beds is almost invariably wanting by reason of deep erosion. A spur of the Terry Peak mass at the head of Raspberry Gulch retains a small remnant of Carbon-

CIRCUS FLATS, FROM BEAR BUTTE, LOOKING SOUTHWEST.

iferous limestone changing to the slope, which may indicate a former upper contact. The upper 300 feet of Terry Peak is of porphyry. Dikes, sills, and thick lenses of irregular form in Cambrian beds make up the rest of the mountain.

The railroad cuts and mines show many details of this structure. On the Burlington Railroad, near Aztec, a contact is shown with quartz-porphyry on the south and Cambrian shales and flagstones on the north, the contact curving from a wavy vertical line to a nearly horizontal one.

In the thick green shales at Portland porphyry intrusions of quite irregular form outcrop in a railway trench, some of these masses being almost elliptical in cross section and matching on opposite sides of the cut. Apparently the igneous material pushed its way through the shales in serpentine masses, like thickened lava on the slopes of a volcano, and such occurrences suggest strongly that the porphyry was very viscous at the time of its intrusion. The phenomenon is quite similar to that shown in Experiment I (fig. 101, p. 295), where the injected plaster spread irregularly in a layer of incoherent coal dust. Cases like this at Portland show that the shales, even when deeply buried under a sedimentary cover, offer as little resistance to the spread of an intrusive as they do to the action of the weather when exposed. They are inherently soft, whether subjected to superficial or subterranean tests. An illustration of this is shown at the bend of the railway east of Whitetail Gulch. Looking north in the cut (fig. 88), one sees that a dark-gray igneous rock with good vertical joints and very perfect horizontal lamellar parting has crumpled and distorted the shales. At the contact the cleavage in the porphyry bends to a west dip, parallel to the surface of deformation. In places the igneous contact followed curves of the deformed shale bedding, strongly suggesting extreme viscosity in the fluid at the time of its injection, and reluctance to follow any but the major stratification parting

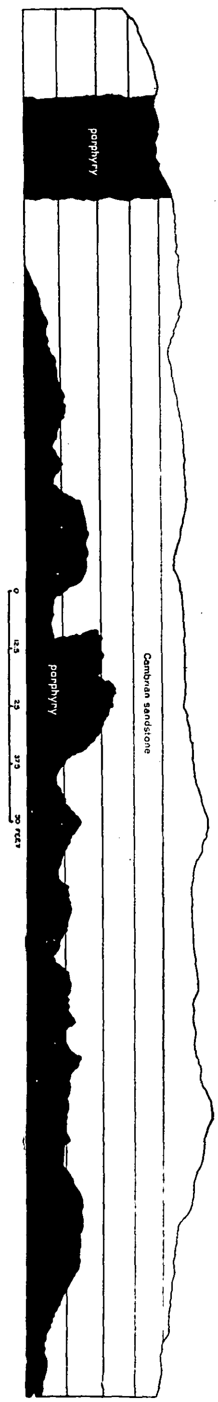


FIG. 90.—Section in railroad cut, north slope of Terry Peak.

planes. Occasionally it cuts these irregularly, as shown at the left of the figure.

Such irregular contacts are not confined to shales. Along the railroad on the northern slope of Terry Peak a dark-green phonolitic eruptive cuts across massively bedded red Scolithus sandstone, and here there is some appearance of violence (fig. 89). Fragments of the sandstone are embedded in the intrusive, and the strata are indurated and metamorphosed, with development of amorphous silica. There is no evidence here of the presence of a very large mass of this porphyry, as shown by a long exposure of its irregular upper contact (fig. 90), where the Scolithus sandstone is indurated to massive quartzite and adjacent cuts along the road are wholly in the igneous rock.

BALD MOUNTAIN.

Bald Mountain, a high northern spur of the Deer Mountain Range, is similar in structure to Terry Peak, but the Cambrian beds exposed are stratigraphically lower. At its base in Nevada Gulch, on the southern side, dikes complicated with faults in schist reach the Cambrian, which appears to have been shattered and shot through with igneous rock in every direction (see fig. 63, p. 188). A coarse breccia occurs on the high eastern spur of the mountain. The Fremont Railroad section on the south side shows at one point a 3-foot dike entering a sill which forms with it a T, like the conduit of the ideal laccolith. The sill is double and its upper member makes a very characteristic upward oblique bend into higher strata, and there comes to an abrupt end (Pl. XXXIV). In another section a narrow dike cuts massively jointed porphyry. In a third case a thick dike with eastward dipping walls and rough columnar joints has a smaller mate that curves like an arch through the Cambrian shaly limestones to unite with it above. The same railroad, on the northeastern side of the mountain, shows many equally various contacts of porphyry and schist. Bald Mountain is capped with a thick remnant of phonolitic porphyry.

SHEEP MOUNTAIN.

Probably the most deceptive of the sill-laccolith mountains involving Cambrian strata is Sheep Mountain, sometimes appropriately called "Roundtop" (Pl. XXXV). Topographically of wonderful dome shape, with the headwaters of Polo Creek encircling its base, this mountain would at first sight seem to the geologist to be an ideal laccolith. In this he is disappointed, however, when he examines the mountain in detail. The structure is so masked by talus that it is not clearly decipherable, but the greater part of the evidence points to a structure like that of Bald Mountain and Terry Peak, with some

COLUMNAR DIKES IN SCHIST, WHITETAIL GULCH.

additional features similar to the unsymmetrical Whitewood Canyon and Deadman laccoliths.

Sheep Mountain rises in the midst of the extensive northern porphyry area of the Terry-Polo complex, 2 miles northwest of Deadwood (Pl. XIX). On the crest of the ridge west of Sheep Mountain the Scolithus quartzite, characteristic of the top of the Cambrian, dips gently away from the mountain. On the south slope of Polo Peak, to the north, the same quartzite dips 65° southwesterly and overlies Cambrian limestone breccia and beds of calcareous and glauconitic sandstone. This dip is that of a bed upturned by the Polo Mountain porphyries. Rhyolite talus fills the hollows between Polo and Sheep mountains, but on such slopes the underlying bed rock is invariably masked. On the eastern slope of Sheep Mountain Scolithus quartzite, dipping eastward, overlies 40 feet of Cambrian beds, and in a small prospect hole the green shales, which are beds stratigraphically next above the quartzite, are seen to be cut across by coarse quartz-porphyry. On the southwestern spur of the mountain (fig. 91) this Scolithus quartzite dips S. 20° W. at an angle of 50°, but a few feet higher on the slope the *basal sandstone* of the Cambrian occurs, with

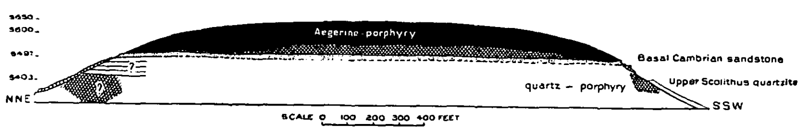


FIG. 91.—Section of Sheep Mountain.

fossils and pebbles, of entirely different aspect from the upper quartzite. This basal member may be traced around the mountain at about the 5,500-foot level, outcropping at six different points. On the west slope are intermediate Cambrian beds dipping southwesterly, showing brecciation and bending to a horizontal position. At one point west of the summit a fine-grained rhyolite was observed breaking upward and westward across glauconitic sandy beds, while the same beds were seen overlain by similar porphyry. The summit of the mountain is a green quartz-ægirine-porphyry, which seems to grade into a coarse white quartz-porphyry to the east and southeast. On the south side of the summit fine-grained rhyolite outcrops under the basal Obolus sandstone, and a shaft 40 feet deep on the slope above is cut in the green ægirine-porphyry to the Obolus sandstone beneath. These relations will be best understood by reference to fig. 91. The upturned Scolithus quartzite on the south, and the basal Obolus sandstone above forming a stratum beneath the porphyry cap, may imply a fault conduit on the south side, as in the Whitewood Canyon laccolith (Section B–C, Pl. XXI); otherwise, the mountain contains Cambrian and rhyolitic porphyries below and an ægirine-porphyry cap, and resembles Terry Peak.

LACCOLITHS.

True laccoliths in the Terry district, bearing to the sills and dikes below the same relation as that observed in the Deadwood district, are represented by Deer Mountain, Polo Peak, Spearfish Peak, Ragged Top, Citadel Rock, and Crow Peak. The masses originally laccolithic, but deeply eroded, are Custer Peak, Woodville Hills, Sugarloaf, Foley and Elk mountains, Little Crow Peak, and thick porphyry bodies north of Blacktail Gulch, at Carbonate, Lead, and at the head of Squaw Creek. Porphyry is revealed by the erosion of Spearfish Creek in its deep canyon at the mouth of Annie and Rubicon creeks and above the mouth of Squaw Creek; these occurrences may be sills or laccoliths.

DEER MOUNTAIN AND WOODVILLE HILLS.

Deer Mountain preserves much more perfect evidence of its laccolithic character than does Terry Peak. The whole group of peaks was known as the "Deer Mountains" by the Newton survey, and was described as follows:

> Terry Peak is the crowning point of an igneous region of considerable extent, having a maximum development in a northwest and southeast direction. * * * The peak stands upon the edge of the plateau. The Potsdam is extensively developed on its eastern side, and with it are occasionally outliers of the Carboniferous. Its sharply pointed summit is the most conspicuous landmark in the northern region of the Hills, and is visible from the plains far to the north and east. * * * The igneous group or range of which Terry is the highest point begins about 3 miles to the southeast, in a cluster of peaks called the Deer Mountains, and there is a nearly or perhaps quite continuous chain of trachytic and rhyolitic outcrops all the way to Terry. The same line continues northward for a few miles beyond Terry.
>
> The disturbance of the sedimentary strata is exceedingly local. * * * The sides of the ridge and of the peak are for the most part covered by a talus of angular and slippery fragments of rock (porphyry). On the summit of the peak the rock is well exposed, and three or four ridges of outcrop appear to radiate a few hundred feet from the central crest, while between them the slopes are composed of weathered fragments. * * * The igneous rocks of this region are varied in their appearance and texture.[1]

Deer Mountain is the southern rounded peak of the range and is a laccolith. The headwaters of Whitetail Gulch cut deep into the porphyry of its eastern slope. The greater mass of the Deer Mountain laccolith is exposed on the south and east slopes of the mountain, and monoclinal ridges or revet hills of limestone rest against the porphyry dome and dip away from it southwest, south, southeast, and east. Gulches along the contact of porphyry and sediments form a semicircular depression around the southern side of the mountain from Whitetail Gulch to Raspberry Gulch, occupied by small streams,

[1] Newton and Jenney, op. cit., p. 193.

JUNCTION OF DIKE WITH SILL, FREMONT RAILROAD, BALD MOUNTAIN.

uniting in pairs to form larger radial valleys in the limestone cover. At the head of Icebox Gulch and the next gulch to the east this kind of drainage is most perfectly shown. East of Deer Mountain, one-quarter of a mile south of the bend of the Burlington Railroad in Whitetail Gulch, a remnant of the limestone cover of the laccolith caps a small conical hill. The exposed laccolith is about 2 miles in diameter, but it is irregularly prolonged northward to the vicinity of Stewart Gulch, where it becomes complicated with the eruptives of Terry Peak and Sugarloaf Mountain. Deer Mountain is the principal igneous body of the range. Its northwestern thin edge is represented by sills in Cambrian at the head of Raspberry Creek. The horizon of intrusion is Cambrian, 100 feet of limestone flags and sandstones forming a cap to the mountain and extending down its northern slope to the complex of sills in the next peak to the north. This Cambrian cap contains a porphyry sill near the summit of Deer Mountain. No such thickness of Cambrian is exposed above the porphyry on the southern flanks of the mountain. The contacts are there either directly with the limestone or about the horizon of green shales at the upper limit of the Cambrian. The rock is in places a green phonolite-porphyry; elsewhere it is a quartz-bearing rhyolite-porphyry, sometimes very coarse. To the eastward the green phonolite extends into flat masses, capping hills about Englewood. Northeast rhyolite-porphyries in considerable masses occur on the hills about Sugarloaf Mountain, which is itself a laccolithic remnant exposing 250 feet of porphyry in the lowest Cambrian beds. Two miles east-southeast from Deer Mountain, across Whitewood Creek, the Woodville Hills expose a residual mass of rhyolite-porphyry 1½ miles in diameter and over 400 feet thick in places, resting across Cambrian strata from lower beds on the north to higher ones on the south, where the porphyry almost reaches the limestones, but erosion has removed all flanking strata.

The Deer Mountain laccolith and the Woodville Hills were masses of intrusive rock thickened under the great limestone and bending it on their southwest sides, while their conduits probably lay farther northeast, and their basement contact is an oblique truncation of Cambrian strata upward from northeast to southwest. A section through them in this direction, then, would show much the same structure as that represented in the section through Dome Mountain in Two-Bit (Pl. XXI, D–E), but in the opposite direction. Deer Mountain bears a similar relation, in position and distance, to the schist area of conduits and a Cambrian area of sills. Subordinate laccoliths are wanting to the Deer Mountain mass, probably because the flat-lying limestones of the plateau to the southwest opposed no initial bends, which would compel the spreading intrusive to break upward. Or possibly former subordinate laccoliths are now entirely removed by erosion. Ragged

Top and Elk Mountain, a few miles to the northwest, are examples of such laccoliths subordinate to the upper Squaw Creek porphyries.

CUSTER PEAK.

Custer Peak was described by Newton as standing "at the eastern margin of the Carboniferous plateau" and very little higher than the neighboring edge of the plateau. It lies 8 miles nearly due south of Deadwood, and from its slopes the headwaters of Elk, Box Elder, and Rapid creeks drain, respectively, north, east, and south. "It is a symmetrical, conical mass, and is a prominent landmark in the northern region of the Hills." Its altitude above sea level is 6,812 feet, and it rises from 800 to 1,000 feet above the valley of Elk Creek at its base on the north side.

The slope of the sides show only a loose mass of angular fragments. * * * On the extreme summit the rock is exposed in a Y-shaped ridge, with the stem of the letter bearing north 35° west. The rock has so perfect a vertical cleavage, following approximately the bearing of the ridge, that it might readily be taken for a bedded deposit, and in its close texture, uniformity, and color it so closely resembles the limestone of the Carboniferous that it might almost be so mistaken on a superficial examination. * * * It is a rhyolite of a light-bluish gray color, and a fine-grained and uniform structure, containing occasional crystals of sanidin and bright black hexagonal tables of biotite. To the east and northeast of Custer, and within a short distance, are two small peaks which appear to consist of igneous rock. * * * The margin of the plateau west of Custer Peak is exceedingly broken, and the composing rocks are not well exposed. A mile or so directly south, however, outliers of the Carboniferous limestone were seen in their horizontal position, occupying the summits of conspicuous bluffs, and immediately west of the peak, within a short distance of its base, are small fragmentary outcrops of the Carboniferous, undisturbed and unchanged. East of the peak and within half a mile of its base there are outcrops of the Potsdam [Middle Cambrian] along the headwaters of Box Elder Creek, showing the usual character of the formation, lying nearly horizontal, and, so far as observed, entirely unaffected by proximity to the igneous peak.[1]

Structurally Custer Peak is like the Woodville Hills. It is a mass of fine-grained rhyolite-porphyry, about 2 miles in diameter, resting across Cambrian strata (Pl. XIX). A small remnant of Carboniferous limestone, with down-curving dip northwesterly from 5° to 45° over Cambrian beds, persists in a synclinal depression northwest of the mountain, and similar limestone outcrops are visible from the summit southward. Outliers of porphyry resting on basal Cambrian beds or directly on the schists cap the hills to the northward. The central peak is surrounded by a rude circle of lower porphyry peaks; the same is true of the Woodville Hills. An elongate porphyry ridge northeast of Custer Peak appears to be a dike, with the usual northwest trend parallel to the Algonkian schistosity. Two and one-half miles north of Custer Peak similar porphyry caps all the hills from Woodville to Strawberry Ridge, a distance of 3 miles northeastward, and these cappings are continuous into the Woodville Hills on the southeast.

[1] Newton and Jenney, op. cit., p. 192.

PANORAMA SHOWING SHEEP MOUNTAIN AND PLEISTOCENE TOPOGRAPHY, LOOKING SOUTHWEST FROM POLO PEAK.

It is apparent that the lower beds of the Cambrian were invaded by a mass of the fine white rhyolite over a very large area now laid bare down to the schist by the erosion of Bear Butte and Elk creeks. A hill one-half mile north of Brownville retains a Carboniferous limestone remnant dipping northeast over porphyry. Similar porphyry, and porphyry breccias, cap the adjacent hills at a distance from Custer Peak of 2½ miles. The synclines which separate Custer Peak from the Woodville Hills and the latter from Deer Mountain afford good evidence, in addition to physiographic proofs (see pp. 274, 276), that these three laccoliths were distinct, independent dome swellings under the great limestone, but the first two were also connected with a great mass of porphyry filling an anticlinal arch between Brownsville and Kirk and extending thence southeast for some distance. A chain of large dikes that were the conduits of this mass may be traced northward from south of Elk Creek, through West Strawberry, Whitewood (Pluma), Gold Run, and Deadwood creeks, to the mouth of Blacktail Gulch, where an immense dike is seen to bend upward into the thick porphyry mass that caps the ridge.

POLO AND SPEARFISH PEAKS.

The igneous masses extending from the greater Terry Peak and Deer Mountain laccoliths to the northeast reach their greatest development in Polo Mountain 3 miles northwest of Deadwood. From Blacktail Gulch north the hills are covered with porphyry, and the northward-flowing creeks have cut gullies through the igneous rock to Cambrian beds beneath. Along the divide at the head of Polo Gulch, Tertiary and Pleistocene clays and gravels occur in large masses, in part concealing the bed rock. In Sheep Mountain a complication of Cambrian and porphyry occurs as described. North of Sheep Mountain, Polo Peak rises to a height of 5,400 feet, and there is another summit north of it. Cambrian beds dip away on the southwest flank of Polo Peak, and occur under the porphyry in Miller Creek on the west, while on the east and southeast the limestones dip away from the irregular porphyry body, which, as a whole, was intruded in the shales beneath the Silurian. The intrusive of the northern peak, however, breaks across the limestone into Minnelusa beds, and the same is true of Spearfish Peak, 4 miles to the west.

The interstream ridges between Spearfish and Polo peaks are capped with porphyry, in part intrusive into the Carboniferous limestone and in part below it. The rock of Spearfish Peak is peculiar and was recognized by Caswell in Newton's report as a phonolite. It is probable that igneous bodies from west of Spearfish Canyon to Whitewood Gulch were continuous prior to the erosion that has separated them into cappings and north-dipping lenticular bodies in the several ridges.

The relation of Polo Peak as a laccolith to the greater masses that were probably once continuous northeast from Terry Peak is similar to that of the eastern portions of the Vanocker laccolith; the greatest difference lies in the fact that over the Polo laccolith the limestone, only 100 feet thick (Pl. XIX), was readily flexed upward as compared with the thick limestones of the vicinity of Runkel. Westward to Spearfish Peak the diminution of porphyries accompanies thickening of limestone. Eastward to Whitewood Canyon the Polo Mountain igneous masses thin to a single sill in the gulch opposite the smelter at Deadwood. East and west, isolated subordinate laccoliths have broken across the limestone, but the region from Deer Mountain to the northern extremity of Polo Mountain was the site of maximum irruption, and igneous fluids there filled the arch of a very large irregular anticline having an axis of north-south trend.

SUBORDINATE LACCOLITHS.

With the exception of Ragged Top, laccoliths demonstrably subordinate to the greater Terry-Polo masses, in the sense of being distinct offshoots, are wanting. The Whitewood Canyon laccolith, already described, is probably as closely connected with Polo Peak as with the

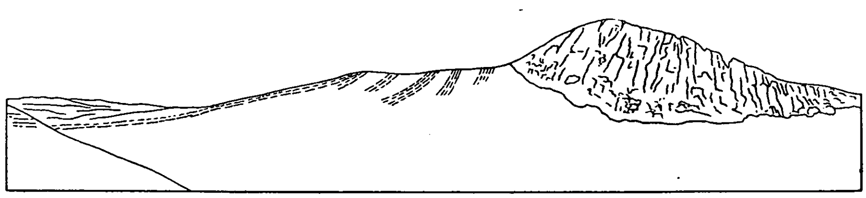


Fig. 92.—South side of Ragged Top Mountain (Irving).

Two Bit eruptives. Crow Peak and Citadel Rock, 4 to 5 miles west of the mouth of Spearfish Canyon, and hence west of the greater syncline, are as much related to the Iron Creek and Cement Ridge porphyries as to those of the Terry district.

RAGGED TOP MOUNTAIN.

Ragged Top is a steep laccolithic mountain, three-quarters of a mile long by one-half mile wide, its greatest length trending east and west, and its form a crescent with horns turned southward. It is about 3 miles west of Bald Mountain, and is surrounded by flat limestones. It has been figured (fig. 92) and described by Irving as follows:

A little to the north of west and about 1 mile distant from Crown Hill, the low dome-like mass of Ragged Top Mountain rises some 400 feet above the level table-land of the Carboniferous plateau. It rises between the two confluent gulches of Calamity and Jackass creeks, the former shallow along the upper part of its course but becoming precipitous as it rounds the western end of the mountain. Here it unites with the more deeply carved gulch of Jackass Creek. Thence the two pass together between almost perpendicular walls of limestone into Spearfish Canyon. * * * In going upward from the west, north, or east [ascending the mountain] one passes over gently sloping strata of Carboniferous limestone which have an increasingly steep dip until within 250 feet of the summit. A rounded bluff of phonolite is then encountered, over whose crest one may readily climb and proceed up a decreasingly steep rise to the flat top of the hill. From this point the mass presents a somewhat unique topographic appearance, for it comprises two almost distinct roughly triangular masses of phonolite. * * * From both of these masses incurving tongues of phonolite run out to the south, circling toward one another so as to include and almost surround a large southwardly inclined amphitheater. * * * If one crosses Calamity Creek to the top of the limestone bench [at the west end of the mountain] the slight, almost imperceptible westward dip of the limestone may be seen to greatly increase as the phonolite is approached, until at the foot of the bluff, or about 20 feet distant therefrom, it has attained an angle of 51°.[1]

This is well illustrated in fig. 92. At numerous points about the mountain Cambrian shales are exposed, showing that the horizon of intrusion is the usual one, but so abrupt is the upward puncture made by the porphyry that it appears at a distance like a neck or a conduit through the limestone. Irving has shown that in a section revealed by the Badger shaft, on the north side of the mountain, the Cambrian shales lie against an almost vertical wall of porphyry, and have been followed to a depth of 316 feet. Irving's conclusion is as follows:

On two sides, namely, to the east and south, the sediments have been worn away from the immediate neighborhood of the abrupt escarpment of phonolite. * * * On the west and north the sediments extend to the very foot of the igneous bluff, where they are upturned at a very high angle. On the very top of the mountain a small portion of Cambrian shale still remains.[2]

This arrangement is precisely what would be expected in a viscous subordinate mass breaking outward and upward to the west from the greater domes at the head of Squaw Creek. At the western end of the mountain the limestones are flexed backward sharply; at the eastern end they were lifted more gently, and perhaps somewhat fractured, as in the case of the Whitewood Canyon, Deadman, and Bear Butte laccoliths. It seems hardly necessary to postulate any considerable faulting to account for the present crescentic form of the mountain. The horseshoe shape accords perfectly with that of Citadel Rock and Inyankara (p. 274), and may be explained by simple erosive action resulting from the inheritance on the porphyry of annular drainage, superposed from domed sediments above.

CROW PEAK AND CITADEL ROCK.

Some 5 miles west and south, respectively, from the town of Spearfish are Crow Peak and Citadel Rock, two elliptical exposures of igneous rock, 2 miles apart, each about a mile long when measured northwest-southeast. Both dome up strata from Cambrian to Permian. Crow Peak, the more northerly of the two, arches the encircling beds more abruptly than does Citadel Rock. Crow Peak is a

[1] A contribution to the geology of the northern Black Hills, by John Duer Irving: Annals New York Acad. Sci., Vol. XII, No. 9, pp. 212-214.
[2] Op. cit., p. 217.

high mountain, Citadel Rock is an isolated butte encircled by a higher ridge of sediments of horseshoe shape. The summit of Crow Peak rises 5,785 feet above the sea; Citadel Rock, 5,450 feet. The relation of these two is not unlike that of Circus Flats and Bear Butte. Circus Flats marked the lower main laccolith of which Bear Butte was a subordinate upshoot. Crow Peak, which strongly resembles Bear Butte, may be subordinate to a large subterranean mass of which merely the crest is revealed at Citadel Rock.

Crow Peak is the highest point in the northern Hills lying so near to the Red Valley. Its proximity to the plains gives to its relief excessive prominence. Seen from the east (Pl. XXIX) the conspicuous elements of its profile are a sharp conical southern peak of porphyry and a steep monoclinal scarp of limestone resting against it on the north side. Thrust up through the limestone where the sediments had long, gentle dip slopes northward, the igneous core is completely

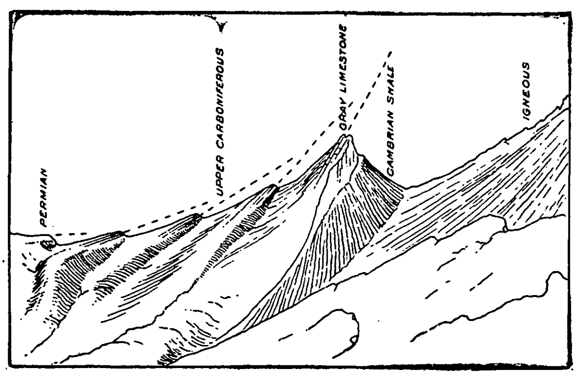


FIG. 93.—South slope of Crow Peak, showing change of dip.

revetted with rounded imbricating monoclinal ridges of Silurian and Carboniferous limestone dipping steeply away on all sides (Pls. XIX and XLI). Wherever the contact was examined closely Cambrian beds were found, and on the north side peripheral sills in Cambrian occupy the hollows in the bend, as figured in the original (Henry Mountains) laccoliths. Dips taken while ascending a gulch on the north side of the mountain varied from horizontal one-half mile north of the mountain to 27°, 40°, 65°, and 89° in Minnelusa, gray limestone, and Cambrian beds. A tunnel at the head of the gulch, cut horizontally for 110 feet southwest into the mountain, passes through 105 feet of porphyry and penetrates for 5 feet at the end a bed of quartzitic sandstone dipping 12°, N. 20° W. The contact of the porphyry with this sandstone is ragged and trends NNW. The sandstone shows *Obolus* and evidently represents the lowest of the Cambrian beds. From this it would appear that the whole Cambrian section is upturned to the northwest by the Crow Peak uplift, and the porphyry traversed by the tunnel appears to be a steeply upturned cross-cutting sill or dike.

The summit of Crow Peak is a sharp edge like that of Bear Butte, trending northwest and running out into a knife-edge, with spurs flanked by steep talus slopes and precipitous walls. High on the east side the sediments lap against the steep laccolith, dipping 51° to the east, and the limestone shows small faulting with western upthrow. On descending the east slope, beds from Cambrian to Minnekahta limestone (Permian) are crossed in a distance of one-half mile, and the transition to low dips and horizontality is very sudden. The most striking revet crags are seen on the south side of the mountain, where they form crescentic ridges with bare limestone crests, separated from one another by V-shaped trenches that give passage to rills which regularly fork into two within the V along the porphyry-Cambrian contact. Fragments of brown sandstone and Scolithus quartzite occur near the porphyry, and in a few hundred yards the geologic section from Carboniferous to Permian shows a change in dip from 60° to 0° (fig. 93). This sudden change of dip in consecutive outcrops of overlapping strata is charac-

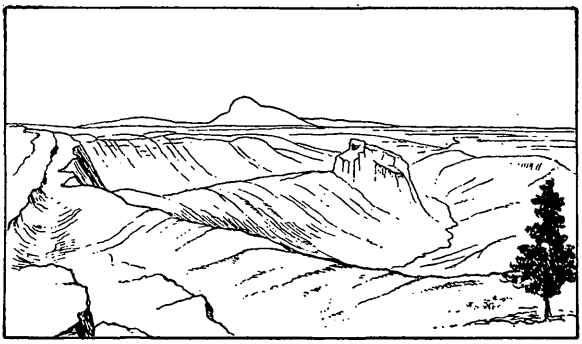


FIG. 94.—Citadel Rock, looking northward toward Crow Peak.

teristic of the steeper laccoliths (see fig. 92), and the distance in which the change takes place is sometimes actually less than the normal thickness of the beds involved. The structure shown would not permit uniform curvature of all the strata over the dome. The only explanation for such structure is that there has been rupture of the hard beds, with stretching, compression, and flow in the soft beds. The soft beds thicken in the concavities and thin on the arch. Crow Peak is encircled on the east, south, and west by Higgins and Crow creeks and their tributaries; on the north a flat upland slope of Minnekahta limestone extends out to the Red Valley, where it abruptly bends downward, while Minnelusa sandstone forms a ridge to the northwest, with anticlinal structure, suggesting the extension in that direction of an elongate subterranean tongue of igneous rock from Crow Peak. The very rapid bend from steep upturning to horizontality is well shown by the present attitude of the Minnekahta limestone, which completely encircles the mountain in nearly horizontal tables, and makes a broad spoon synclinal on the south side (Pl. XLI).

Citadel Rock has been uncovered by erosion in much the same fashion as Circus Flats. Branches of Robison, Johnston, and Higgins creeks have so eroded the dome of limestone that was above the laccolith that the Minnelusa cover is removed, and one north-flowing stream has breached the gray limestone and Cambrian; with its headwater forks it has eaten out an annular valley in the porphyry about a spur which has a columnar castellated tower rising in the center; the crest of the "Citadel" is 400 to 500 feet above the gulches on either side (fig. 94, Pl. XLI). The northern end of the Citadel Rock spur still retains a veneer of Cambrian beds. The Cambrian, Silurian, and Carboniferous section is clearly shown in the horseshoe rim of sediments that incloses the annular valley, and within this rim, on the southeast side of the basin, a sill occurs in the Cambrian. The columnar Citadel is connected with the encircling escarpment by a singularly straight ridge of porphyry; the limestone horseshoe rises to a height of 200 feet above the summit of Citadel Rock.

It is clear that Crow Peak stands high by reason of the steep inclination of peripheral contacts and the great height of the porphyry topographically, whereas Citadel Rock, topographically lower and with contacts less steep, has until very recently been subjacent to easily eroded Cambrian shales, which were hollowed out as a basin beneath the salient, hard Carboniferous limestones and sandstones. So completely is the Citadel concealed within its encircling rampart of forested hills that it has never been noticed by earlier geological explorers, although the actual area of porphyry exposed is almost as great as that of Crow Peak.

SUMMARY OF TERRY DISTRICT.

The Terry district of laccolithic porphyries contains types characteristic of a deeper zone than the Two Bit district, just as the Two Bit district is stratigraphically lower than the Vanocker district. The conspicuous features of the Terry-Polo complex are conduits and eroded remnants of laccoliths. Erosion has gone deeper because the region as a whole is higher. Conduits are represented by stocks in schist and by innumerable dikes which follow Algonkian lamination. Some of these filled fissures inclined west, others east. The one set spread to the east and the other to the west when the porphyry reached fissile, flat-lying Paleozoic beds. Sills were formed in the Cambrian, and these thickened into laccoliths. By reason of a thinner Cambrian section, sills were less numerous and thicker than in Two Bit. The major laccoliths are preserved with their flanking strata in the edge of the Carboniferous plateau and in the northern Paleozoic escarpment. Eruptive masses like Spearfish Peak broke outward and upward across initially dipping limestones. A characteristic type of mountain left by erosion is dome shaped, with a laccolith cap, and sills below. The

Terry intrusives as a whole occupied a great arch between Spearfish Creek and Whitewood Creek, beneath an axial line of thinnest limestone. Where the limestone broke on the flanks of the arch the rupture gaped below, and viscous magma oozed out through the fractures, to harden in small domes of intense flexure, like Ragged Top. To the northwest, in the general trend of Custer Peak, Woodville Hills, Deer Mountain, Terry Peak, and Ragged Top (a trend parallel also to the dikes), masses of intrusive rock rise through Upper Carboniferous and Permian limestone to form a lower southern laccolith, Citadel Rock, barely breached by erosion, and a higher and steeper northern one, Crow Peak, that forces up the sediments steeply about its flanks.

LACCOLITHIC INTRUSIVES OF SUNDANCE DISTRICT.

The Sundance district contains two greater centers of igneous activity. The one on the east resembles somewhat the Terry district, containing rocks from Algonkian to Permian, with dikes, sills, and laccoliths. This has been called the Cement Ridge complex, the name being that of the highest porphyry summit, a forested peak comparable to Terry Peak in its position at the edge of the limestone plateau. Large masses of porphyry, the main laccoliths, occur about the headwaters of Beaver Creek and Iron Creek, and Black Buttes, somewhat separated from the rest, forms a laccolithic uplift of considerable size adjacent to the Red Valley on the west side of the Black Hills. Subordinate laccoliths are the Needles on the north, and Spottedtail Dome and Inyankara Mountain on the west.

The second igneous center is the Bearlodge Range, an elongate uplift of Paleozoic rocks with igneous core, trending northeast and southwest, lying northwest of the Black Hills uplift proper, and separated from it by the Red Valley at Sundance. Subordinate to the greater medial intrusion, which reaches its culmination in the Warren Peaks, minor laccoliths have broken through Mesozoic beds on both flanks of the range; these form the Sundance Hills on the southeast and the Little Missouri Buttes and Mato Teepee on the northwest.

The data recorded here for the Sundance district were obtained during a reconnaissance of two weeks' duration in October, 1898, made with a view to comparing the igneous phenomena of the northwest with those more thoroughly studied in the Deadwood and Terry districts. In this excursion the writer was efficiently assisted by Dr. J. D. Irving. The Cement Ridge country, Black Buttes, Inyankara, Sundance Hills, and Warren Peaks were accorded very brief examination en route to Mato Teepee, where a longer stay was made in order to settle, if possible, disputed questions concerning the origin of that extraordinary monolith and its companion hills, the Little Missouri Buttes.

CEMENT RIDGE COMPLEX.

LACCOLITHS.

CEMENT RIDGE AND IRON CREEK.

Topographically Cement Ridge, 2 miles south of Welcome, extending as a height of land far to the south, marks the same sort of culminating porphyry center as Terry Peak to the east and Warren Peaks to the west; it forms the divide from which streams flow east to Spearfish Creek and west to the Grand Canyon. West of Cement Ridge the stratified rocks dip away very gently, the Minnelusa sandstones of Spottedtail, Rattlesnake, and Cold Springs valleys appearing almost horizontal and exposed for great distances. It was in one of these valleys farther to the south that Winchell first saw the Minnelusa rocks, and he gave the Indian name of the creek to the formation. The wide valley formed by the "Red Beds" south of Sundance shows a striking symmetry of topographic forms on either side. To the northwest are seen the long level summits of the Bearlodge Mountains, with the two laccolithic outliers, Sundance Mountain and Green Mountain ("Little Sundance Dome") in the Red Valley at their feet. To the east Cement Ridge forms a similar long crest, with Black Buttes rising abruptly from the Red Valley at its foot; and north of these buttes occurs a long dome, hitherto not noticed by geologists, that corresponds in position on the eastern side of the valley to Green Mountain on the western. This hill, here called the Spottedtail Dome, is encircled by a rim of Minnekahta limestone, as in the case of Green Mountain (Pl. XVIII).

The summit of Cement Ridge is porphyry, apparently intruded about the base of the Cambrian, for the basal quartzite of that formation forms a ledge dipping at a low angle off the mountain on the west at the head of Rattlesnake Creek, and conglomerate underlies the porphyry on the east side. About the head of Beaver Creek the country is densely forested and shows but few outcrops. The float is Cambrian and porphyry. Large laccolithic bodies occur on Iron Creek south of Bear Gulch. These again are in part intruded at the base of the Cambrian, for the basal conglomerate overlies them (Pl. XIX). Iron and Deer creeks flow east to Spearfish Canyon. They apparently drain the eastern flank of a laccolith of large size and relatively gentle curvature. The region between Bear Gulch post-office and Cement Ridge shows alternations of Algonkian, Cambrian, and porphyry, indicating the presence of many dikes and sills. The dikes west of Bear Gulch have a general NNW. trend, and the usual tendency of the porphry to form hill cappings was observed, as at Lead, indicating the presence of eroded remnants of sills and laccoliths.

BLACK BUTTES AND SPOTTEDTAIL DOME.

Newton mentioned "a nameless peak northeast of Inyankara," composed of igneous rock. This igneous mass proves to be a group of hills of some size, containing laccolithic intrusions in strata ranging from Cambrian to Permian. The Black Buttes must not be confused with "Black Butte," an old name for Spearfish Peak. They lie west of Cement Ridge, separated from it by a wide area of Minnelusa beds lying almost horizontal, so that they form a separate center of irruption.

The Black Buttes are a group of hills composed of porphyry, which breaks through and uplifts by intrusion stratified sediments from Cambrian to Red Beds. Approaching the Buttes from the northern side, one observes that the several radial creeks have cut V-shaped trenches in Minnekahta limestone and Minnelusa limestones and sandstones. Looking to the north from the summit of the northern butte, the Minnekahta limestone on the eastern border of Red Valley is seen to lie rather flat, conforming to very gentle dips noted in the valleys on the western flanks of Cement Ridge. Three and a half miles to the north, however, is seen the long, low, Spottedtail Dome, exposing Minnekahta limestone dipping away in both directions, and a Minnelusa core in a long ellipse of northwest-southeast axis. The northern hills of the Black Buttes are three in number; the two western ones are sharp, conical peaks of porphyry; a more elongate one to the east is composed of Carboniferous limestone. On the northern side of the middle hill porphyry was found directly in contact with Minnelusa sandstone, here indurated to quartzite. From the summit of the hill the Black Buttes are seen to be an irregular group of hills, occupying an area of some 20 square miles. The hills inclose basinlike depressions, and in one of these were found prospecting tunnels and shafts cut through glauconitic and calcareous Cambrian shales.

The porphyry breaks across strata from east to west, forming intrusive sills and small laccoliths at progressively higher horizons. Gray limestone is uplifted by the porphyry in the peak farthest to the southwest. In the Cambrian shales mentioned a small dome was traced in three outcrops, the quaquaversal curvature being indicated by radial dips. There are numerous small conical porphyry-capped hills, producing topographic irregularities in the inner basins. In a tunnel about the central portion of the Black Buttes an upright contact of porphyry and gray limestone was found. The section through the uplifted limestone on the southwest is similar to that through the Deadman laccolith (Pl. XXI, F–G), with the difference that, in the Black Buttes, Minnelusa sandstone dips under the porphyry instead of being beveled across by it (Pl. XXXVI). The Black Buttes as a whole form a small isolated igneous center, involving all the Paleozoic rocks, the porphyry spreading outward and stratigraphically upward toward Inyankara. Inyankara Mountain is undoubtedly an offshoot of the greater Black Buttes laccoliths. Spottedtail Dome may cover a large laccolith somewhat analogous in position to that of the Black Buttes and possibly on the same line of conduits beneath, but the porphyry lies topographically too low to be dissected by the present drainage, and hence is not as yet revealed.

SUBORDINATE LACCOLITHS.

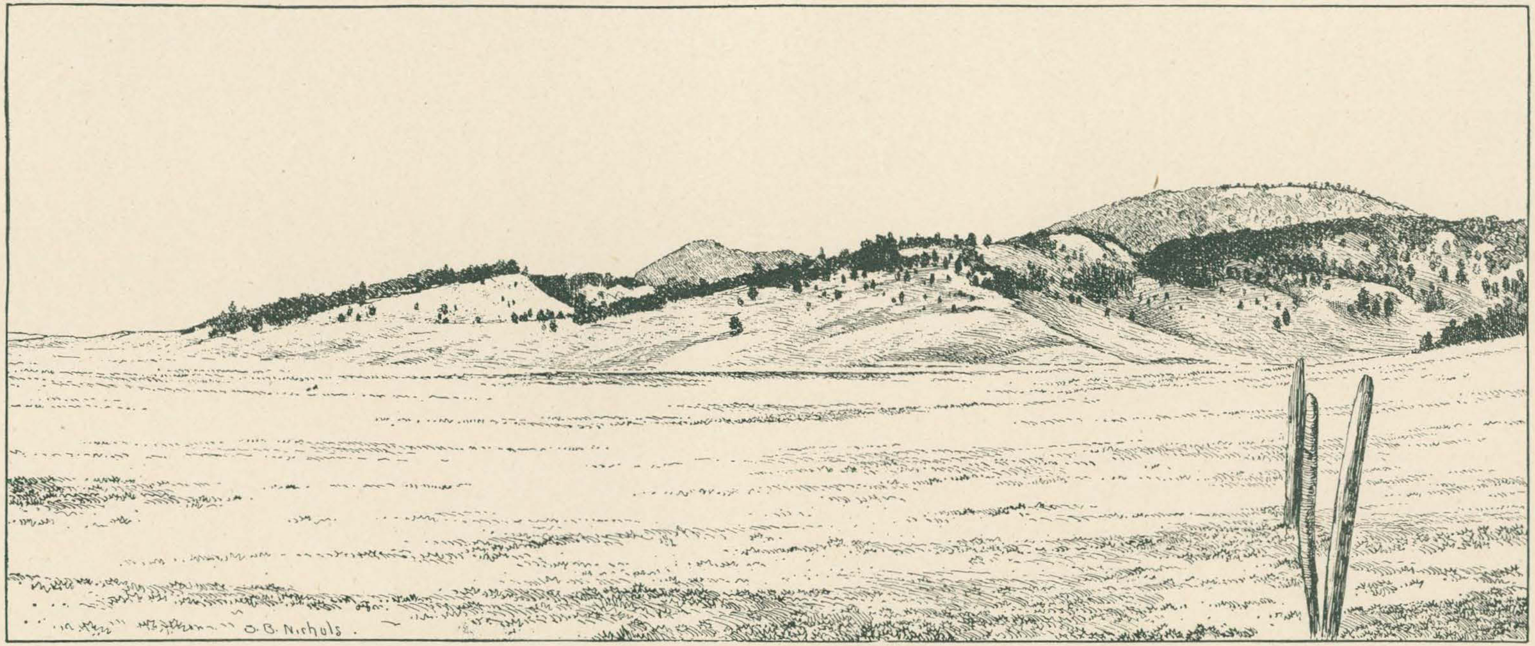
THE NEEDLES.

A porphyry mass between Beaver Creek and Bear Gulch, passing into large dikes southward, is locally known as "The Needles," or Connors Peak. This eruptive body shows characteristics similar to some of those of the better-known laccoliths, but the hills being densely wooded and the rocks little exposed it is difficult of investigation without extended study. The eruptive cuts Carboniferous limestone on the north and east, and upturned Cambrian strata are seen on the west and south, while porphyry occurs on the southwest directly in contact with the coarse pegmatite and schists of Nigger Hill. There is thus a region of vents through the Algonkian exposed in this Nigger Hill district, and dikes of porphyry cutting the Algonkian rocks are found farther south on the main road to Welcome. In general the Needles may be described as a mass of porphyry of irregular form breaking across beds from Cambrian sandstone on the south and west to Carboniferous limestone on the north and east. Its castellated pinnacles form a prominent feature in the landscape.

Irving describes the Needles as follows:[1]

> This porphyry uplift * * * consists of a series of extremely sharp conical peaks * * * which show the most perfect columnar parting that the writer has seen in the Hills, with the exception of those exposed in the Devil's Tower. The columns are vertical, and are broken across by a jointing which shows a rough resemblance to the ball and socket jointing of basalt. Three of these conical peaks are especially high, one of them rising 500 feet above the bed of the creek below.
>
> Viewed from the south, they bear, collectively, strong resemblance to a huge dike, but on ascending the highest of them, one is impressed with the almost plug-like character of the mass. The Carboniferous limestone can be seen to the east, north and northwest, forming a wall about the uplift. On the west there seems to be an extension of the porphyry. On the south great blocks of indurated sandstone occur and the Cambrian is extensively exposed in this direction. * * * In between the lower porphyry hills exposures of Cambrian shale occur, as if in its intrusion the rock had included a portion of that series above itself, and had elevated this to the level of the surrounding limestone. [Compare Sheep Mountain, Dome Mountain, and Whitewood Canyon laccolith, fig. 91 and Pls. XX and XXI.]

[1] A contribution to the geology of the northern Black Hills, by J. D. Irving: Annals New York Acad. Sci., Vol. XII, No. 9, p. 224.



BLACK BUTTES, FROM THE SOUTHWEST.

It will be seen from this description that the Needles are a subordinate laccolith like Ragged Top, flexing back the massive limestone on the side remote from the greater Cement Ridge masses, and were injected probably in a highly viscous condition through the Cambrian beds on the northern border of the larger southern laccolith. Lying a short distance west of Crow Peak, the Needles occupy a similar position structurally. The rock of the Needles is somewhat unusual—a diorite-porpyhry without mica, containing phenocrysts of automorphic hornblende, sanidine, and plagioclase in a groundmass of plagioclase, magnetite, and orthoclase.

INYANKARA MOUNTAIN.

Inyankara Mountain was described by Winchell[1] more accurately than by Newton. The mountain rises on the outer side of the Red Valley 4 miles southwest of Black Buttes. It has a height of 6,313 feet above the sea and some 1,400 feet above Inyankara Creek, which curves in a semicircle around the north side of the mountain. Its striking circular symmetry—a cone in the middle of a horseshoe ridge—has been variously compared to a hat, saucer, etc. Winchell describes the mountain as follows, and the observations quoted accord with the writer's:

> Its summit, which rises high enough to mark it as an important peak among the hills that surround it, has the shape of an inverted saucer, with another smaller inverted saucer lying on the top. * * * Before reaching it we pass over three or four foothills, composed of Jurassic and Cretaceous. * * * These formations are not greatly disturbed by the uplift, but still show a very perceptible dip away from the mountain. At the foot of the mountain * * * we enter upon the Carboniferous limestone, which has a dip of about 30° from the horizontal, varying from 20° to 60°, sometimes presenting shoulders that have a confused dip, or stand vertical. Over this we climb to a height of about 500 feet to the top of a circular ridge which incloses the main columnar center of the mountain. * * * Crossing a wooded glen * * * we ascend the peak from the south. The shape of the summit, which at a distance has the aspect of a small saucer lying on a larger one, both inverted, is caused by the central mass rising above the rim or ridge, by which it is nearly surrounded. The only opening in this rim is towards the north 10° east, where it is entirely wanting. The ridge is about three-quarters of a mile distant from the central mass, in all directions, and gives the outline of the larger saucer. It does not rise as high as the central mass. * * * The intervening space is occupied by a dark valley, narrow, and shaded with Norway pines. It is very difficult, and in many places impossible, to pass from the ridge to the center across this gorge, the rock rising sheer up on nearly all sides about the central mass. * * *
>
> The Carboniferous limestone seems to be warped into a wave-like surface when exposed on some of the lower flanks, a fact also noticed at other places, and lies at a high angle of incline all about the mountain's base. The rock * * * is igneous, thrust through the sedimentary strata. There is a very marked system of perpendicular jointage planes that cut the main ridge east and west, the individual planes

[1] Geological Report on the Black Hills, by N. H. Winchell: Reconnaissance of 1874, by Captain William Ludlow, Engineer Department U. S. A., Washington, 1875, p. 17.

being about 10 inches apart or closer. Another system runs northeast and southwest, the planes being 4 feet apart, and tipped (their tops) toward the southeast about 10°; while a third system runs perpendicular to the last, and has the tops inclined toward the northeast about 10°. These larger divisions of the rock cause, on being weathered, the columnar structure seen all about the sides of the central mass. There is, besides, on the western side of the central mass, a fourth system of joints, that slope toward the west at an angle of about 45°, which gives the whole mass at that point the appearance of being a heavy-bedded, upheaved sedimentary rock. * * * The east side of the horseshoe ridge is made up of much the same kind of rock, but weathers whiter. It is very much cut up by divisional planes, and stands up in vertical dike-like ridges in some places on the east and southeast.

Newton failed to recognize the Carboniferous or Jura-Cretaceous in the encircling beds, nor did he note that the horseshoe rim is formed in part of porphyry. He was under the mistaken impression that the purple Permian limestone and the Red Beds were the only strata affected by the igneous uplift, and that this same limestone formed the annular ridge. The annular valley about the central porphyry core has been commonly supposed to represent the contact between porphyry and sediments. The writer visited the rim of this valley, and the first ridge outside of the deep gorge that surrounds the central eruptive dome proved to be porphyry, as stated by Winchell, a case by no means uncommon in these laccolithic masses, and resulted from the superposition on porphyry of an annular valley originally formed in sediments (see Citadel Rock, fig. 94). The Inyankara horizon of intrusion, so far as revealed by the eastern contact, is the Minnelusa formation, which here forms a dense white quartzite in contact with the porphyry. One or two sills of porphyry were crossed in their normal position, i. e. the angle formed by buckling of strata about the base of the uplift. The hard and soft beds of Minnelusa, Permian, Trias, and Jura form a series of concentric ridges and valleys inclosing the inner porphyry dome.

Inyankara Mountain represents a stage in denudation much like that of Citadel Rock. It is, however, a steeper dome, intruded stratigraphically higher, and may be classed genetically with Crow Peak and Bear Butte. It is probably subordinate to the greater mass of the Black Buttes. Relative to Bear Butte and Crow Peak it represents an earlier stage of uncovering by erosion. In future centuries the flanking sediments will wear lower, the porphyry will assert its more resistant quality and stand in much greater relief, and the annular valley will lose definition until it persists only in the mountain profile, which will remain divided rudely into three parts, a central high summit and irregular lower ridges on either side (see fig. 97).

BEARLODGE COMPLEX.

LACCOLITHS.

The greater porphyry masses of the interior of the Bearlodge Range may be considered the principal laccoliths to which the Sundance Hills are subordinate. It is not clear that Little Missouri Buttes and Mato Teepee are subordinate to the Bearlodge core in the same sense, for, as will be shown, there is good reason for the belief that Mato Teepee is a subordinate extension from the Little Missouri Buttes as a center. In this case the spread of the igneous magma was southeast, toward the Bearlodge Range, instead of away from it. As the rock of the Little Missouri Buttes and Mato Teepee is lithologically very different from known specimens from the Warren Peaks and Sundance Mountain, and contains inclusions of the older rhyolitic porphyries, it is probable that the Little Missouri Buttes laccolith was injected independently of and later than that of Warren Peaks. This is borne out by evidence which shows that the dip of sediments away from the greater Bearlodge uplift existed at the time of the Mato Teepee intrusion. It is probable that both of the greater intrusions came up through fissures in the Algonkian inclined eastward from the vertical, and therefore had a tendency to spread onward to the east. In this sense, then, Little Missouri Buttes must be considered the main laccolith to which Mato Teepee is subordinate. Both will be treated together here, however, as subordinate laccoliths to the Warren Peak mass.

WARREN PEAKS.

The Bearlodge Range proper has been fully described by Newton[1] and Jenney,[2] and this description needs no repetition in detail. Warren Peaks, the highest summits of the range, are bare, rounded, grass-covered hills of coarse granite-porphyry, reaching a height of 6,654 feet above sea level. Seen from east or west the peaks are not conspicuous, because the slopes are long and gentle. The structure, which has been called a miniature copy of the Black Hills, is that of an elongate laccolithic uplift extending about 20 miles northeast and southwest, with a porphyry core exposed for 8 miles. Subordinate intrusions occur on the flanks, where rocks from Cambrian to Jura-Cretaceous dip away in all directions. Northwest and north the trunk drainage from the range flows radially to the Belle Fourche River. Rectangular systems of branch streams are formed by subsequent development along soft strata. The Minnekahta limestone forms on the slopes its characteristic V-shaped gateways. Seen from Mato Teepee on the northwest, a larger valley on the slope of the

[1] Report on the Geology and Resources of the Black Hills of Dakota, by Henry Newton and Walter P. Jenney: U. S. Geog. and Geol. Surv. Rocky Mountain Region, Washington, 1880, pp. 199.
[2] Op. cit., p. 283.

Bearlodge Range shows three pairs of benches; one bounds a wide, flat valley above; a lower trench corresponds with the present valley of the Belle Fourche; and a smaller, lowest trench suggests a recent uplift. The highest bench is formed of Lower Cretaceous strata; the next lower of Jurassic. A columnar sill was found high on the northwest slope of the range in Jurassic ripple-marked sandstones. On the east side of the range the canyons are deep and the dips higher, sometimes between 30° and 40°.

SUBORDINATE LACCOLITHS.

SUNDANCE HILLS.

In the Red Valley southeast of Warren Peaks two laccolithic hills occur, occupying on that side of the Bearlodge uplift a position symmetrical to that occupied by Mato Teepee and the Little Missouri Buttes on the northwest side. The Sundance Hills appear to be outliers, bearing to the greater laccolith the relation of lateral lenses in normal subordinate position, filling the bends and injected through peripheral concentric fractures (Pl. XLIV). They have been described by Newton[1] and Russell.[2] The southern and larger mass, Sundance Mountain, is composed of porphyry, intruded through Permian and Trias to Jura on its eastern side, hence probably injected from the west, i. e., from the direction of the Bearlodge Range. Porphyry cliffs occurring across Sundance Valley on the western side of the town appear to be the sheet of which Sundance Mountain is the thickened eastern termination.

The porphyry of Sundance Mountain, a fine-grained rhyolite, shows at a distance a yellow-greenish color, induced by a characteristic lichen noted both here and on Mato Teepee in great abundance on the face of the vertical cliffs. The porphyry extends in an irregular lobe from the main mass of the mountain to the westward, where rounded low hillocks covered with porphyry slabs occur at levels a hundred feet or more lower than the Red Beds on the northern face of the mountain. A hundred yards to the north the Red Beds, entirely free from porphyry débris, dip 14° under the mountain S. 60° E. There is thus evidence on this side of the eruptive breaking across Minnekahta limestone and Red Beds. The Red Beds recur at the foot of the mountain on the north, without any appearance of dipping away from it, showing distinct horizontal bedding. Jurassic beds occur east of the mountain. On the flanks of the Bearlodge Range to the northward the Minnekahta limestone dips southeast, the south-flowing drainage cutting through it the usual V-shaped gateways. The dome of Green Mountain (Little Sundance dome) is remarkably symmetrical and

[1] Op. cit., p. 197.

[2] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, 1896, p. 29.

isolated, but in structure is altogether similar to Elkhorn or Spottedtail dome, with a Minnelusa crest and an encircling shell of Permian limestone. A short distance west of Sundance there is a dome-shaped hill which appears to be another buried laccolith like Green Mountain.

LITTLE MISSOURI BUTTES AND MATO TEEPEE.

Descriptions by previous writers.—Jenney wrote as follows,[1] describing the appearance of Little Missouri Buttes and Mato Teepee (see fig. 95) from the summit of Warren Peaks:

To the west (magnetic), some 20 miles away, Bear Lodge Butte [Mato Teepee] and the Little Missouri Buttes appear in line. From this distance the former resembles in appearance the huge stump of a tree, its surface curiously striated vertically from top to base, and, being perched on the crest of a high, flat-topped ridge, it becomes a very prominent landmark, which, once seen, is so singular and unique that it can never be forgotten. Although the Bear Lodge country is an elevated region, and the different streams have a considerable fall before reaching the Belle Fourche, yet the topography is quite peculiar in the prevalence of long, flat-topped ridges or mesas between the narrow and deep valleys and canyons of the creeks. This is due to the resistance to erosion offered by hard and continuous strata of sandstone of the Jurassic and Cretaceous formations, which are here almost horizontal in their bedding, with a gentle slope away from Warren Peaks.

That part of Newton's description which accords with the writer's observations may be quoted:[2]

The Bear Lodge (*Mato Teepee*).—This name appears on the earliest map of the region, * * * though more recently it is said to be known among the Indians as "the bad god's tower," or, in better English, "the devil's tower." * * * It stands on the immediate western bank of the Belle Fourche, about 4 miles southeast from the Little Missouri Buttes. It was not reached by the Warren expedition, but while the Raynolds expedition was in the vicinity of the Little Missouri River two attempts, the last successful, were made by Mr. Hutton to reach it. He recorded, however, no particular description of it, so that when we reached it in 1875 our examination had all the charm of novelty. Its remarkable structure, its symmetry and its prominence made it an unfailing object of wonder. It is a great rectangular obelisk of trachyte [phonolite] with a columnar structure, giving it a vertically striated appearance and it rises 625 feet, almost perpendicular, from its base. Its summit is so entirely inaccessible that the energetic explorer, to whom the ascent of an ordinarily difficult crag is but a pleasant pastime, standing at its base could only look upward in despair of ever planting his feet on the top.[3] * * * Within a half mile of the banks of the Belle Fourche the shaft rises with its broad base of débris from the plateau formed by the lower Jurassic sandstone. Its dimensions were

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[1] Op. cit., p. 284.

[2] Op. cit., p. 200.

[3] Both Newton and Russell remark on the absolutely inaccessible character of the summit. Russell says, "The strongest and most experienced mountain climber must pause when he has scaled the rugged cliffs which form the immediate base of the tower and gains the point where the individual prisms make their abrupt curve and ascend perpendicularly. Beyond that point no man has ever reached, and, it is safe to say, never will, unaided by appliances to assist him in climbing." Such appliances have recently, however, been used; with the aid of iron bars driven into the angle between two sloping columns, a rude ladder was constructed by an enterprising climber, and the ascent to the summit has been made, a fact attested by a small flag, visible from below, which was left on the highest point of the tower. A member of the United States Geological Survey has also made the ascent.

determined by Captain Tuttle, the astronomer of the expedition, who calculated them from measurements with the sextant. The height of the summit above the river was found to be 1,126 feet, while approximately its elevation above the sea is 5,260 feet. The width of the summit from north to south is 376 feet, and the width at base is 796 feet. In an east-and-west direction the diameters are less.

The rock * * * has a crystal-like structure on a grand scale, which from a short distance gives the column the appearance of a fascicle of gigantic fibers. From the base, which is considerably broader than the body of the peak, each fiber-like crystal or column rises in a bold curve to the bottom of the vertical obelisk, which it then follows to the summit. * * * The strata from which this igneous column springs are not in the least disturbed at the nearest points where they could be examined, about 50 or 75 feet from the base, but the sandstones * * * are converted into a compact white quartzite.

The Little Missouri Buttes stand on the plateau of Dakota sandstone, about 4 miles west [northwest] of Bear Lodge and near the divide between the headwaters of the Little Missouri River and the Belle Fourche. They[1] * * * are said to be called by the Indians the "buttes which look at each other." Though prominent landmarks, they rise only between four and five hundred feet above their base. They are about one-half * * * of a mile distant from one another, but they are so thoroughly covered around their bases with débris that their intimate structure and relation could not well be determined. The Cretaceous sandstone forming the floor of the surrounding plain could not be ascertained to exhibit any disturbance or change of structure due to proximity to the igneous matter. Each peak has the same general conical form so often described, and a similar system of cleavage planes was also observed. Some cross planes give locally an appearance of columnar structure. The rock is a greenish-gray trachyte, similar to that of the Bear Lodge; but though it contains many crystals of feldspar, it is not so highly crystallized as the rock from the latter peak.[2] At the base of the Buttes in one or two localities a rock was found exceedingly light and cellular in structure, yellowish in color, and very like a volcanic tufa. As the result of a microscopic examination, Mr. Caswell designates it a rhyolitic breccia, including fragments of both sandstone and rhyolite.

Professor Russell's vivid description gives some idea of the solitary grandeur and beauty of the tower:[3]

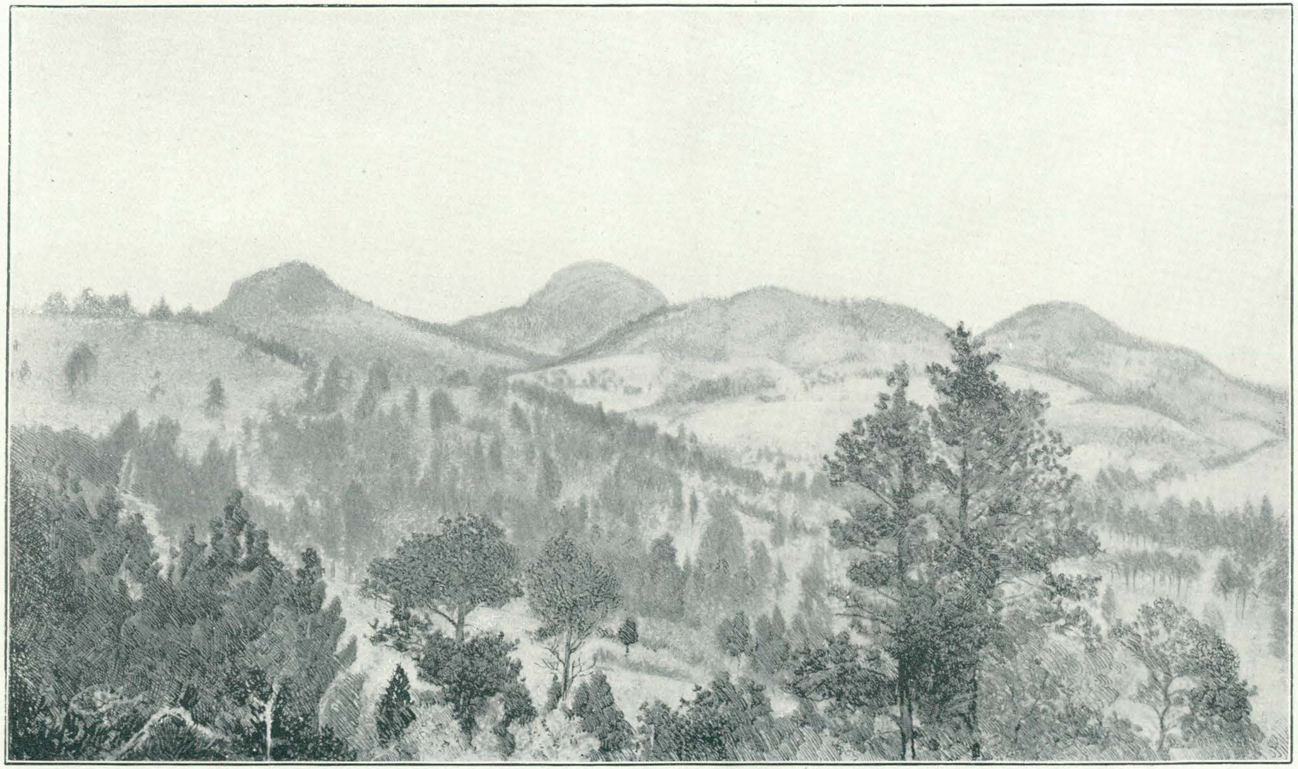
When Mato Teepee is seen from almost any locality in the valley of the Belle Fourche within a radius of several miles, one is not only forcibly impressed by the grandeur of the monumental form that dominates the landscape, but is delighted by the brilliant and varied colors of the rocks forming the sides of the valley and the immediate base of the tower. The Red Beds in the lower portion of the river bluffs show many variations of pink and Indian red, and have been sculptured into architectural forms of great beauty. The less brilliant Jurassic sandstones resting upon them and forming the upper portions of the bluffs, serve to carry the eye from the rich colors below to the dark forest of pines that grow above and to the still more somber precipices of the great tower which always appears in bold relief against the sky. * * *

The shaft of the column is composed of clustered prisms which extend from base to summit without cross divisions. These prisms are usually pentagonal, although other forms are not uncommon. * * * Each prism tapers somewhat toward the

[1] Newton and Russell both describe Little Missouri Buttes as three in number, occupying angles of a triangle. There are four distinct hills, occupying corners of a quadrilateral.

[2] L. V. Pirsson (Am. Jour. Sci., Vol. XLVII, 1894, pp. 341–346) determined these rocks to be phonolite rich in soda feldspar.

[3] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, 1896, p. 32.



LITTLE MISSOURI BUTTES, FROM THE SOUTHEAST.

top, and near its upper extremity is cracked and discolored by weathering. At the base of the tower the columns in most instances, except at the southeast corner, curve abruptly outward, and at the same time increase somewhat in size. On the west side they become nearly horizontal. * * * Near the base of the tower, just above the treetops, the rock loses its columnar structure, becomes massive, and breaks with an irregular fracture. On the sides of the tower there are a few places where the lower portions of individual prisms have fallen away, leaving the upper 200 or 300 feet still in place. In such instances one has a good view of a section of the prisms, which are seen to be four, five, or six sided. Owing to the abrupt outward curvature of the columns at the west base of the tower, the fragments that have fallen from above have been thrown farthest out on that side and now form an extremely rugged talus in which fragments of huge columns lie piled in endless confusion one on another, suggesting the ruins of some mighty temple.

Northwest slope of Bearlodge Range.—When seen from a distance, along the road southwest of Warren Peaks, the Little Missouri Buttes are more prominent than Mato Teepee; they rise above the plains in a

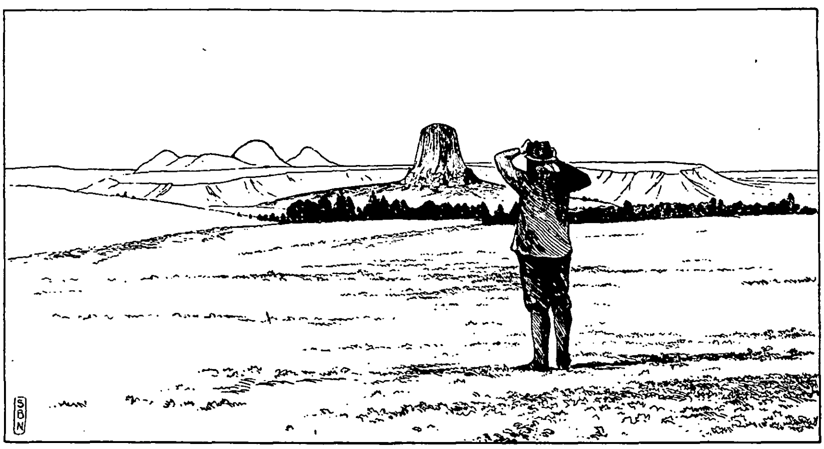


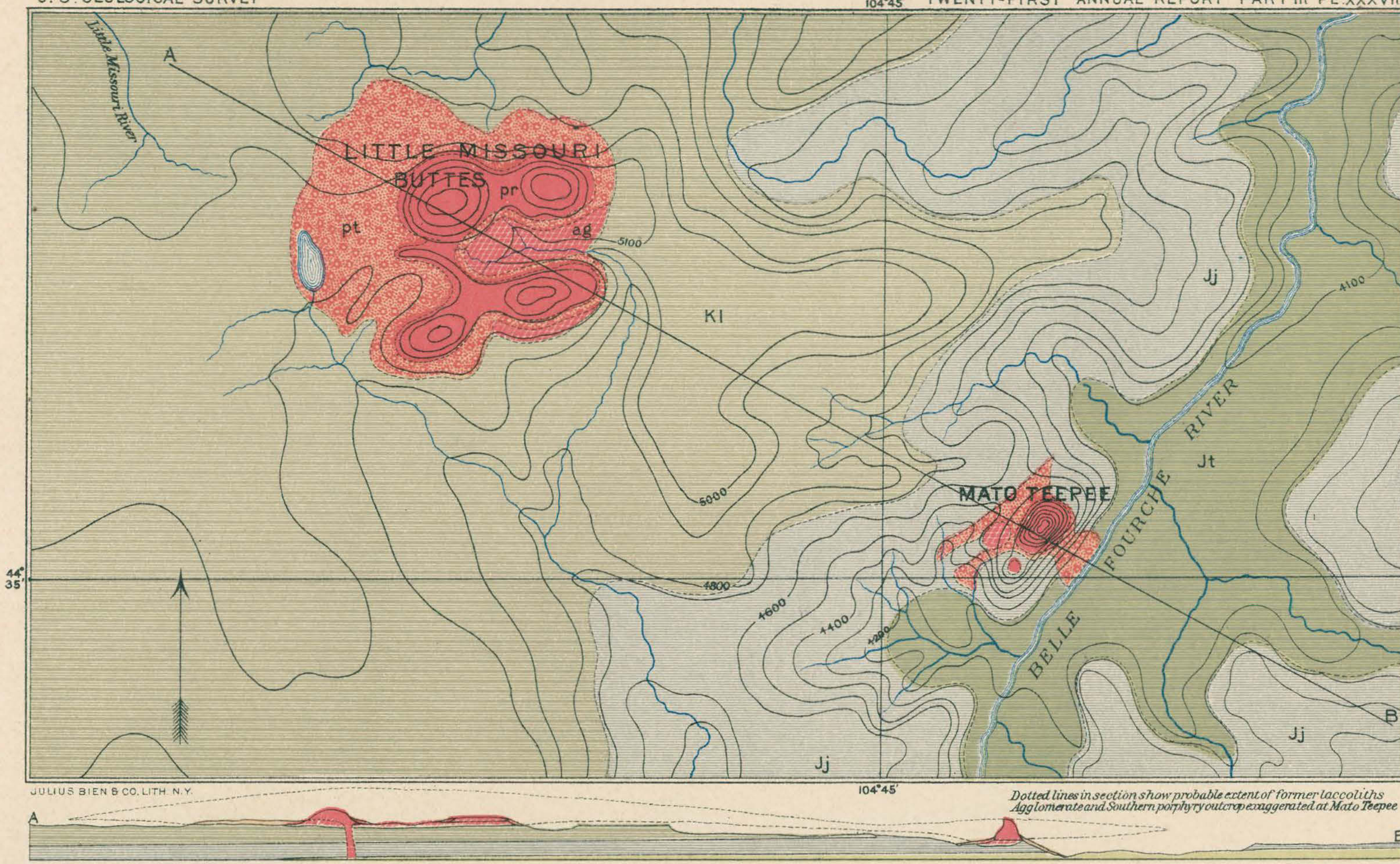
FIG. 95.—Mato Teepee and Little Missouri Buttes from the southeast.

thronelike mass composed of four prominent dome-shaped hills (Pl. XXXVII), below which the tower sinks to comparative insignificance. The valley of Miller Creek on the northwest slopes of the Bearlodge Range is cut in Jurassic beds. Porphyry was encountered at one place on the road between Sundance and Mato Teepee, a fine-grained rhyolite occurring apparently as a sill. The most prominent outcrops on Miller Creek are mollusk and belemnite beds, a smoky fine-grained limestone, and a warm reddish wind-pitted sandstone, which forms prominent cliffs on the lower courses of the streams that drain the northwest flank of Bearlodge Range. The Little Missouri Buttes rest upon a platform of Lower Cretaceous sandstone, which forms a long terrace east of them, and this terrace stands at a considerable height above the base of Mato Teepee, which rests upon an oval platform of Jurassic shales, 3 to 4 miles to the southeast (fig. 95

and Pl. XXXVIII; see also Pl. XVIII). The northwestern slope of the Bearlodge Range is long and gentle, so that in looking up to the Warren Peaks from this side one would not suspect their height above the surrounding plains, so gradual is the slope. Seen from the east the Jurassic sandstone underlying Mato Teepee shows a distinct synclinal sag under the tower, dipping gently inward on either side of the mass of talus that forms a long slope down to the Belle Fourche bottom land (fig. 95).

LITTLE MISSOURI BUTTES.

The sediments between Mato Teepee and Little Missouri Buttes are in general horizontal, showing occasional aberrant dips due to the washing out, from beneath, of the soft red beds, and sometimes these dips vary widely in direction and amount within a distance of a hundred feet. The level bench of horizontal strata, conspicuous under the Little Missouri Buttes, is composed of white and buff sandstone of the Lower Cretaceous; and at the eastern foot of the northeastern butte, a hundred yards from the base, occurs yellow sandstone dipping gently west-southwest under a rounded hill slope covered with porphyry débris. In the gulch between this northeastern peak and the highest northwestern butte occurs a narrow spur consisting of red, weathered, porous, tuff-like material, much decomposed, carrying coarse fragments of pink granite, yellow-red sandstone, coarse Cambrian sandstone, and other rocks, in a vesicular matrix, of which but little is present in proportion to the quantity of inclusions. The rock resembles the breccias associated with the Deadwood and Terry porphyries (p. 187). The vesicles are largely decomposition cavities. Bowlders a foot or more in diameter, of granite or sandstone, occur scattered over the slopes in the basin area inclosed by the Little Missouri Buttes. From the summit of the highest peak Cretaceous strata may be seen on the north, northeast, southeast, and south, very near the porphyry. In all cases the bedding appears undisturbed by the eruptives, and has a slight westerly dip. The four buttes are all composed of porphyry. The rock on the summit is frequently fused at the edges of joint blocks to buff porcelaneous material, probably fulgurite produced by lightning. The Warren Peaks from this summit are more impressive than when seen from lower levels—culminating long slopes which rise gently on both sides. Far to the northward the snowy summits of the Bighorn Range may be descried. Granite fragments were included in the porphyry mass of the western butte, similar to those found in the breccia at the base of the buttes. The northeastern peak shows some columnar structure, with almost horizontal columns, the pentagonal column ends projecting from the face of the rock. There are also ledges trending north and south which stand out like dikes in the clefts of the rock mass, but they show no evidence of being litho-



LEGEND

LOWER CRETACEOUS		JURATRIAS: JURASSIC		JURATRIAS: TRIASSIC		IGNEOUS					
Kl	Sandstones, and shales	Jj	Sandstones, limestones and shales	Jt	Red marl and gypsum	ag	Eruptive agglomerate	pr	Porphyry	pt	Porphyry talus

GEOLOGICAL SKETCH MAP AND CROSS SECTION OF MATO TEEPEE AND LITTLE MISSOURI BUTTES, BLACK HILLS, WYOMING.

BY T. A. JAGGAR JR. 1900

Horizontal and vertical Scale

1 0 1 2 MILES

Contour interval 100 feet.

logically different. The spur extending southward from the foot of this peak is covered with rounded bowlders of coarse granite, trap, sandstone, and pegmatite, though none of these occur in the rocky talus above, at the foot of the porphyry wall; evidently the breccia lies under the porphyry.

The Little Missouri Buttes are four in number, the two northern ones being the highest and the most smoothly rounded in form. They are arranged at the corners of a quadrilateral, from one-half to three-quarters of a mile apart, and the porphyry is apparently continuous through the whole group except on the eastern side, where a stream has cut a canyon through it into the soft agglomerate that underlies it. This agglomerate occurs within the area of the Buttes on both sides of this stream and south of the southeastern butte. The talus slopes mark the contact between agglomerate and phonolite. Fifty feet above the gulch between the two eastern buttes occurs buff sandstone showing a dip of 7° directly under the northeastern butte, nearly due north. The same sandstone, practically horizontal, appears under the porphyry mass on the south side of the gulch. As the soft agglomerate occurs at the base of the several hills, especially in the central basin, it is probable that the presence of this deep-cut hollow in the midst of the hills is due to its less resistant character.

That the porphyry extended formerly over a much wider area than is now shown is proved by the presence of wide, flat accumulations of coarse porphyry fragments more than half a mile from the Buttes west and northwest. This creeping talus of weathered rock appears to have dammed one of the smaller streams on the southwest, and there a small pond is seen. The irregular coarse heaps of platy shingle with the pond in their midst resemble a moraine. A singular curved ridge extends from between the two southern buttes northwestward, consisting of igneous rock; below it, from a steep cliff at its western end, is seen a ridge trending northeast and southwest that resembles a dike. It is probable that this is one of the conduits which erosion is beginning to reveal beneath the porphyry.

The Little Missouri Buttes are encompassed by streams north, south, and west, which show traces of radiation and irregularly encircle the porphyry mass. The southern stream enters the Belle Fourche at an abnormal angle, forming with it a barbed junction. The Buttes reach their culmination in the northwestern peak, which was determined by the Newton survey to rise 5,563 feet above the sea. The northeastern hill comes next in height, while the southern ones are more elongate and lower. Probably the high northwestern peak bears the same relation to the others and to former peaks above the wide western talus that the central point of Custer Peak and the Woodville Hills bear to their outliers (see pp. 274, 277).

MATO TEEPEE.

Drainage.—Mato Teepee, on careful examination, exhibits many laccolithic characters, while in detail it shows close geologic relationship to Little Missouri Buttes. A stream encircles the tower on

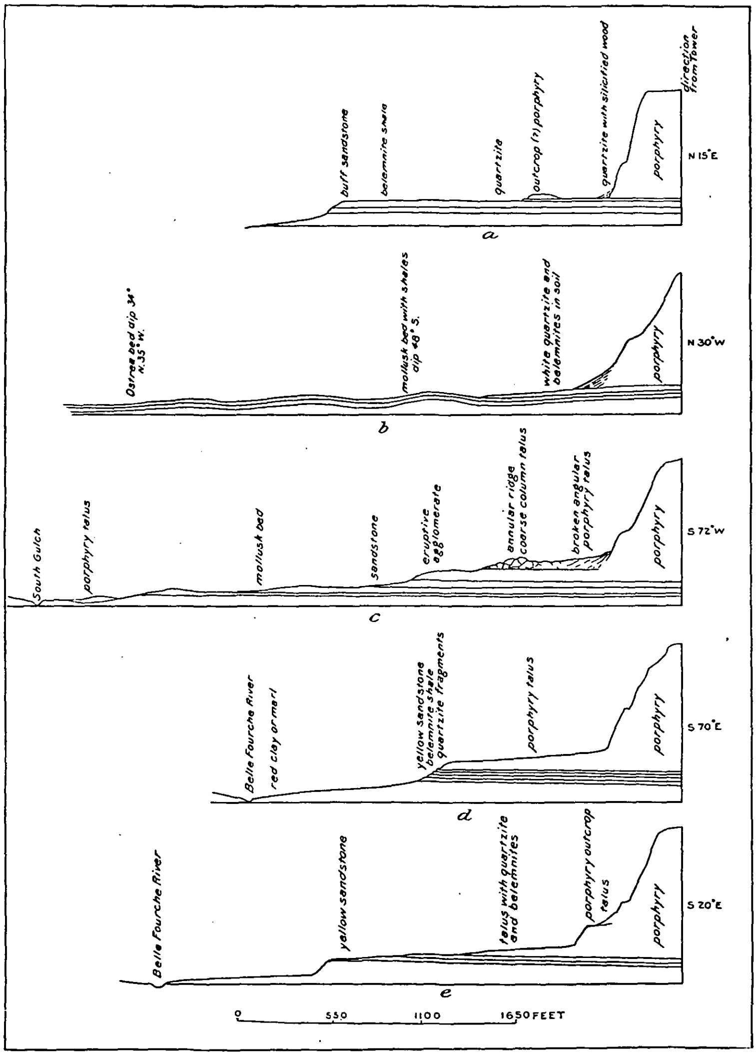


FIG. 96.—Radial cross sections from Mato Teepee.

the north, taking its rise in a basin under the Lower Cretaceous bench. A similar stream encircles the southern end of the Jurassic platform, the divide between the two streams being a gently sloping sinuous ridge that extends to the foot of the Little Missouri bench. This bench, with the spurs that run out from it northeast and south, is singularly symmetrical (as shown on the map and in fig. 95) in the way in which it forms a semicircle about Mato Teepee as a center. To the east of the tower the Belle Fourche trunk stream has moved, probably by monoclinal shifting, down the gentle west dip of the soft Red Beds directly to the base of the tower, and its action is undercutting the Jurassic platform in a straight line parallel to the strike of the Mesozoic beds as a whole.

Stratigraphy.—Mato Teepee is underlain by Jurassic beds stratigraphically and topographically lower than those on which the Little Missouri Buttes rest. The latter loom to the westward high above the tower, resting upon the Lower Cretaceous sandstones which form the long horseshoe bench, the top of which is on a level with a point not far below the top of the tower.

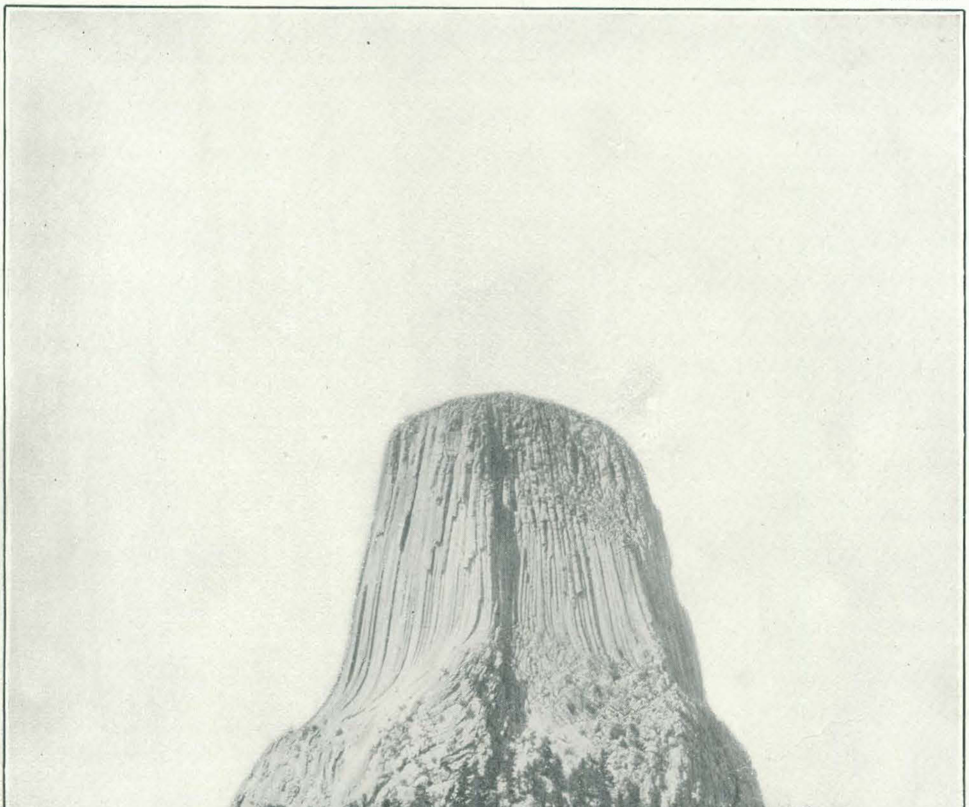
A hundred yards northwest of the tower, following the narrow divide between the encircling streams, a white fine-grained quartzite outcrops in the characteristic greenish soil of belemnite shale (fig. 96). A hundred yards farther west along the divide a shell bed (*Tancredia*) occurs, carrying concretions and dipping due south about 48°. Above and below are green shales, and the strike of the outcrop seems to curve. A little farther west oyster beds appear, dipping 34°, N. 35° W.; but these beds followed west along the strike become more nearly horizontal under the Little Missouri bench of horizontal strata. At the foot of this bench are green and purple clays capped by buff sandstone. A section up the slope shows progressively green shales, oyster beds, red clays, a second green shale bed carrying many large belemnites, and then thick buff sandstone of slight northerly dip. The greater part of the bench is made up of white and buff Lower Cretaceous sandstones. The oyster beds mentioned may be followed along the base of the cliff, showing dips varying from NNW. at a very high angle (45°) to SW., NW., SE., all in a distance of a few hundred feet. Such variations are entirely localized and independent of the general structure of the Jurassic strata of the region, and the most careful examination of the localities where these aberrant dips were found failed to show any evidence of disturbing igneous intrusions or other sources of violent deformation. It is believed that these dips are induced locally by erosion, the soft red beds being washed out from beneath in the adjacent gulches.

The accompanying sections (fig. 96) show the structure of the platform beneath Mato Teepee, which in general consists of level-bedded Jurassic sandstone, marls, shale, and quartzite; any variations from horizontality being rather of the nature of dip toward the tower than away from it (Pl. XXVIII). This again is probably due to the great weight of the tower pressing down the beds and squeezing out the soft red clays that have been exposed by erosion in the encircling valleys. N. 25° W. from the tower about 1,000 yards occur two quartzite ridges showing scattered fragments of quartzite on the side toward the tower, but without sufficient outcrop to give clear evidence of dip. About the same distance N. 55° W. in the gulch the buff standstone appears, dipping 2° due north. Two hundred yards due north of the tower there is an outcrop of quartzite very fine in texture, so as to appear almost like flint, of gray color, with a vertical lamination trending east and west, and 25 yards nearer the tower adjacent to the quartzite occurs a large mass of porphyry that appears to be an outcrop. On a small knoll N. 75° E. of the tower, only 30 yards from the porphyry talus, directly at the foot of the great basal bench, there is an outcrop of quartzite carrying fossil fragments of silicified wood, and this quartzite is abundant here in the tangled roots of fallen trees, indicating that this bed is the uppermost member of the Jurassic strata that underlie the eruptive mass. If there were any upturning about a vent there would be lower beds exposed here. This quartzite undoubtedly occurs higher than the belemnite shales that cover the ridge on the southern side of the tower. The quartzite varies, in places consisting of distinct clastic grains, and elsewhere being of fine-grained aphanitic texture. The platform bench northeast of the tower is not so long as on the southwest side. It extends northwest for some 2,000 yards, and the greenish belemnite shales here crop out below the quartzite. In a large ant-hill composed of coarse grit were found many small fragments of young belemnites. The best point of view for observing the synclinal sag, under the tower, of the buff Jurassic sandstone that is the principal cliff maker in the bench is the road near Ryan's ranch, on the eastern side of the Belle Fourche Valley. From this point the great talus of porphyry fragments that extends from the tower to the very border of the stream may be best observed, and on either side the sandstone is seen to dip inward gently, forming a V-shaped sag of wide angle in which the apex is immediately below the great columns.

The Jurassic section is approximately as follows, from the tower down:

Quartzite.
Tancredia limestone.
Smoky, fine-grained limestone.
Belemnite shales.
Oyster bed.
Bluff of tender buff sandstone (sometimes pink).
Green shales.
Thick shell bed, forming a hard band.
Buff marl.
Gypsiferous red beds (marl).

Structure of the tower.—The tower is sharply divided at a point more than a third of the distance from base to summit by a line that marks the beginning of the columns and a bench formed by the upper



MATO TEEPEE, FROM THE SOUTH, SHOWING HORIZONTAL JURASSIC STRATA BELOW.

limit of the massive uncolumnar base. This massive lower portion is jointed variously, showing sometimes a flat, vertical, rough lamellar parting and in other places irregular joints (Pl. XL). It contains not a trace of the perfect columnar habit of the upper portion, which is seen, however, to merge into the lower portion locally where the columns curve out and are lost in the massive bench. On the SSW. corner the basal mass rises to a height of from 40 to 50 feet above the talus, and a narrow columnar band resembling a dike extends downward and outward into the base from the curved lower portion of the upper columns. This band is about 40 feet wide. Seen from this side the upper columns slope back about 4° or 5° from the vertical on the western side of the tower and 10° to 12° on the eastern side. On the southwest face of the tower the columns make a curve outward, of long radius in a western direction at the base, ending in a horizontal position at the bench that marks the top of the massive base. This base or pedestal extends all around the tower and is nowhere entirely concealed under débris. The columns are marked horizontally by faint ridges or swellings that give to the rock locally an appearance that resembles bedding. This is most marked in the upper quarter, where there are a number of overhanging columnar masses left without support below because the straight and upright lower portions have fallen out, leaving clinging remnants above. The upper part is cross jointed and irregularly cracked, as though more weathered. The whole mass has a yellowish-green color, produced by lichens. The summit is flat above and slopes gently on the eastern side, falling off at a sharp angle on the extreme east corner and becoming vertical below. The western face is a vertical columnar cliff to the highest summit. Many of the columns appear in places to be large hexagonal or octagonal masses above, but where broken away below a single column becomes divided into a double or triple fluting that resembles a gothic pillar composed of independent pentagonal pieces. Many of the columns unite above to a single larger column, in groups of two or three, precisely like solidified columnar starch. On the south side the columns diverge downward east and west, with straight medial members (Pl. XXXIX). The base of the eastern curving columns is here overlapped by massive shells or laminæ.

Single columns found scattered in heaps about the outer margin of the talus at the base of the tower average 6 feet in diameter and have pentagonal or weathered roundish cross section. In one place a single column, resting in its niche on the tower's face, was seen to be divided into five separate blocks, like a masonry pillar, and this was supported below by a half column, split longitudinally, occupying a downward continuation of the same niche. In another case seven columns, together in a bunch, had fallen away below, but were still clinging above. The rock that forms the massive base was carefully examined at many points in comparison with the rock of the fallen columnar fragments, and no positive difference in texture could be seen. The rock was carefully examined for inclusions, and some basic aggregates, large broken feldspar masses, and a substance resembling diorite were found embedded in the coarse porphyry, but no granite or other rocks characteristic of the agglomerate were found in the Mato Teepee porphyry, though large granite fragments are quite abundant in the porphyry of the greater peak of Little Missouri Buttes.

Mato Teepee agglomerate.—At the foot of the tower on the WSW. side, immediately below the main talus and encircled by porphyry talus slides, is a small rounded grassy hill strewn with rounded subangular or irregular fragments of granite, limestone, Jurassic sandstone, Cambrian quartzite and glauconitic sandstone, purplish rhyolite, a little slate or schist, black shales of two varieties, flint, and coarse pegmatite. This extraordinary accumulation of fragments was found to be an agglomerate similar to the one that underlies the porphyry of the Little Missouri Buttes. It here outcrops only in this small elliptical spur or hill, about 150 yards in length, trending S. 72° W. from the tower, and completely surrounded by bowlder slides of talus material that unite below the foot of the agglomerate hill and extend down the gulch into the valley. How much more of this agglomerate may be present under the talus it is impossible to say; but it is significant that on the opposite side of the tower the Jurassic quartzite is found to within a stone's throw of the foot of the steep talus, and no trace of the agglomerate occurs, nor was this agglomerate found anywhere else about the tower. A trench was excavated in the hill in order to obtain specimens of all the fragments and of the matrix, the last appearing to be a decomposed porphyry. The most conspicuous fragments of the agglomerate are granite, in either rounded or angular forms, varying in size from small pebbles to bowlders 1 or 2 feet in diameter. The rounded fragments have a somewhat faceted character, unlike the smooth polish of stream-rolled material. A limestone bowlder of characteristic Carboniferous habit, containing spirifers and other fossils, about a foot in diameter, was found to be encased in a shell half an inch thick, which could be broken away, parting smoothly from the rounded surface beneath, as though the mass had been subjected to calcination by heat. Except for the greater variety of contained fragments, this agglomerate is essentially like the one found in the Little Missouri Buttes and those of the eastern laccoliths. Excursions were made over sections through the platform in directions radial to the tower as a center, south, southwest, west, northwest, northeast, east, and southeast, and also completely around the foot of the tower and up to the top of the massive pedestal in two places, without discovering any other outcrop of the agglomerate. Some of the sandstone formations represented in the agglomerate have a crust in which no individual sand grains can be seen, and this appears to be the product of fusion. West and northwest of the agglomerate hill Jurassic strata, showing horizontal bedding, outcrop in the gulch, and apparently lie directly beneath the weathered agglomerate.

On the southern end of the platform a hundred yards from the base of the tower there is a wide, flat, rounded porphyry knoll, exposing some 30 to 40 feet of surface that appears to be an outcrop in place. S. 35° E. from the tower, at a distance of 30 feet, there is a faint swell or ridge in the talus, and an exposure of massive porphyry forming a steep cliff. This also shows every evidence of being in place. The faint elevation here observed in the accumulated jumble of bowlders at the tower's base seems to be a persistent character on all sides, the fragments forming an ill-defined annular ridge, separated from the wall talus at the base of the tower by a faint depression 20 to 30 yards in width. It is probable that this ridge has been produced by the rebound of large fragments striking the pedestal or the wall talus and being forced outward so as to fall in a ring away from the immediate base of the mass. It is noticeable that the fragments of columnar material are more abundant in this outer ridge, while the inner talus is composed of flakes from the pedestal and smaller blocks of irregular form. This is to be expected, as the huge columns falling from a height and meeting obstruction in the projecting pedestal necessarily must bound or roll away for some distance (Pl. XL). It must not be imagined, however, that this arrangement is in any sense symmetrical or even striking, for the jumble of bowlders is in many places confused and entirely disorderly.

The Mato Teepee agglomerate contains in abundance two varieties of carbonaceous shales, the one breaking in small rectangular blocks of dark gray color, the other in soft, flat, coaly laminæ. Such shales are not known to the writer below the Lower Cretaceous and Benton, terranes which are *stratigraphically higher than the present location of the breccia.* This is very strong evidence in favor of the Mato Teepee intrusion being an offshoot from the Little Missouri Buttes, for the latter were probably intruded in Benton carbonaceous shales. The identity of the Little Missouri and Mato Teepee breccias is unquestionable; they contain the same kinds of fragments, and their matrices are not essentially different. The matrix of the Mato Teepee breccia is too soft for slicing; the powder under the microscope resembles a granite arkose, and granitic material is most abundant among the coarser fragments. This granite, brought up from the depths, is either Archean or an intrusive in the Algonkian. It is different from the Nigger Hill or Harney granites, and resembles rather the Archean granites of the Rocky Mountains. The powder carries much kaolin, quartz grains, brown mica, and occasional transparent feldspar flakes. The quartz grains are broken or have a faceted surface, suggesting corrosion.

Little Missouri agglomerate.—The Little Missouri agglomerate is sufficiently hard for thin slicing. The microscopic section shows small angular fragments, reaching a maximum of 1 to 2 millimeters in diameter, of quartz, orthoclase, microcline, pieces of fine-grained porphyry with ægirine, magnetite, and calcite, in an earthy brown groundmass. The groundmass, when examined under a high power, is seen to consist of a nearly isotropic base with specks of brown iron oxide. Here and there transparent portions of the base show a faint felty polarization. Ferromagnesian constituents in general are not preserved; there are one or two doubtful cases that may be idiomorphic outlines of an original hornblende or augite crystal, preserved by paramorphic masses of calcite. The thin section shows no evidence of true vesicular structure. The hand specimen is very porous, but this is due to the dissolving out by weathering of carbonates, etc., from pseudo-amygdules, probably largely marking the loci of former bisilicates.

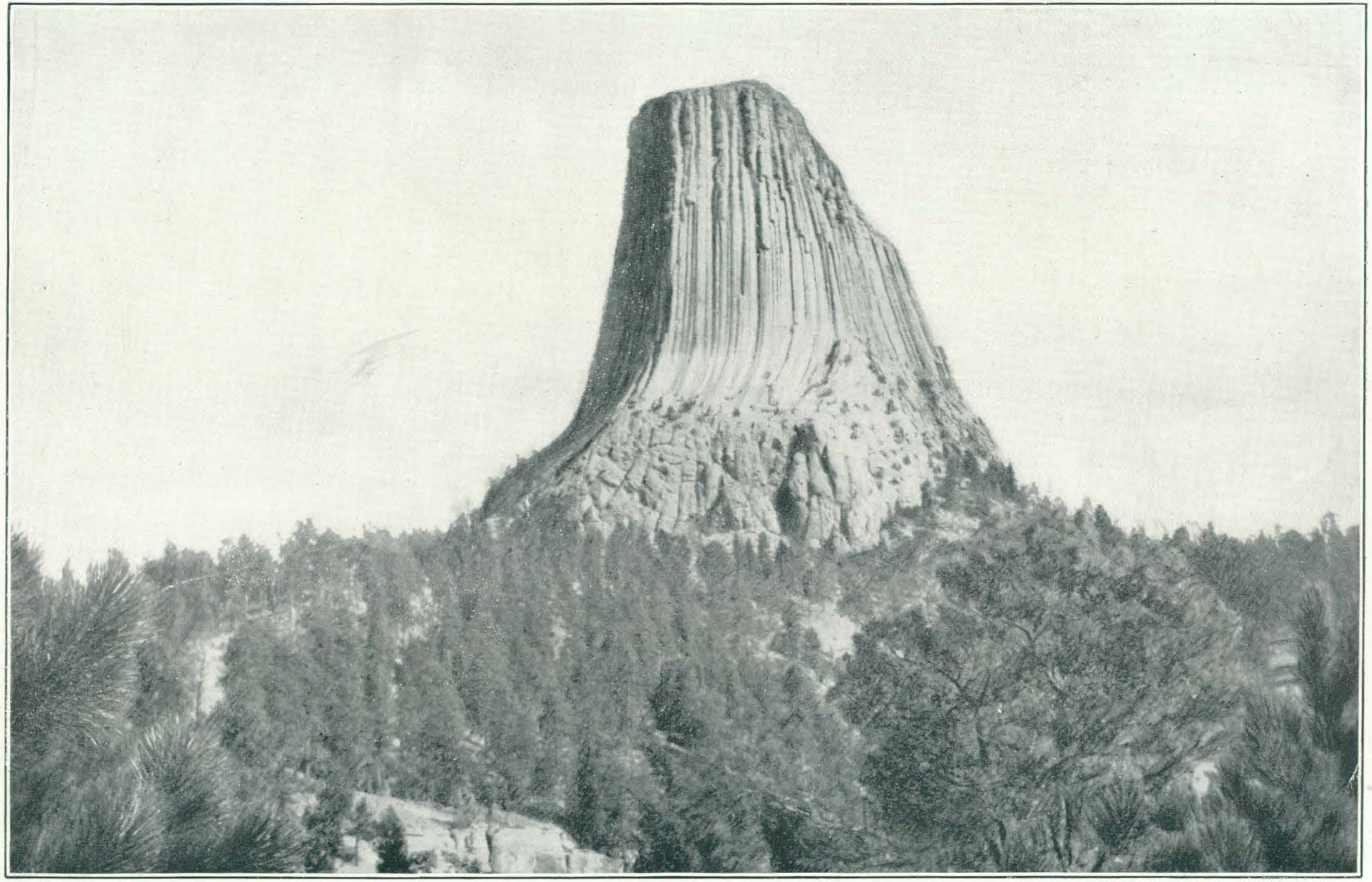
Evidences for laccolithic origin of Mato Teepee.—It is probable that these breccias were the first and most fluid injections of a magma which rose rapidly and with some violence through fractures from Algonkian to Cretaceous. The conduits were dikes now nearly concealed under the Little Missouri Buttes. The laccolith spread southeastward in Benton shale, met an opposing northwest dip off the Warren Peak flanks, broke downward through the Lower Cretaceous sandstone, and formed a subordinate Mato Teepee laccolith in soft Jurassic strata.[1]

Seen from the valley of the Belle Fourche, at the base of the tower on the south (Pl. XXXIX), the Jurassic strata beneath the tower appear absolutely horizontal. These strata are massive buff sandstone above, and clays, marls, and limestones below. The columns from this point of view show best their tendency to flare outward. As this flaring is symmetric rather to a point within the tower than to an axial direction, it is probable that the tower represents nearly the center of the original lens.

The massive base bears the same relation to the columns as the medial portion of the dikes figured in Pl. XXXIII. Were it exactly the equivalent of the dike, we should expect other columns below, the massive portion being in the middle. It is probable that the presence of a muddy breccia as a lowest stratum for the laccolith interfered with the development of basal columns, and probably also the action of gravitation makes the contraction expend itself less symmetrically in a horizontal lens than in an upright dike. The present upper surface of Mato Teepee is smooth and possibly represents nearly the actual upper contact, from which the shales have been weathered away.

The geologic section (Pl. XXXVIII) shows an ideal reconstruction

[1] Judd has figured a sill of basalt in Skye, which breaks downward across strata after spreading along a higher horizon. Volcanoes; Internat. Sci. Series, Appleton, 1881, fig. 56.



MATO TEEPEE, FROM SOUTHWEST END OF JURASSIC PLATFORM.

of the original laccolithic masses. Mato Teepee was simply a sill or subordinate lens from the Little Missouri Buttes laccolith. The encircling drainage favors the hypothesis that the Mato Teepee mass was lenticular, so that streams became adjusted about the peripheral slopes. Possibly the conduits of Little Missouri Buttes were inclined to the east from the vertical, so as to inject the magma in the direction of Mato Teepee. The injection was thus eastward, toward Warren Peaks—i. e., in the same direction as those which formed the Sundance Hills, on the opposite side of the Bearlodge Range. Injected southeast through beds gently dipping away from Warren Peaks, the spreading igneous rock, as usual, truncated bedding planes obliquely, so that the first injections charged with brecciated material reached the Mato Teepee region at a horizon lower than that of the conduit. The soft breccia probably had its greatest development in the region between Mato Teepee and the Little Missouri Buttes, hence those portions of the laccolithic mass occupying this intermediate region were the first to be eroded away. The presence of this undermining breccia accounts for the steep walls of Mato Teepee and Little Missouri Buttes. It is probable that the persistence of Mato Teepee at all is due to the fact that it represents the most perfectly columnar portion of the original laccolith, and the spread of the columns at the base is architecturally necessary for the maintenance of the shaft. The tower may thus be considered a geological case of "survival of the fittest."

The proofs that Little Missouri Buttes were the main laccolith of which Mato Teepee was a subordinate offshoot, may be summarized as follows: The Little Missouri Buttes form the larger mass today, encircled by the larger streams, and show evidence of conduits beneath in the shape of dike ridges, a large mass of breccia at the base, irregular and horizontal columns, and inclusions of granite in porphyry. Mato Teepee shows evidence of smaller size and lenticular form in the arrangement of the smaller encircling streams, and shows only a little of the breccia at the base, and that on the side of the Little Missouri Buttes; the breccia contains fragments of black shale from the Little Missouri Buttes horizon; the vertical columns give evidence of an extended horizontal upper cooling surface, and the Jurassic beds below give evidence of a horizontal basement; flat porphyry outcrops on the Jurassic platform give evidence of former greater horizontal extension of the Mato Teepee porphyry; entire absence of dikes or deformed sediments indicates that the porphyry came into its present position through lateral conduits from the greater mass.

Other hypotheses.—There are three other hypotheses for the origin of Mato Teepee that should be tested: (1) May the conduit be in the slopes of the Bearlodge Range to the southeast? (2) May these eruptives be extrusive lavas? (3) May the conduit lie beneath the tower? With regard to the first possibility, the slopes of the Bearlodge Range were crossed in two directions by the writer and no trace of igneous rock of the Mato Teepee type was found. There are undoubtedly sills in Jurassic strata far up the slopes, near the Warren Peaks, but the rock shows no resemblance to that of Mato Teepee, and the distance is at least 10 miles. The same strata recur between, without intrusions. The second alternative may be quickly dismissed as unworthy of serious consideration. The only feature resembling an extrusive lava is the Little Missouri breccia. Similar porous breccias occur in twenty places in the Deadwood and Terry districts associated with unquestionable intrusives. The rock of Mato Teepee is similar to many phonolites in the Terry district that were unquestionably pre-Oligocene, and if the Mato Teepee laccolith was contemporaneous with them it was covered by at least 4,000 feet of strata at the time of its injection. The evidence from physiography, from petrography, and from geology points to intrusive origin. The third question has been answered in the last paragraph; the most conclusive evidences against a subjacent conduit to the Mato Teepee mass are the presence of black shales in the agglomerate, the undisturbed horizontal beds which the tower rests upon, and the vertical columns.

CHAPTER III.

PHYSIOGRAPHIC FORM OF ERODED DOMES.

There are few localities where the consistency of individual strata so obviously produces characteristic erosion forms as in the Black Hills. Attention has been called to the characteristic benches or taluses, escarpments or valleys, that belong to each formation. Hard rocks make the mountains; soft rocks make the valleys; the great plains, relatively a lowland, are composed of very gently dipping soft rocks. In order to trace out the history of present-day topographic forms produced by laccolithic intrusions, the important geologic features to be considered are distribution of hard and soft strata, their thickness above the eruptives at the time of intrusion, the effect of that intrusion on the initial surface, and the relation of intrusion to the greater uplift that initiated or modified the greater drainage.

DISTRIBUTION OF HARD AND SOFT STRATA.

Distribution of hard and soft strata in vertical column (fig. 60 and Pl. XIX) has already been discussed in connection with the selective action of intrusive magmas, which spread most easily along the shales. The members "competent" to resist deformation are equally competent to resist erosion. The porphyry itself is perhaps most resistant; next, the great limestone; third, the Permian limestone (Minnekahta), a wonderfully persistent scarp maker, despite its thinness. Both the Minnelusa and Jura-Cretaceous formations make hills and ridges, and Niobrara limestone forms conspicuous buttes above the soft shales of the plains.

Between the hard members occur soft, erodible shales which progressively increase in thickness upward concomitantly with a similar decrease in the hard beds. Above the Cambrian shale horizon of intrusion there are in general three strong, hard members and three soft. The hard ones are the Siluro-Carboniferous (900 to 1,500 feet), Jura-Dakota (600 to 1,000 feet), and Niobrara (500 feet); the soft members are the Permo-Trias (300 to 400 feet), Benton (500 to 800 feet), and Pierre (2,000 feet), and above are incoherent Upper Cretaceous and Laramie beds.

The thickness of strata above the intrusives (p. 185) may have been between 5,000 and 8,000 feet, if the intrusion took place in Eocene time, and it has been shown that geologic evidence favors uplift of the

Black Hills at the same time. Some deformation by folding took place, and this was complicated by the porphyries into what may be aptly called pustular deformation, to use Newton's word, without, however, implying superficial action. The igneous bodies were separated by interdome synclines with axes, in many cases, trending radial to the greater Black Hills uplift.

UPWARD ABSORPTION OF DOME FLEXURE.

From the elongate oval or elliptical dome of the Black Hills that extended for more than 100 miles, warping up Cretaceous and perhaps early Tertiary strata, streams poured down the slopes and flowed away to the sea, from the moment the arch was exposed to rainfall. Such streams had courses radial to the uplift, consequent upon the initial slopes. If there was no actual initiation of drainage, and the uplift went on pari passu with the erosive action of an already existent river system, the evidence from the present drainage shows nothing to prove it. The most conspicuous features of the greater streams at the present time are their avoidance of the uplift and their deflection around it north and south, the radial courses of the streams which rise within the uplifted area, and the deeper erosion, into the flanks of the dome, of the eastern streams—i. e., streams of greatest fall from source to junction with the Platte and Cheyenne rivers. To what extent were the first consequent streams influenced by dome-shaped masses of intrusive rock in strata 6,000 feet below them?

In diagrammatic reconstruction of domed strata the beds are usually represented as maintaining uniform thickness around the bends.[1] The same rule is frequently followed in representations of folded strata. It will readily be seen that such construction entails radial enlargement of a fold transmitted from a thin stratum below to a thick one above; logically, with such construction, the upper stratum will have greater dip length than the lower one, and is so represented. In other words, a small curve in the depths can be constructed to transmit a great curvature to the surface a thousand feet above. Certainly such a construction has no foundation in observed fact. In miniature and on a large scale folds diminish in size upward by lateral absorption of motion. Willis has shown that the transmission and size of a fold are dependent on the rigidity and thickness of strata involved. Massive limestones under load bend; thin-bedded shales flow, fault, and crumple. Shales involved in and above a dome of limestones pushed up from below become stretched and thinned on the arch, while they

[1] Geology of the Henry Mountains, by G. K. Gilbert, 1880; frontispiece, figs. 8, 9, 18, 73.
Cross sections showing Mount Holmes bysmalith, by J. P. Iddings: Mon. U. S. Geol. Survey, Vol. XXXII, Part II, Pl. V; Jour. Geol., Vol. VI, 1898.
Contrast with these Hesperus Mountain and La Plata Mountains, W. H. Holmes: Hayden Survey, 1875, Pl. XLV, opposite page 271. Holmes clearly perceived the tendency of domical curvature to diminish upward.

thicken and crumple in the sag. In soft clays there is probably a certain amount of squeezing flow. Evidence that such thinning of clays over laccolithic arches actually took place is abundantly shown in the crushed Red Beds on the flanks of Elkhorn, Crook Mountain, Crow Peak, and Bear Butte. The result of such failure of soft beds to transmit doming is a gradual dying out of the dome upward (figs. 75 and 98), in the same way that a monoclinal or anticlinal fold or a fault may die out. The rapidity of absorption will depend upon the softness of upper beds; as the Black Hills section becomes progressively softer upward the conditions are the more favorable for absorption of flexure in small vertical distances.

The manner in which doming dies out, and the relative distribution of hard and soft beds, is shown in fig. 98 (p. 277). There is some direct field evidence of absorption of dome flexure. Rapid diminution in dip of flanking beds upward on the side of a laccolith shows within a few hundred feet of strata a diminution in curvature. This is clearly shown on the south side of Crow Peak, the west side of Kirk Hill, and east of Bear Butte (figs. 83 and 93, Pl. XXX). Such diminution in dip is conspicuous in laccoliths having most intense dome flexure.[1] Another evidence is presented by Circus Flats; the outcrop affected by the subterranean dome is hardly larger than Bear Butte (Pl. XXX). By analogy with other subordinate laccoliths, Bear Butte is much smaller than the underground main laccolith of which it is an offshoot. The Circus Flats ellipse in Benton shale has probably not more than half the diameter of the laccolith beneath. Lastly, miniature domes and lenses in Cambrian shale (figs. 65, 66, 67) show absorption of the flexure which they cause, a few feet above, and similar effects are produced by laboratory experiment (Pl. XLIII).

EROSION STAGES REPRESENTED IN THE BLACK HILLS.

Attention has been drawn to the evidence by analogy shown in the several stages of erosion from covered dome to uncovered laccolith, that in part demonstrates the originally intrusive character of all of the younger porphyries of the Black Hills. Six cases have been selected (Pl. XLI) which illustrate the progressive denudation of the laccolith and the arrangement assumed by the drainage which throughout the several stages has served as transporting agent for disintegrated material. The six types are Elkhorn Mountain, Crook Mountain, Citadel Rock, Kirk Hill, Crow Peak, and Pillar Peak. Two others should be added to this list: Circus Flats (Pl. XXX) and Mato Teepee (Pl. XXXVIII).

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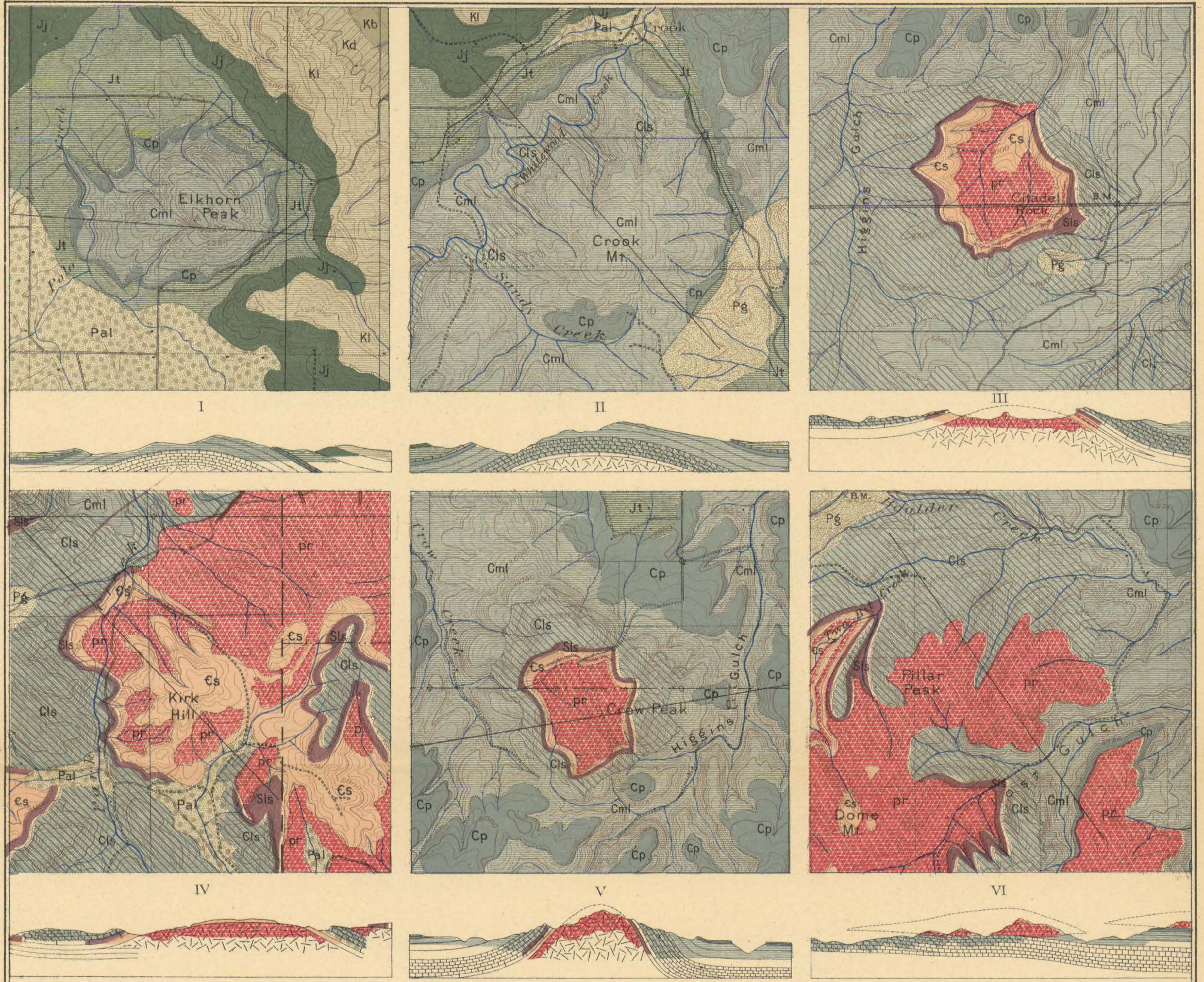
[1] Compare cross section of Mount Hillers, fig. 26 of Gilbert's Henry Mountains; also sections of Thunder Mountain, figs. 44 and 45 of Weed and Pirsson's Little Belt Mountains: Twentieth Ann. Rept. U. S. Geol. Survey, 1900, p. 365.

CIRCUS FLATS.

Circus Flats represents the earliest stage of laccolith erosion in the region of the Black Hills. The buried eruptive dome has deformed strata up to and including Benton Cretaceous. Small streams radial on the dome of Dakota sandstone have shifted until that northern stream, which has greatest fall to its junction with Spring Creek, has mastered the others and eroded out a hollow in the center of the dome on soft Triassic red marls (Pl. XXXII). Subsequent streams concentric to the dome follow annular valleys on soft beds, and the greater stream, Spring Creek, turns aside to encircle the dome on the east and north, following Benton shale and avoiding Dakota sandstone. The initial course of this greater stream was northeast, off the Black Hills uplift. The initiation of such drainage took place when the Black Hills were first subjected to atmospheric erosion. How such erosion came about is not known, whether from recession of an Eocene lake or by rainfall which continued while the uplift took place. That the streams flowed radial to the uplift is amply shown by their present distribution. The drainage features of Circus Flats may be summarized as follows: Deflection of a trunk stream superposed upon the dome through a thickness of several thousand feet, now eroded away; local development of radial branch streams on a hard stratum; local mastery by one of these streams within the area of the dome; development of concentric subsequent streams on soft strata: a hill has been converted into a basin surrounded by a horseshoe-shaped ridge, and drainage radial outward has become radial inward.

ELKHORN PEAK.

In Elkhorn Peak, higher on the flanks of the Black Hills, erosion has carried away the upper beds, and the soft Red Beds form here a valley around a hard Minnelusa sandstone dome which stands in relief. The sandstone dips away from the summit on all sides, and is incised by erosion most deeply on the southwestern side, but in no case is the underlying gray limestone exposed. Minnekahta limestone forms revet crags on the flanks, with steepest dip on the east and southeast. Above it the Red Beds have been closely compacted within a synclinal fold southeast, where a narrow valley separates Elkhorn Peak from hills of Jurassic and Cretaceous strata. On the northern, western, and southwestern sides Minnekahta limestone passes by gentle curvature under the broad Red Valley at Centennial Prairie. The drainage on the slopes of Elkhorn is chiefly radial, small gullies of subsequent development tending to follow the soft layers, producing in many cases a rectangular system. Larger streams, as in the case of almost all the laccolithic domes of this region, form an encircling valley about the base of the mountain in soft red Triassic marl. When



LEGEND

PLEISTOCENE		CRETACEOUS			JURATRIAS		CARBONIFEROUS			SILURIAN	CAMBRIAN	IGNEOUS	
					JURASSIC	TRIASSIC	PERMIAN						
Pal	Pg	Kb	Kd	Kl	Jj	Jt	Cp	Cml	Cls	Sls	Єs	pr	
Meadow bottom land Alluvium	Ancient stream gravels	Benton dark shales	Dakota brown sandstone	Lower Cretaceous sandstones and shales	Sandstones limestones and shales	Thick red marls and gypsum	Minnekahta thin limestone over red bed	Minnelusa limestones and sandstones	Massive limestone	Arenaceous limestone	Shales, limestones, and sandstone	Porphyry	Dikes

GEOLOGICAL MAPS AND CROSS-SECTIONS

ILLUSTRATING

STAGES IN EROSION OF LACCOLITHIC DOMES

BLACK HILLS, SOUTH DAKOTA

BY

T. A. JAGGAR JR.

1900

Horizontal and vertical Scale

1 ½ 0 1 2 3 4 Miles

1 ½ 0 1 2 3 4 5 Kilometers

Contour interval 50 feet

Datum is mean sea level

Topography by W. H. Herron and Arthur Stiles

Colored portions of sections indicate rocks exposed

JULIUS BIEN & CO. LITH. N.Y.

Elkhorn was formerly at the Circus Flats stage these streams flowed in an annular valley within the Dakota escarpment. They have shifted down the monoclinal dip along easily eroded Red Beds.

From the slopes of Elkhorn Mountain small streams radiate with wonderful symmetry, and the dipping strata indicate a quaquaversal almost diagrammatic in its regularity. The presence of Permian limestone as the highest flanking stratum lends a special beauty to the symmetry of the mountain. This limestone, characteristically from 30 to 40 feet in thickness and uniform on all sides of the Black Hills, underlain by 90 to 100 feet of soft red sandstone and clay, forms habitually a gentle dip slope ending in an abrupt escarpment, and drainage radial from the hills cuts V-shaped gateways through it that are among the most picturesque features of the region. In the same manner small gateways are cut through this limestone where it encircles smaller laccolithic domes, and this has been figured and mentioned by Russell[1] in his description of Little Sundance dome. Elkhorn is a repetition of Little Sundance dome (Green Mountain), and these covered laccolithic domes are by no means exceptional.

South and east lies a portion of the Red Valley, through which Polo Creek flows northward, its channel falling within the rampart of the Permian limestone for a mile along the western base of the mountain. The geologic structure east of Elkhorn is a broad syncline, while on the southwest side the beds have a gentle monoclinal dip northeast, interrupted by the buried laccolith. Within the small area shown (Pl. XLI, fig. 1) the regional dip of the strata is uniformly northeastward. Polo Creek has a northeast trend, but on reaching the dome it bends northwest and then resumes its northeasterly course. The striking characteristics, in brief, of the Elkhorn drainage are, first, radial rills; second, encircling branch streams; and third, diversion of the trunk stream from its course by the covered laccolith. The crescentic escarpments of Permian limestone show the structure which suggested to Newton the simile of a puncture upward through a bundle of paper by a sharp-pointed pencil.

CROOK MOUNTAIN.

Crook Mountain shows drainage features similiar to those of Elkhorn, but erosion on the northwest side of the dome has revealed Carboniferous limestone under the Minnelusa beds. Permian limestone does not completely encircle the mountain, but has been carried away by the headwaters of Sandy Creek, and for a distance of a mile and a half it has been removed by the active erosion of lower Sandy Creek and Whitewood Creek, the latter being the trunk stream which skirts the northwest flanks of the mountain. The geologic structure is

[1] Igneous intrusions in the neighborhood of the Black Hills of Dakota, by I. C. Russell: Jour. Geol., Vol. IV, p. 29, and Pl. I, fig. B.

somewhat more irregular than in the case of Elkhorn, Sandy Creek occupying a synclinal valley between Crook Mountain and a laccolith to the southwest, and Crook Valley on the east is the northern appressed extension of the Boulder Park syncline.

The drainage features repeat the small concentric rills, the radial smaller streams, and the encircling larger streams. The largest stream of all, however, again as in the case of Elkhorn, does not remain outside of the Permian limestone rampart on the soft red marl, but has cut its channel into the side of the dome, carving out a deep canyon in a lower formation. Whitewood Creek is one of the master streams of the region, having in general, like Polo Creek, a course consequent upon the greater northeast slope of the Black Hills uplift, but it shows at several points evidence of stream capture and diversion due to complications occasioned by irregular distribution of hard and soft beds. In both this case and that of Elkhorn there is a strong suggestion that these greater streams were superimposed upon the laccolith from a position unaffected by the doming when their channels lay stratigraphically higher. Both of them are deflected from a course that higher upstream approaches the dome directly. In the case of Crook Mountain, if this course were continued through the mountain it would cross the summit; in the case of Elkhorn it would cut off a considerable portion of the northwest flank.

In Spiegels Gap, on the northwest side of the mountain, a reversal of drainage through one of the Minnekahta limestone gateways has produced one of the most remarkable topographic curiosities in the Black Hills. The Red Valley makes an abrupt bend northwest of Crook Mountain, and the Red Beds are compressed into very narrow limits on the flanks of the arch. The Permian limestone here forms the crest of an escarpment that rises 400 feet above the bottom of Whitewood Canyon. The small stream occupying the narrowed Red Valley outside of the escarpment joins Whitewood Creek at Crook City. The usual V-shaped gateways through the limestone give evidence of a former radial drainage from Crook Mountain into the Red Valley, but Whitewood Creek, after cutting its deep gorge in the flanks of the dome, has reversed all these streams, and Spiegels Gap, the most conspicuous of the V-trenches, appears like an artificial notch or gash; the overhanging scarp within extends to the bottom of the notch, and within the V the slope is very steep inward toward the mountain, extending down to the bottom of the canyon.

CITADEL ROCK.

In the case of Citadel Rock a laccolith crest has been revealed by a single radial stream gaining the mastery on a dome of the Elkhorn type; annular valleys have been eroded out through Minnelusa sandstone, gray limestone, Silurian, and Cambrian to the porphyry intruded in

Cambrian shales. Compared with Circus Flats, Elkhorn Peak, and Crook Mountain, progressively, the actual elevation of the Citadel Rock laccolith is found to be the highest. Relative to a common base-level as members of a single erosion grade, Citadel Rock should be eaten more deeply than Crook Mountain, the latter more deeply than Elkhorn, and Elkhorn than Circus Flats. That such is the case is made clear by comparison of the several sections constructed in natural proportion and with a common base line 3,000 feet above the sea (Pl. XLI).

Citadel Rock stands as an isolated monolith with vertical walls on a spur that projects into the midst of a circular basin, above which rises a ring-shaped escarpment of limestone 200 feet higher than the top of the Rock and from 400 to 600 feet above the gulches cut in porphyry that encircle it. The two encircling gulches are superposed upon the

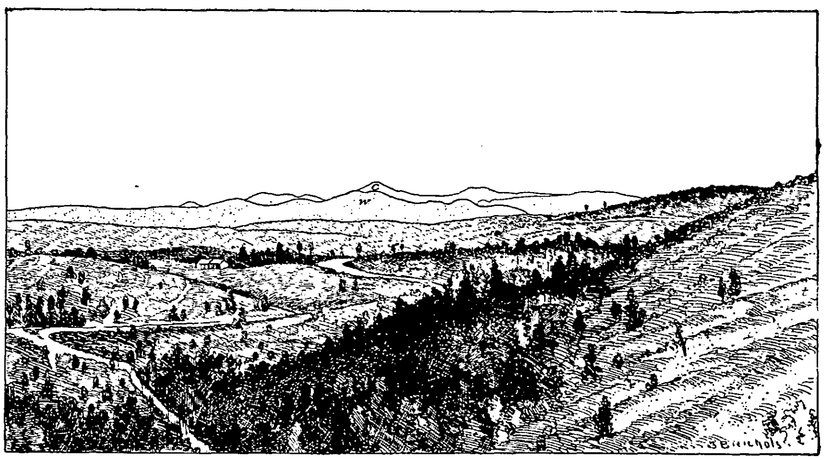


FIG. 97.—Custer Peak and Woodville Hills from Bald Mountain.

porphyry from former concentric subsequent stream The dip of the porphyry-Cambrian contact on the crest of the dome was insufficient to carry the drainage down the porphyry slope by monoclinal shifting. The result is an inherited annular drainage on the porphyry.

The annular drainage of Citadel Rock is not confined to the small streams within the core. A portion of Higgins Gulch partly encircles the laccolith on the west side, and other small streams curve around it in Carboniferous horizons on other sides. Such streams may shift down the dip along soft beds either by capture or by monoclinal shifting until the dip becomes insufficient to produce such shifting. The final result will be a series of encircling streams about or upon a laccolith remnant, and these mark the original outer limits of domical flexure in upper beds, or may define the position of the original rim of the laccolith itself.

Superposed annular valleys.—In Inyankara a more advanced stage of erosion is shown of the same type as Citadel Rock, with an annular valley in porphyry, an encircling escarpment of sediments, and a central peak which rises above the surrounding escarpment. Custer Peak and the Woodville Hills (fig. 97) represent similar phenomena in flatter laccoliths more completely eroded. In these cases the inherited annular valley has lost definition, so that there is left a central peak with peripheral porphyry knobs, a section through basement strata, and only slight remnants of flanking beds. In Little Missouri Buttes a still later stage is shown. No trace of flanking sediments there remains; erosion has eaten through the middle of the laccolith almost to the basement stratum, and the central peak is surrounded by masses of talus on the west and north and by lower knobs on the east and south. There is, however, a distinct remnant of the inherited annular valley about the highest peak of Little Missouri Buttes (Pl. XXXVIII). In the case of Mato Teepee, about which two small gulches and the western bench form remarkably perfect semicircles, the annular valley is inherited on strata underlying the laccolith. This perhaps marks approximately the former border of the porphyry area.

KIRK HILL.

Kirk Hill (Pl. XLI) forms an eastern extension of the Vanocker laccolith. Here erosion has progressed sufficiently to expose porphyry in the region of maximum corrasion on the flanks of the dome, which is still capped, however, by a veneer of Cambrian beds with fingering extensions on the interstream spurs. To the northeast the porphyry is continued into high hills at the head of Deadman Creek. Kirk Hill is thus a laccolithic arm or lobe from a greater mass. The structure of the sediments west and south is synclinal, and on the southeast there is a synclinal sag that separates this lobe from another extension of the Vanocker laccolith.

On Kirk Hill radial small streams are well shown, but since the sedimentary shells which cover the dome have been in great part removed, the small rill beds of concentric subsequent arrangement are lacking, except in a few cases on the southwest side, where Silurian and Carboniferous limestones still form crescentic escarpments over the soft shales. Park Creek is an encircling stream following the western syncline, and other streams encompass the hill on the south, southeast, and northeast. At the northwestern base of the hill Park Creek has cut through the syncline, and for a short distance follows the contact of porphyry with overlying sediments, but at no point has the porphyry mass been dissected to a sufficient depth to reveal the stratum on which it rests.

In topography Kirk Hill marks a stage of denudation later than Citadel Rock, for the flanking sedimentaries have weathered well down the slope of the laccolith, leaving a hill shaped like a low dome with remnants of strata clinging to the summit. The transition from annular valley to rounded hill is a repetition of the process shown between Circus Flats and Elkhorn Peak. Kirk Hill represents the third and last cycle in the development of hills over the laccolith. The first was the hill of Dakota sandstone that preceded the Circus Flats stage; the second was the Minnelusa sandstone hill, represented in the Elkhorn, Spottedtail, and Green Mountain domes; the last case, like Kirk Hill, is represented in Deer Mountain, Dome Mountain, and other laccoliths.

CROW PEAK.

At Crow Peak (Pl. XLI, fig. 5) the porphyry stands at greater height above base-level than at any point hitherto described in this chapter. As a result, erosion has carried down the flanking sediments and left the steep-sided laccolith in high relief. The resistant limestones, however, still cling to the slopes on all sides. Immediately about the mountain radial gullies are conspicuous. Crow Peak on the west and portions of Higgins Gulch on the east and south partially encircle the laccolith. Citadel Rock occurs a mile and a half SSE. from Crow Peak, in the direction of the greater Terry center of irruption. The difference from the Kirk Hill stage consists in the absence of capping Cambrian beds and the greater relief; Crow Peak is also structurally different in its more intense dome flexure.

PILLAR PEAK AND BEAR DEN MOUNTAIN.

The sixth stage of erosion is shown in Pillar Peak and Bear Den Mountain (Pl. XLI), where the beds capping and flanking the laccoliths have been entirely eroded away, and erosion has revealed the underlying strata and some of the conduits through which the intrusive rose (see Pl. XX for general relations). On the south is shown the stratigraphic series, from Algonkian through Cambrian, Silurian, Carboniferous, Minnelusa, and Permian, which underlie the Bear Den laccolith at its northern end. Bear Den Gulch separates the Bear Den laccolith from the Dome Mountain mass, on whose eastern flanks the limestones dip steeply under the Bear Den laccolith, and thence the dip diminishes to a condition of approximate horizontality in a broad, flat depression northeast. In Cambrian beds about the town of Galena are shown sills and a dike complex that marks the locus of intrusion for the Bear Den porphyry, which spread northeast, breaking across strata. The initial structure of these laccoliths was a great, swollen mass beneath Silurian and superincumbent strata on the present site of Dome Mountain, and smaller offshoots which broke across and domed up higher beds. The lower side of a strike fracture across limestones may be followed from Dome Mountain to Pillar Peak. It is probable that this fracture extended across Lost Gulch, and that Pillar Peak and Bear Den Mountain were at one time continuous, the lower contact of the porphyry progressively truncating strata along a horizontal fracture plane across gentle northeast dips. The west side of Pillar Peak shows porphyry on gray limestone. On the east side of the same mountain the porphyry overlies Minnelusa sandstone. The Bear Den porphyry overlies Permian limestone in the northern part of the mountain.

Considering Pillar Peak and Bear Den Mountain parts of a single laccolith, the drainage is seen to have produced an inner basin, a horseshoe ridge, and outer encircling drainage. The inner basin is Lost Gulch, cut through the basement strata; the horseshoe ridge is of porphyry, composed chiefly of the laccolith remnants; Two Bit and Bear Butte creeks, encircling the whole, probably define the original laccolith perimeter, though now their canyons are cut in limestone below and away from the porphyry. As a stage beyond that of Kirk Hill in physiographic development, this horseshoe ridge of porphyry is like the limestone ridge about Citadel Rock. Lost Creek, the north-flowing stream on the former hard rock hill, worked faster than the other radial streams and gnawed through the porphyry to softer rocks below, there to erode out an interior basin. This is the third and last stage of inner basins. The first was Circus Flats, with a Dakota rim; the second, Citadel Rock, with a Carboniferous rim; and in the Pillar–Bear Den case the rim is formed of porphyry. Stratigraphically the last case differs from the others, for the horizon of intrusion is higher. Other types of the last stage are numerous; a horseshoe-shaped laccolith remnant incloses the city of Lead; Ragged Top is shaped like a crescent and is encircled by two pairs of streams. Woodville Hills, Custer Peak, and Little Missouri Buttes retain a central high peak with an annular valley in porphyry about it, and the outer crescent of porphyry has a number of culminating summits.

SUMMARY OF EROSION STAGES.

The cases cited show that laccolithic domes deflect regional master streams, and that subordinate drainage conforms strikingly to the relative resistance of rocks exposed. An early stage produces a dome-shaped hill with radial drainage. One radial stream gains advantage over its fellows and eats out the central portion of the dome to a soft stratum beneath. The outward dipping hard beds are undermined and drainage formerly radial outward becomes radial inward; a former mountain becomes a quaquaversal basin inclosed by a horseshoe ridge. Recession of this ridge and continued erosion on the soft bed uncovers an arch of harder rock. Monoclinal shifting on the soft bed becomes easier than deep cutting into the dome, so that the flanking beds are eroded down and a new radial drainage forms with two pronounced encircling streams (fig. 98). In the figure the radial progression from the Circus Flats stage through the several stages described is shown by profiles inscribed on a common dome. The alternations from domical mountain to horseshoe-shaped ridge will continue under the erosive action of changing subordinate drainage until the porphyry is reached. Here monoclinal shifting is no longer possible, owing to lack of monoclinal structure. Annular drainage superposed on the crest of the laccolith may persist so as to be retained as a characteristic feature of both plan and profile in old laccolithic mountains. If the last monoclinal shifting takes place along the contact of por-

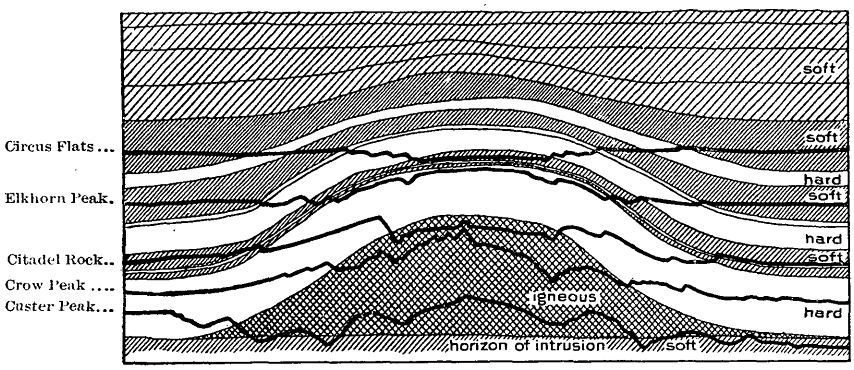


FIG. 98.—Diagram illustrating development of erosion profiles on laccolith domes.

phyry and capping sediment, annular drainage which has shifted down this contact will eventually be superposed upon the stratum beneath the laccolith, marking there a peripheral limit for the original igneous mass even after the porphyry has been eroded away.

EROSION PROFILES.

The section diagrammatically represented in fig. 98 corresponds in thickness and consistency to the Paleozoic section from Silurian limestone to Pierre shale and higher. A laccolith is represented in the normal position, under the "competent" Siluro-Carboniferous member. The three hard members, progressively thinner upward, are Siluro-Carboniferous, Jura-Cretaceous, and Niobrara; the three soft members, progressively thicker upward, are Red Beds, Benton, and Pierre. These thicken at the sides of the arched hard strata, and the dome consequently fades out to horizontality above. The profiles show types, represented by separate cases in the Black Hills, made by laccoliths intruded at about the same horizon. These profiles are projected irrespective of scale, on the cross section of an ideal dome, to show their mutual relations to a uniform process of erosion.

In Circus Flats there is a basin on a soft stratum; in Elkhorn the basin is divided in two by the resistance of the central hard stratum, and the two lateral depressions mark the encircling drainage. In Citadel Rock the dome has been eaten through and the basin is repeated, with higher walls, because encompassed by the thicker and harder limestone; annular drainage is superposed on the porphyry. In Crow Peak the porphyry shows greater power of resistance to erosion, and streams are gnawing along the contact of laccolith and sediments. In Custer Peak several pairs of annular streams have been superposed on the porphyry; some of these have cut through to the basement strata, and only on one side is the laccolith rim preserved. The conspicuous feature of the profile is the bilateral symmetry of central peak and lateral spurs. The outermost streams that can be traced as encircling the mountain lie within the original limits of the porphyry.

LITTLE MISSOURI BUTTES AND MATO TEEPEE.

Little Missouri Buttes and Mato Teepee mark two stages further, but their profiles can not consistently be inserted on this diagram, because their basement strata are Jura-Cretaceous; otherwise the process is the same. If we denude the Custer Peak profile a little further, removing all trace of flanking sediments, and leave a steep central peak, a lower knob on one side, and a train of talus on the other, we shall have the profile of Little Missouri Buttes (see Pl. XXXVIII, section). If we leave only a small columnar remnant of porphyry with an annular valley in the sediments about it, we shall have Mato Teepee (fig. 95). In this erosion scheme the conduits have no considerable effect; they are dikes or lateral sills, which may be eroded soon or late in the process, according to their position.

RELATION OF PRESENT ELEVATION TO DEPTH OF EROSION.

Laccoliths intruded about the same horizon are more deeply denuded in proportion to their present height above base-level; the following table shows the relative heights above sea level of the profiles (compare fig. 98), from deeply buried laccolith in the plains to porphyry remnant in the Hills:

	Present profile.	Crest of laccolith (approximate).
	Feet.	*Feet.*
Circus Flats	3,000	2,500
Elkhorn Peak	4,520	4,000
Citadel Rock	5,450	5,500
Crow Peak	5,785	6,000
Custer Peak	6,812	7,500

This table gives present altitudes of topography immediately above or below the initial crest of the laccolith. In Citadel Rock the altitude is nearly that of the actual porphyry upper contact; in Circus Flats and Elkhorn Peak the porphyry probably lies from 500 to 800 feet below; in Crow Peak and Custer Peak much has been eroded away. Therefore the actual differences in elevation of the laccoliths were greater in every case, as shown in the second column of the table. As all of these were intruded under and arched Siluro-Carboniferous limestones, and the depth of their uncovering (fig. 98) varies with their height above sea level, it is clear that the present profiles are products of an erosion process which affected all alike. Hence the grouping of individual cases in series to represent erosion stages is justified by their relation to a common base-level.

CHAPTER IV.

THEORETICAL CONCLUSIONS.

SUMMARY OF FIELD EVIDENCE.

In the preceding pages it has been shown that igneous intrusions of rhyolite and phonolite porphyries accompanied or immediately followed a great movement or uplift in the area now occupied by the Black Hills. This uplift arched the horizontal strata of the plains into an elongate dome; schists beneath, with nearly vertical bedding and lamination, moved up by faulting and slipping, frequently on planes of schistosity. Erosion has removed a portion of the sedimentary cover completely, exposing two kinds of sections whereby the solid geometry of structures within the uplift may be studied. One is a beveling across the top of the dome, exposing a ground plan; the other is a deep trenching by streams through the flanks, exposing vertical cross sections. The igneous matter rose through the steeply inclined schist laminæ and spread out among the sediments which lay across them unconformably. Erosion beveling has exposed dikes in the schist and flat masses in the later strata. The walls of erosion trenches show the thickness of the sills and lenses and sometimes their junction with feeding dikes.

The intrusives are confined to the northern portion of the uplift. The southern portion was occupied by massive ancient pegmatite granites, themselves pre-Cambrian intrusives in Algonkian strata. Probably they acted as a rigid cementing and hardening agent to prevent fracturing in the southern schists; the northern, less indurated phyllites cracked and faulted more readily to permit the younger intrusives to rise from the depths. The northern exposed schist areas contain many hundred dikes and some stocks; these must have induced movements of horizontal extension in the schist, and such movements are attested by bedding plane faults at the base of the Cambrian. The dikes have a common trend and dip parallel with schistosity. The dip gave them tendency to spread in the Cambrian in one direction more readily than in another. In Cambrian thin-bedded strata with many shale horizons, sills formed in great number. Above lay the thick limestone; it resisted upward movement of the porphyries and locally became domed and arched. Beneath it were found the principal laccoliths of larger size, the largest where the limestone was thinnest. Some of them were unsymmetrical, partly because they were injected into strata possessing an initial dip, partly because their conduits sloped and the magma was forced forward in one direction. On one side the limestone was flexed beyond the breaking point; a fracture opened and admitted the igneous fluid to higher horizons, forming subordinate laccoliths. The subordinate laccoliths are characterized by still greater lack of symmetry; their sides are steeper than those of the main laccolith; they fault and crumple the beds about them. Associated with dikes, sills, and laccoliths are breccias composed of fragments of the rocks through which the igneous magma passed. There is no evidence that the intrusives were connected with surface volcanics. In general the phonolites are younger than the rhyolites; none of the larger main laccoliths are formed wholly of phonolite; the phonolite broke through the larger bodies of rhyolite-porphyry and solidified in smaller masses at higher horizons. The greater number of subordinate laccoliths, however, are of rhyolite-porphyry; these include Bear Butte, Deadman, and Whitewood Canyon laccoliths, Crow Peak, Inyankara, and Sundance Mountain. The magmas which formed the subordinate laccoliths were beginning to solidify and hence were more viscous; this is proved in part by fewer sills, by domes of smaller ground plan and greater convexity, and by diminution in total volume of intrusive rocks in the higher strata. The characteristic forward and upward movement of intrusive through strata is by way of strike fissures. The lower contact of sills and laccoliths frequently truncates or bevels strata obliquely across the bedding. The horizons where a single stratum is followed for some distance are composed of soft shale confined between harder beds.

Erosion has left laccoliths covered, partially uncovered, and deeply dissected, and in places has removed them entirely or left only scattered remnants. Conduit, basement contact, wedge, flank, crest—all parts of the laccolith are exposed, in plan and section, in different places in the Black Hills. The evidence quoted points to Eocene time as the age of intrusion. There were several thousand feet of strata above the laccoliths, and the soft Cretaceous shales absorbed laterally the doming produced by individual intrusive masses. Trunk drainage consequent on the Black Hills uplift was deflected by adjustment to the domed hard strata that were gradually uncovered; branch drainage, dependent on the relation of rainfall to form and texture of surface, continually changed with the discovery of hard and soft strata, producing hills in hard domed beds and annular valleys in soft ones. Such annular valleys were eventually superposed on porphyry, and persist in several deeply dissected laccoliths, such as Custer Peak and the Woodville Hills. Where an annular valley on the contact of porphyry and flanking sediments became superposed on the basement stratum, its course preserved approximately the outline of the laccolith after the same was in great part eroded away.

HISTORY OF INTRUSION.

The history of intrusion in the northern Black Hills is believed to be intimately associated with the history of the larger deformation. Intrusion is not conceived to have been in any sense a cause of the greater uplift, but an effect. The intrusions were a small incident in a great movement of elevation. The greater uplift probably took place after the close of the Laramie, along with similar movements in the Bighorn Range and the Rocky Mountains. Whatever their cause, these movements were colossal and involved a considerable section of the earth's crust; doubtless there had been similar movements about the hard granite core of the Black Hills from the earliest Paleozoic times. There was unquestionably some deformation prior to the laccolithic intrusions, for these broke across previously brecciated Cambrian flags, and encountered dips already initiated. The post-Laramie uplift was accompanied by profound fracturing. The fractures reached downward to a zone where molten rock was under pressure. The liquid shot upward into every ramification of the fracture system; Algonkian, Paleozoic, and Mesozoic beds were in some sense under compressive stress, rising slowly, the hard, competent members supporting the arch, the soft beds following the lead of their more resistant neighbors. Diversity of structure and consistency produced minor differential movements of faulting and folding. The upturned schist beds slipped like cards on edge to make undulations in the basal Cambrian quartzite, which also faulted in places. Springing into every weak place, spreading the beds and crumpling the soft ones wherever there was tendency to gaping by reason of the greater burden assumed by the more rigid strata, the igneous magmas reached the Cambrian through countless fissures in the schist beneath. The change in structure at the Algonkian-Cambrian unconformity was especially favorable to the development of local weakness that would give advantage to an igneous wedge. The Paleozoic horizon least compressed lay under the Carboniferous limestone. The thick limestone member, most "competent" to support load under lateral pressure, relieved the soft shales beneath in many places. The porphyry magma was itself probably under pressure and capable of independent dynamic action relative to individual beds invaded; whether that pressure was in any way limited by the actual volume of magma available, or what hydrostatic or thermal law governed it, we have no means of knowing, but it is quite certain that the pressure of igneous fluid relative to the condition of the limestone was sufficient locally to arch up and break through that stratum and some of the superjacent beds. That it did not do this until it was beginning to solidify is in part suggested by the fact that only a relatively small volume of porphyry broke through the limestone to higher horizons. The fact of local doming and fracturing of the limestone by the porphyry does not of necessity imply that the lava in each of those domes lifted the load; it bent and pimpled the limestone within an arch of enormously greater magnitude, composed of several competent members that were collectively supporting the total weight of sediments. The fact that the greatest doming of limestone over porphyry at the Terry-Polo complex took place where the limestone was thinnest shows that it was not the weight of superincumbent beds, but the inflexible quality of the thicker limestone which resisted doming. It is equally clear that the size of the laccolith is entirely independent of load; the smaller Ragged Top and the greater Deer Mountain laccoliths are both intruded at the same horizon; the Vanocker porphyry mass, probably the largest single laccolith exposed, reaches the Upper Carboniferous, while comparatively small subordinate laccoliths, like Crow Peak and the one in Whitewood Canyon, are intruded under Obolus beds at the base of the Cambrian.

APPLICATION OF EXPERIMENTS.

Mr. Howe's experiments prove that low viscosity favors wide lateral extension to form sills; high viscosity produces thick lenticular bodies. They show, also, that the intrusive thickens into domes where a resistant overlying stratum locally thins. Howe has demonstrated further that a stratigraphic obstacle to horizontal spreading may cause a sill to thicken into a laccolith. This was the first effect of the initial dip encountered by the Dome Mountain magma in spreading, and of the upward bend over the earlier Warren Peak uplift encountered by the Little Missouri Buttes magma when injected through horizontal beds. The first experiment shows that irregular serpentlike bodies may push their way through thick beds of incoherent material; this is analogous to the irregular intrusions at Portland. In a dome of hard beds radial fractures form on the crest and concentric fractures open downward on the periphery. The former, if developed by erosion, would guide radial drainage; the first peripheral fractures give egress to the intrusive to form subordinate laccoliths. Such overturned domes as Ragged Top or Bear Butte, thickest on the sides away from the conduit, are well illustrated in Experiment IV, where it is shown that a magma rising through an inclined conduit forms an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical.

DISCUSSION OF PUBLISHED THEORIES AND DESCRIPTIONS.

EFFECT OF LOAD (GILBERT).

The Black Hills, like the Henry Mountains, contain smaller laccoliths in the upper zone and larger ones in the lower. This is believed by the writer to be due solely to increased viscosity, diminished pressure of injection, and more incoherent beds in the upper horizons. Gilbert gave less value to the influence of viscosity and greater value to variation in load. He concluded "the pressure of injection remaining constant, the limital area of a laccolite is a direct function of its depth beneath the surface. The limital area is greater when the depth is greater, and less when the depth is less."[1] This conclusion was reaffirmed by Gilbert in the fall of 1896 in connection with his description[2] of Twin Butte. So far as our experiments go, they seem to indicate that the dome curvature of a laccolith is greater under a greater load, hence for the same volume of intrusive the area is smaller. In an experiment with a load of shot on the surface of strata, they were domed up rapidly in the center; without the shot the laccoliths spread out more widely and formed a lower arch (Experiments IV and V). In both cases the injected wax was cooled for the same period and was uniformly viscous. Under greater load the shale horizons are more closely compacted and less easily split apart. With the same viscosity and pressure of injection an intrusive lens under load can more easily increase its convexity to produce lateral thickening and crumpling of superjacent soft beds than it can spread as a wedge to lift a great volume of heavy strata. Hence, in those cases where load has any effect, if viscosity, volume of magma, and pressure of injection are constant, the area of a laccolith is probably greater when the depth is less. This appears to reverse Mr. Gilbert's conclusion, but the constants mentioned alter his problem, and the experimental analogy is incomplete. The influence of varied load is believed to be inconsiderable in the Black Hills, so much greater was the influence of varied viscosity and pressure of magmas and texture of beds invaded. The size and curvature of individual laccoliths were modified by variation in thickness of the stratum immediately superjacent, by texture and thickness of the shale horizon selected for intrusion, by distance from and dynamic relation to conduits and other laccoliths or sills, by stratigraphic obstacles, and by concomitant regional folding and faulting. The composition of magmas may have had some effect, too, in determining rate of solidification and consequent viscosity.

ANALOGOUS DESCRIPTIONS BY HOLMES.

The absorption of doming vertically was suggested in a paper by Holmes published in 1877, where, in describing the Sierra El Late, a typical laccolith was figured[3] diagrammatically, though such structures were as yet unnamed. The figures compared show "arching of strata produced by intrusion of single mass uniformly distributed" (a laccolith) and "degree of arching really produced by the irregular intrusions." The second figure showed much less arching, due to "a sort

[1] Geology of the Henry Mountains, p. 84.
[2] Laccoliths in southeastern Colorado: Jour. Geol., Vol. IV, 1896, p. 821.
[3] Hayden's Report, 1875, U. S. Geol. and Geog. Surv. Col. and adjacent Terr., p. 272, Pl. XLVI, fig. 2.

of absorption of the shales, so that at least half of the space through which the trachyte is distributed is occupied by the crushed and metamorphosed fragments of shale." Most observers agree that shale beds are favorite horizons of intrusion.

The intrusions of basalt in Mount Everts, in the Yellowstone Park, figured by Holmes[1] (fig. 99), show a relation of conduit to intruded lens or sill, similar on a small scale to that of the subordinate laccoliths of the Black Hills (compare sections Pl. XXI). These basalt masses are said to be intruded in Cretaceous sandstones, shales, and lignite, the beds dipping 5° to 13.°

[The intrusions] cross from horizon to horizon, breaking through the beds and pushing them aside, and bending and crushing them in a most remarkable manner. * * * The masses * * * are very irregular in thickness, reaching in places 40

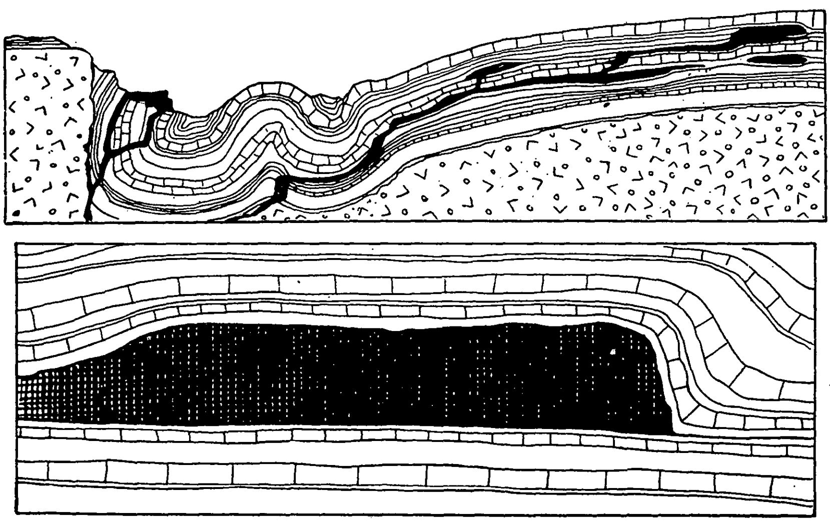


FIG. 99.—Intruded basalts of Mount Everts, Yellowstone Park (Holmes)

to 50 feet. They lie in rude sheets approximately with the strata, but bearing the strongest evidence of their intrusive character. The irregular bed that outcrops along the crest of the ridge is in places 40 feet in thickness, but generally falls far short of this. Its position in the strata points very clearly to its intrusive character. It does not lie in any one horizon, but breaks across the strata at all angles, crushing the severed edges back upon themselves. * * * It rests chiefly in a series of coal shales and sandstones. * * * In the heavier masses this basalt has a rudely columnar structure and weathers down in very small angular blocks. In the thin tongues that have been thrust out from the main mass into the surrounding strata, there is a tendency to form small prisms at right angles to the surface. * * * The strata which inclose this basalt dip to the northeast at angles from 10° to 15,° the line of the great fault which defines their northern limit being about 2 miles distant. It seems probable that the intruded basalts may have originated in or rather reached their present position through this fault, the crushing of the strata indicating generally an intrusion from that direction.[2]

[1] Hayden's Report, 1878, II, U. S. Geol. and Geog. Surv. Terr., p. 10, Pl. VI.
[2] Op. cit., pp. 10, 11.

The lower enlarged figure is a mass seen in the western face of Mount Everts, and in form is remarkably like the end of an unsymmetrical laccolith with lateral conduit (Experiment IV, Pl. XLIV). It is a mass "300 feet long by 12 to 15 feet thick, and appears in the face of a steep wall of dark shales and laminated sandstones. It has been forced in between the yielding strata, folding them up almost at right angles at the ends, as shown in the figure" (fig. 99).

WORK OF CROSS, WEED, AND PIRSSON.

The bibliography of laccoliths was thoroughly reviewed by Cross,[1] and other descriptions of laccolithic mountain groups in Montana have recently been published by Weed and Pirsson.[3] Cross recognized in the Mosquito Range and Tenmile district the influence of orographic movements concomitant with intrusion. He says: "In regions where the beds are under orographic stress, almost or quite to the point of folding, a magma would find intrusion on certain planes a comparatively easy matter." Cross points out the prevalence of departures from regularity due to oblique intrusion across bedding, structural weakness, earlier intrusives, and incoherent strata. His sections through Mount Marcellina and the Anthracite Range, unsymmetrical laccoliths, are closely similar to cases in the Black Hills. In his ideal restorations of arched strata above Mount Marcellina the size of the arch in strata far above is represented as greater (in dip length) than that of the stratum next to the laccolith, a questionable construction if any of the strata involved are soft and yielding.

Pirsson's sections from the Judith Mountains express the relation of main laccoliths to subordinate peripheral bodies. He concludes that the important factors in the production of laccoliths are pressure of injection, viscosity, gravity, load, and cohesion of strata. His discussion of cause, comparing the mechanism to a "vast hydrostatic press," seems to neglect the possibility of orogenic deformation preceding and initiating intrusion. "Suppose a fissure extending upward through comparatively undisturbed strata and forming a dike, and that it does not reach the surface." This is Professor Pirsson's premise. Such a fissure could only arise from differential shortening of strata in an arc of the earth's crust. Pirsson conceives that the force of injection is partly expended in overcoming internal viscosity and gravity, and "whatever remains over above these two is used in lifting the sediments." No mention is made of lateral expenditure of energy

[1] The laccolithic mountain groups of Colorado, Utah, and Arizona, by Whitman Cross: Fourteenth Ann. Rept. U. S. Geol. Survey, Part II, 1893, p. 157.

[2] Op. cit., p. 236.

[3] Geology and mineral resources of the Judith Mountains of Montana, by W. H. Weed and L. V. Pirsson: Eighteenth Ann. Rept. U. S. Geol. Survey, Part III, 1898, p. 437 Geology of the Little Belt Mountains, Montana, by W. H. Weed, accompanied by a report on the petrography of the igneous rocks of the district, by L. V. Pirsson: Twentieth Ann. Rept. U. S. Geol. Survey, Part III, 1900, p. 387.

in folding and faulting strata, except that "resistance to splitting" is believed to influence resulting laccolithic structures.

It seems to the writer that the hydrostatic press analogy must not be pushed too far; it necessitates preexistent or gaping conduits through which lavas rise to spread out "at some horizon where the conditions are right,"[1] The lava is required to do all the work of lifting superincumbent strata by breaking and splitting its way forward. If the dynamic conditions of the Rocky Mountain region gave evidence of quietly gaping internal fissures with strata otherwise undisturbed, it is quite probable that, when the fissures were full of lava, under some obstacle to further upward flow, the lava would penetrate soft beds horizontally and lift the load, were the pressure of injection sufficient. But the orographic stress which raised thousands of square miles by great folds and faults all through the Rocky Mountains produced results on an enormously greater scale than what is observed in small laccolithic mountain groups. In many places intrusions accompanied or followed the greater movements; in many places faults and folds occur contiguous to laccoliths. The greater the horizontal extent of a warp of gentle curvature the less conspicuous it will be in a region where intrusives are very conspicuous; yet the fold will lift the load and generate fissures and weak places where the intrusive may expend its energy in localized splitting and arching of strata. The Henry Mountains and the Judith Mountains are laccolithic mountain groups where no connection is observable between regional deformation and laccolithic intrusion; yet great folds and faults are shown to exist in the immediate vicinity of the Henry Mountains.[2] In the Black Hills the relation between orogenic déformation and intrusion can be clearly traced only in the region of conduits (p. 188); in the other mountain groups no deep conduits have been described.

"PLUTONIC PLUGS" AND "SUBTUBERANT MOUNTAINS."

This discussion would be incomplete without some reference to Professor Russell's theory of "plutonic plugs" and "subtuberant mountains."[3] After a visit to the Sundance Hills and Mato Teepee, Russell concluded that these intrusions differed from laccoliths in being less spread out horizontally, and he called them "plugs." Bear Butte and Inyankara are still better examples of pluglike forms; they are steep-sided laccoliths of small size. The word "plug" seems to the writer an unnecessary one, and somewhat misleading, as it suggests the stopper for a circular hole. Owing to his failure to visit the dike district, as Mr. S. F. Emmons[4] has shown, Russell was unfamiliar with the lateral conduits characteristic of subordinate laccoliths, and his casual visit to Mato Teepee led to the unwarranted conclusion that the conduit lay beneath.

[1] Pirsson, Judith Mountains, p. 584.
[2] Gilbert, Geology of the Henry Mountains, p. 11.
[3] Jour. Geol., Vol. IV, 1896, pp. 23, 177.
[4] Science, N. S., Vol. X, No. 236, 1899, p. 24.

The comparison of small domes with great ones led to the suggestion that possibly such uplifts as the Black Hills, Bighorns, or Park Range were occasioned by the injection of igneous cores. For some reason stress is laid on the fact that the present cores of the uplifts are granite, though it is also stated that these granites are usually ancient ones from which the encircling sediments were derived. The name "subtuberant mountains" was suggested for such uplifts. There is, it is true, an attractive similarity between the drainage of the Black Hills and that of Circus Flats or the Bearlodge Range. Both are quaquaversals with radial streams. Beyond this there is no structural similarity. The Harney granite is pre-Cambrian. If an intrusive in the depths occasioned the great uplift in laccolithic fashion, there is no evidence for the existence of any horizontal splitting planes on which it might spread. The Rocky Mountain ranges are not smoothly elliptical, but irregular, elongate, and frequently bent; even the Black Hills mass has extensions northwest and southwest that show it is not a simple dome.

There are Tertiary granites and diorites in the Cordilleran district, and undoubtedly the intrusives as a whole added their share to movements of extension. It has been shown that in the northern Black Hills the schists were extended laterally by dikes that invaded them; the sediments above were displaced both horizontally and vertically by dikes, sills, and laccoliths that increased their bulk by a few cubic miles. Throughout western North America there have also been great uplifts of an Archean complex, accompanied by folding and faulting that affected later rocks. Much of this deformation was contemporaneous with intrusion. What are the criteria to suggest which was cause and which effect?

An answer to this question is suggested by extending Professor Russell's analogy to its logical conclusion. We are convinced that the doming of beds over the laccolith is due to the intrusion of igneous rock. The criteria that lead to this conviction are that many stages are found with igneous rock at the core, that the conduit is shown in definite relation to beds deformed and shape of laccolith, that the process may be imitated in miniature experimentally, that no such domes without an igneous core are found in the region, and that the igneous material is the larger feature more conspicuously in evidence than the deformation that it causes. There are large masses of porphyry, but its intrusive character is proved by small railroad cuts and canyon sections. Compare with this the arching of great mountain ranges. Large igneous cores intruded at the time of uplift are not usually found; the conduit is not shown in relation to beds deformed; experimentation in miniature produces such folds by horizontal pressure;[1] such uplifts are found in many regions without

[1] The mechanics of Appalachian structure, by Bailey Willis: Thirteenth Ann. Rept. U. S. Geol. Survey, Part II, 1892.

an igneous core; and deformation is the large feature, more conspicuous than the intrusives. Moreover, the latter are frequently found related to deformation as an effect. Volcanoes and intrusions occur along fault lines, or, as in the Black Hills, intrusives locally rise through fault fissures and distort folds, the same faults and folds occurring elsewhere as parts of a movement immeasurably greater than anything accomplished by the igneous rocks.

"BYSMALITHS."

Iddings[1] has described Mount Holmes, in the Gallatin Range, as a mass of dacite-porphyry 3 miles long and 2 miles wide, which was believed to have forced upward "a more or less circular cone or cylinder of strata, having the form of a plug, which might be driven out at the surface of the earth or might terminate in a dome of strata resembling the dome over a laccolith." The name "bysmalith" was invented for application to such fault laccoliths. The only fault described is a great one, affecting Archean and Paleozoic strata and extending far to the northward from the west side of the igneous body, and as this was stated to have probably acted as conduit, it was not immediately occasioned by the intrusion. Sections are presented[2] representing a stock-like mass in nearly horizontal strata, and over one of these was drawn a reconstruction of 10,000 feet of domed strata with a cone section faulted, which passes into a fold above. The arch immediately above the igneous rock of Mount Holmes is represented with a dip length of 1¼ miles, while 9,000 feet higher the arch has greater curvature and a dip length of nearly 3 miles. In the descriptive portion of the text, which is brief, it is stated in one place that "nearly two-thirds of the circumference of the Holmes mass is exposed as a nearly vertical plane of contact crossing almost horizontal strata." Another statement is that "in all cases examined the neighboring limestones dip away at angles of 40° to 55°." These statements seem contradictory. In the diagram section the dips shown are from 2° to 10°. The sections and the text indicate that the mass described resembles the steep-sided laccoliths of the Black Hills, and that it breaks across strata, in the manner of a stock.

UNSYMMETRICAL LACCOLITHS.

There seems to the writer to be no need in a classification of igneous bodies for hypothetical forms. Faults occurring in a closed curve, while not impossible, are dynamically improbable. The first fault formed over an unsymmetrical laccolith is at one side and usually prolongs itself. Others may form from displacement on radial or peripheral fractures in the region of maximum flexure. As soon as such fractures open, however, they fill with magma that releases the strain and forms new subordinate bodies. Such bodies have been

[1] Mon. U. S. Geol. Survey, Vol. XXXII, Part II, 1899, p. 16.
[2] Op. cit., Pl. V.

described in detail in this paper in the sections treating of Whitewood Canyon laccolith, Pillar Peak, Deadman and Tilford laccoliths, Bear Butte, and Ragged Top Mountain. Mount Marcellina, described by Cross, Black Butte (Judith Mountains) and Barker Mountain (Little Belt Mountains), described by Weed and Pirsson, and Mount Hillers, described by Gilbert, all show similar sections. Structures of this kind have now been recorded in sufficient number to show that the unsymmetrical laccolith with lateral conduit is a common type. Thunder Mountain, in the Little Belt Mountains, described by Weed and Lindgren,[1] shows sections closely similar to Crow Peak (fig. 93). Weed calls it an irregular laccolith or "bysmalith," but states that the cross section is strikingly like that of Mount Hillers, which is a typical unsymmetrical laccolith.

SUMMARY OF THEORETICAL CONCLUSIONS.

The following are the theoretical conclusions of this paper in brief: Laccoliths, as shown by Gilbert, are subterranean volcanic phenomena which do not reach the surface, and in the Black Hills they resemble volcanoes in being accompanied by breccias. As they solidify beneath the surface, they cool and become more viscous upward. The lower laccoliths are large because of obstruction by massive strata; the upper ones are small and steep-sided because the magma is more viscous, is probably under diminished pressure, is diminished in volume, and is intruded in soft, thick shales. The upper laccoliths are usually subordinate unsymmetrical offshoots of the lower. The lower main laccoliths frequently show some bilateral or concentric symmetry to the conduit. The conduits are usually dikes. The load may be lifted by orogenic forces, while the intrusion is a subordinate feature permitted by fracture. Laccolith arching is transmitted radially upward only by competent hard strata, and is absorbed laterally by shales. The bottom of the laccolith is not usually a single stratum, but an oblique plane which truncates strata. The conduits of subordinate laccoliths are fractures, gaping downward in hard strata on the flanks of main laccoliths. The texture of strata is important in determining intrusion horizons; shale beds are favorable horizons for intrusion; alternations of shales and hard strata, thin bedded, favor the production of sills. The inclination of a conduit strongly affects the direction of spreading of a sill or laccolith. By lateral deformation the laccolith doming may be completely absorbed upward in thick shales, so that higher beds lie horizontal. Trunk drainage superposed on the dome is deflected by hard beds; branch drainage becomes continually readjusted by monoclinal shifting and capture. Annular valleys are characteristic, and may be inherited from sediments above, by superposition on igneous rock beneath.

[1] Tenth Census, Vol. XV, 1886, pp. 696–737.

CHAPTER V.

EXPERIMENTS ILLUSTRATING INTRUSION AND EROSION.

By Ernest Howe.

INTRODUCTION.

Gilbert has shown that in the Henry Mountains a liquid or viscous magma rising from the interior of the earth, instead of reaching the surface and there building volcanic mountains by successive eruptions, has "stopped at a lower horizon, insinuated itself between the strata, and opened for itself a chamber by lifting all the superior beds. In this chamber it congealed, forming a massive body of trap."[1] As a result of the intrusion the superjacent strata were domed upward, fractured, and otherwise deformed. To intrusive bodies of this type Gilbert gave the name "laccolites" (laccoliths).

The following experiments were undertaken with a view to imitating as far as possible the processes involved in the formation of laccoliths and the resulting deformation of the invaded beds. In general, the method employed was to supply certain theoretical conditions and to attempt to construct the laccolith under these conditions.

ACTIVE AND PASSIVE AGENTS.

The agents which govern the development of a laccolith are of two kinds and may be termed, for convenience, active agents and passive agents. The active agents are the viscous or liquid magma and the force which causes this magma to rise from the heated interior of the earth and intrude itself between certain layers of the sedimentary rocks of the earth's crust. These sedimentary rocks and the physical properties peculiar to them are the passive agents. In taking up these experiments the problems were to supply, first, a series of stratified deposits which would correspond to those found in nature, and, second, some liquid or viscous substance which might be injected into the sediments and which would subsequently solidify. The first presented no serious difficulties. It was found that an excellent sedimentary column could be made by sifting plaster of paris, coal dust, marble dust, and sand into a shallow tank containing water. The plaster solidified after settling and its relative rigidity might be

[1] Geology of the Henry Mountains, by G. K. Gilbert: U. S. Geog. and Geol. Survey Rocky Mountain Region, 1877.

considered as corresponding to that of massive limestone in nature. The coal dust served as a substitute for shale, and the marble dust and sand took the place of sandstones. A number of materials suggested themselves as suitable for the intrusive magma, but the means of injecting them presented mechanical difficulties.

PRELIMINARY EXPERIMENTS.

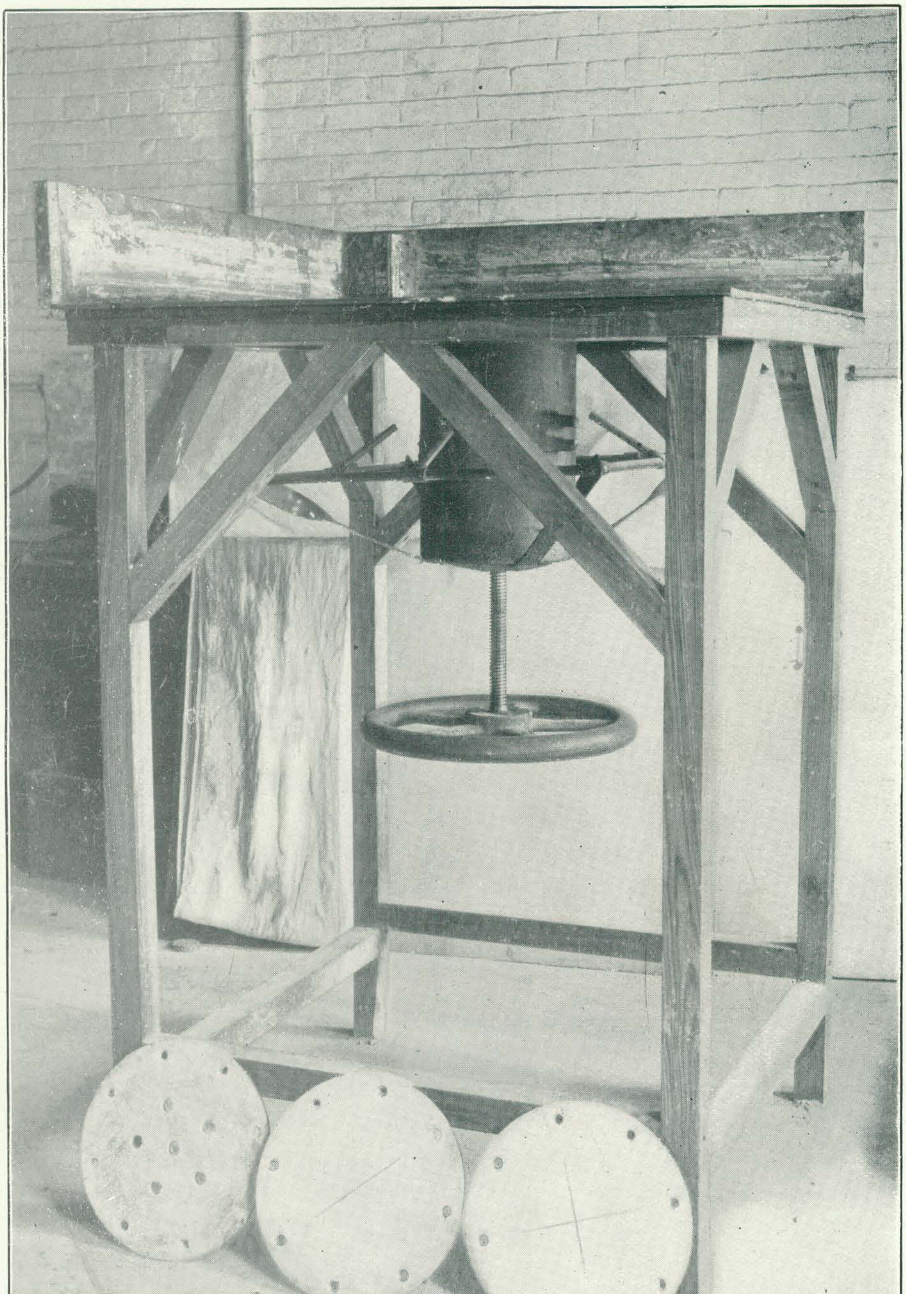
Before undertaking any very extensive experiments it seemed best to perform a few with the rather crude apparatus at hand. A small circular pan of tin, 2 feet in diameter and 3 inches deep, was employed to hold the sediments. It had a hole in the center in which a cork might be fitted and a smaller hole at the side to permit the water to be drawn off. The pan was half filled with water, the openings below being closed, and the following series of sediments were deposited in order from the bottom upward, in layers of somewhat variable thickness, to a depth of about 1½ inches:

13. Sand.
12. Marble dust and plaster.
11. Sand.
10. Coal dust.
9. Plaster.
8. Marble dust.
7. Sand.
6. Plaster.
5. Coal dust.
4. Marble dust.
3. Marble dust and plaster.
2. Coal dust.
1. Plaster.

After settling, the excess of water was drawn off and the whole was allowed to dry for twenty-four hours. This method was followed in all subsequent experiments and was found to be quite satisfactory. Next a perforated cork was substituted for the one already in the central aperture, and a glass tube was inserted in it, which in turn was connected by a rubber tube with a rubber bag containing a mixture of plaster and water and supported by boards between the jaws of a vise. The mouth of the bag was closed and the vise was slowly tightened until most of the plaster had been forced through the tubing into the sediments. The results of this experiment will be described in detail later (Exp. I, figs. 101 and 102). It is for the moment only necessary to state that the experiment was quite satisfactory as far as it went; but this and several others performed on the same apparatus, although more or less successful, showed that the scale was too small, that the method of injection was inadequate, and that the material used for injection was not to be relied upon, as there was no means of regulating its liquidity or viscosity and preventing its very rapid solidification.

CONSTRUCTION OF APPARATUS.

After some study of the good and bad points of the preliminary apparatus, the instrument figured in Pl. XLII, and in cross section in fig. 100 was constructed. The principal working parts of the apparatus are the sheet of boiler plate *a* (fig. 100), the cylinder *c*, the piston head *p*, the screw *s*, and the conduit plate *d*. The boiler plate,



MACHINE FOR INTRUSION EXPERIMENTS.

one-quarter inch thick and 3 feet square, is supported by the frame *f*. At its center was cut a hole of the same diameter as the inside of the cylinder, $8\frac{1}{4}$ inches. The cylinder, of cast iron, is bolted to the under surface of the boiler plate directly beneath the hole. Working

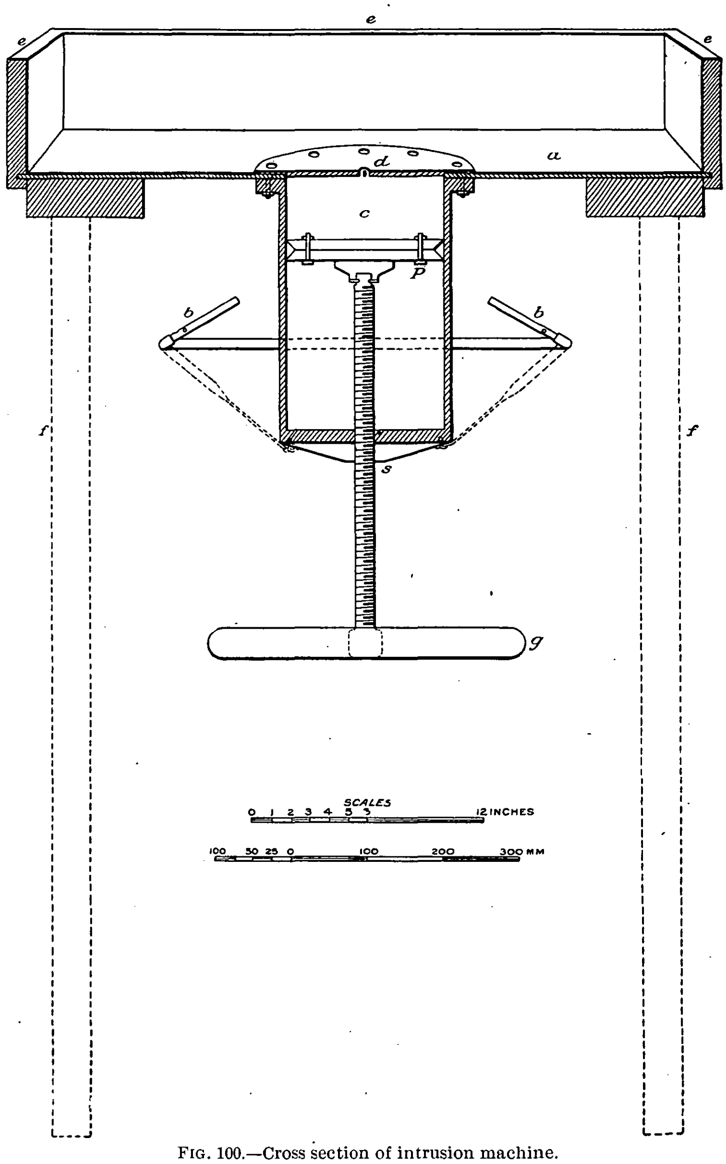


FIG. 100.—Cross section of intrusion machine.

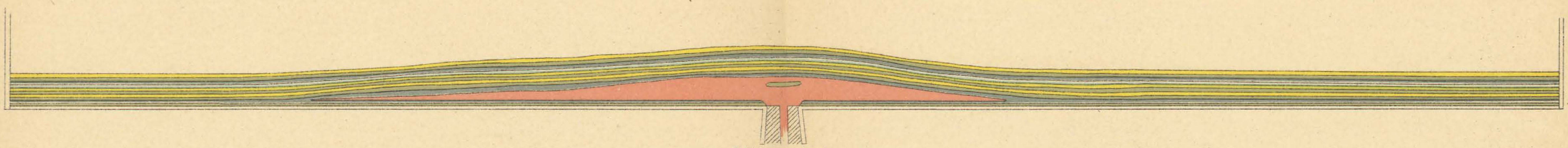
in the cylinder is the piston head, composed of two beveled disks of cast iron, bolted together, the open space caused by the beveling being packed with hemp. This piston is forced up and down by means of a screw *s*, operated by the wheel *g*. The pitch of this screw is one-fifth inch. The conduit plate *d* is one of the three shown at the base of the apparatus in Pl. XLII. The first has a long, narrow slot cut through the center; the second has two of these slots intersecting at the center at right angles to each other, while the third has a series of 6 holes in which plugs may be screwed. Some of these plugs serve to close the apertures, while others are pierced or have small tubes of brass running through them and extending above the surface of the plate. By means of these plates conduits resembling fissures or of the hypothetical tubular form may be used. The method of operating the apparatus is as follows:

The piston is first brought down to its lowest point and the cylinder is filled with wax, which is melted by means of the Bunsen burners *b b*. The level of the wax is then brought to the top of the cylinder by advancing the piston a short distance, and one of the conduit plates is bolted to the boiler plate over the mouth of the cylinder. Next the grooved boards *e e* are fitted over the extending edges of the boiler-plate and their ends are screwed together. All joints or openings are painted with melted wax or paraffin to make them water-tight. The tank is then ready for receiving the sediments, which are deposited in the manner already described. This having been accomplished the excess of water is drawn off through a tap near the bottom of one of the boards. After the sediments have dried sufficiently the Bunsen burners are lighted and allowed to play on the cylinder for a few minutes longer than the time required to melt the wax, determined at the first melting. The gas is then turned off and injection is started by slowly turning the screw. As has been already said, the pitch of the screw is one-fifth inch and the inside diameter of the cylinder is 8¼ inches. Thus one complete turn of the screw would advance the piston one-fifth inch and a little over 10 cubic inches of material would be forced out of the cylinder, or for an advance of 1 inch of the piston 53 cubic inches of wax would be injected into the sediments. After the injection has been accomplished the sides of the tank may be removed and the model sectioned and photographed.

Of the following five experiments described the first two were performed by means of the preliminary apparatus and the last three with the special instrument.

EXPERIMENT I. IRREGULAR INTRUSIONS.

Process.—The sedimentary section has already been given for this experiment (p. 292). It was found later, on cutting the model after intrusion, that the individual layers were not so uniform in thickness as they should be, and especial attention was paid to this in all later experiments, more time being given for each layer to settle before the next was added, and greater care being taken to insure an even distribution of material.



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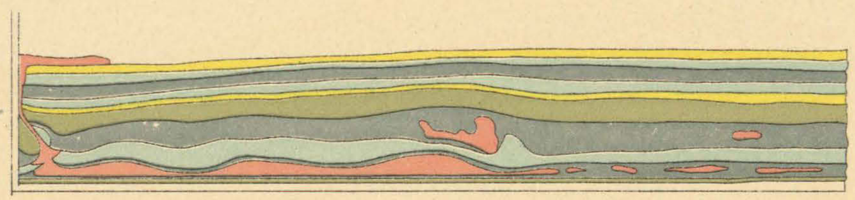

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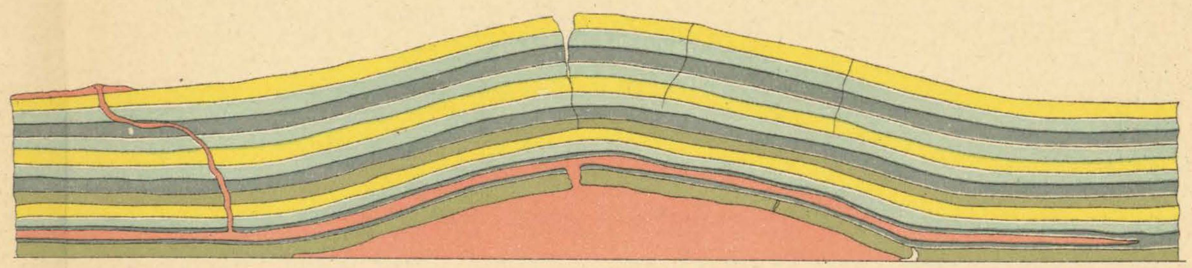

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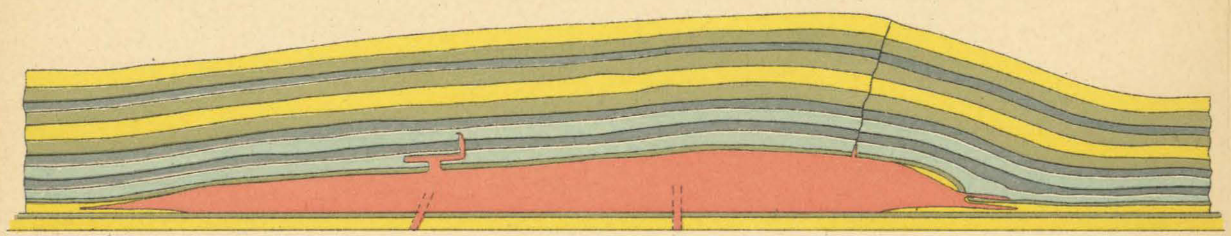

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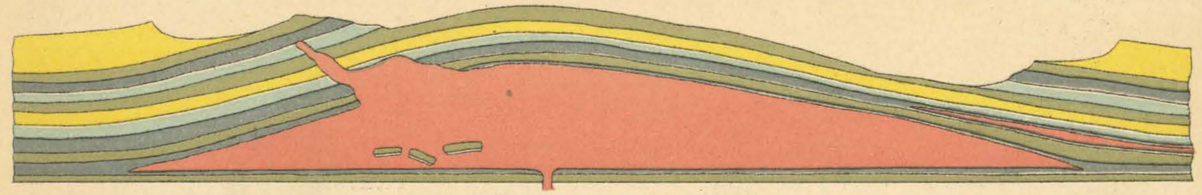

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CROSS SECTIONS OF EXPERIMENTAL MODELS

ILLUSTRATING

INTRUSION AND EROSION

BY ERNEST HOWE

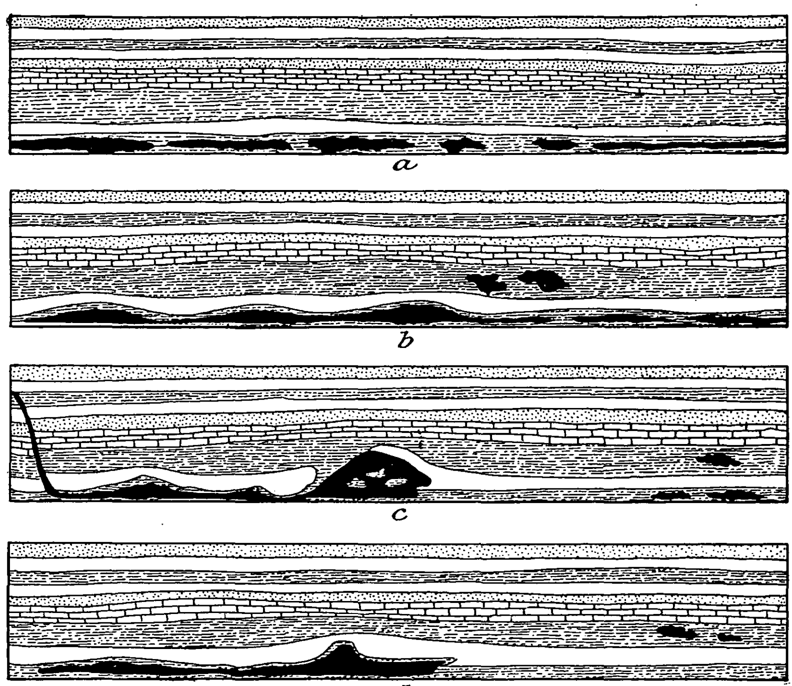
1900

EXPLANATION

Plaster | Marble | Sand | Coal | Intrusive

JULIUS BIEN & CO. LITH. N.Y.

The plaster and water which was to be injected had about the consistency of thick cream, and was colored red to distinguish it from the plaster layers in the model. The time required for the intrusion was of necessity rather short, as the mixture of plaster and water solidified very rapidly. An even pressure was maintained by means of the vise for two minutes, at the end of which time most of the plaster had been forced into the model. Slight oscillation occurred on the surface during intrusion, but there was no fracturing and no marked doming. Just before injection was stopped the intrusive material broke through the sediments near the edge of the pan and flowed out on the surface.



a, *b*, *c*, *d*

FIG. 101. Sections. Experiment I.

Cross sections.—As soon as the plaster had hardened the model was cut in sectors, the first to be removed being directly opposite the point where the plaster had flowed out. In this region it was found that the intrusive had spread as a thin sheet in the first coal-dust layer and extended continuously from the center about halfway to the edge of the pan. From this point sections were made at intervals of one-half inch at the perimeter (of which fig. 101, *a*, *b*, *c*, and *d*, and sec. 2 of Pl. XLIII are examples), and very soon marked variations were encountered. The intrusion was approaching nearer to the edge, and seemed to have entered the coal as fingers from the main sheet, small isolated patches being encountered as shown on the right-hand side of sec. 2 of Pl. XLIII and in *a*, *b*, and *c* of fig. 101. As the region of eruption was approached still greater irregularities occurred; several fingers of the intrusive were found in the second coal horizon, and considerable deformation of the adjacent beds was noted (*b*, *c*, and *d*, of fig. 101). Sec. 2 of Pl. XLIII is drawn from the edge of the pan at the point of extrusion, halfway to the center. It is more or less generalized, but will serve to bring out the several points characteristic of this experiment. It will be noted that above the horizon of massive plaster in the middle of the column practically no deformation has taken place, most of the irregularities being due to bedding, while the beds below have been much disturbed. Just below and to the right of the intrusion in the second coal horizon the marble-dust layer has been folded, and a little farther on (*c*, fig. 101) this fold develops into a fracture through which the intrusive has risen and forced its way as a finger into the stratum of coal dust. Near the edge another fracture occurred and through this the intrusive flowed to the surface. In the lower horizon of intrusion considerable variations in the thickness may be observed, and also a tendency to form local lenticular swellings.

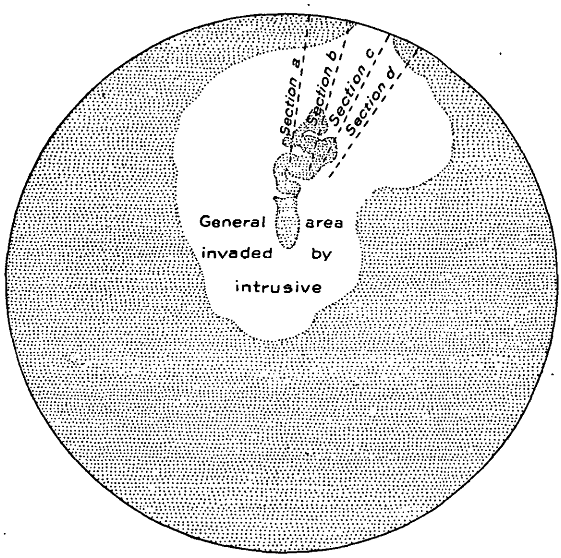
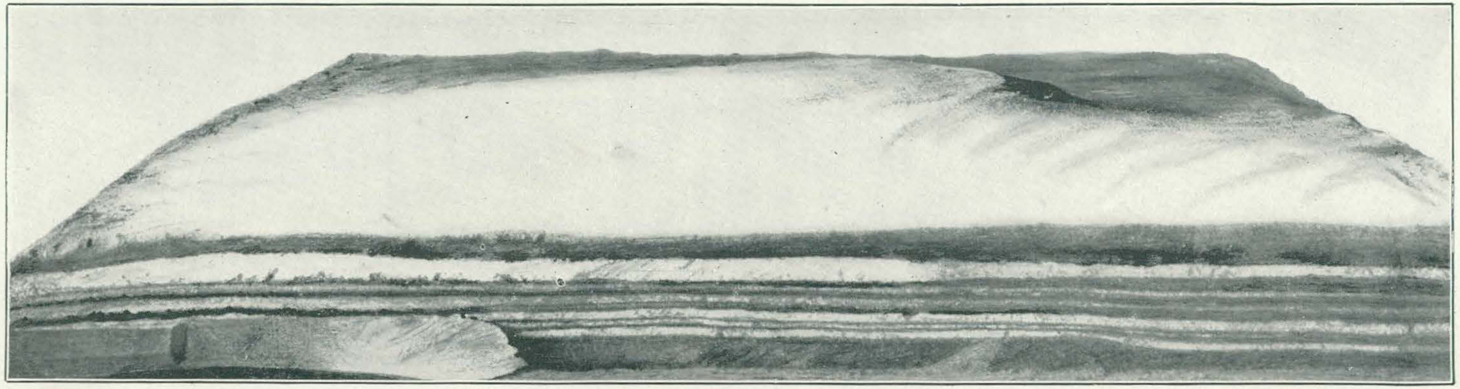


FIG. 102.—Ground plan of laccolith, Experiment I.

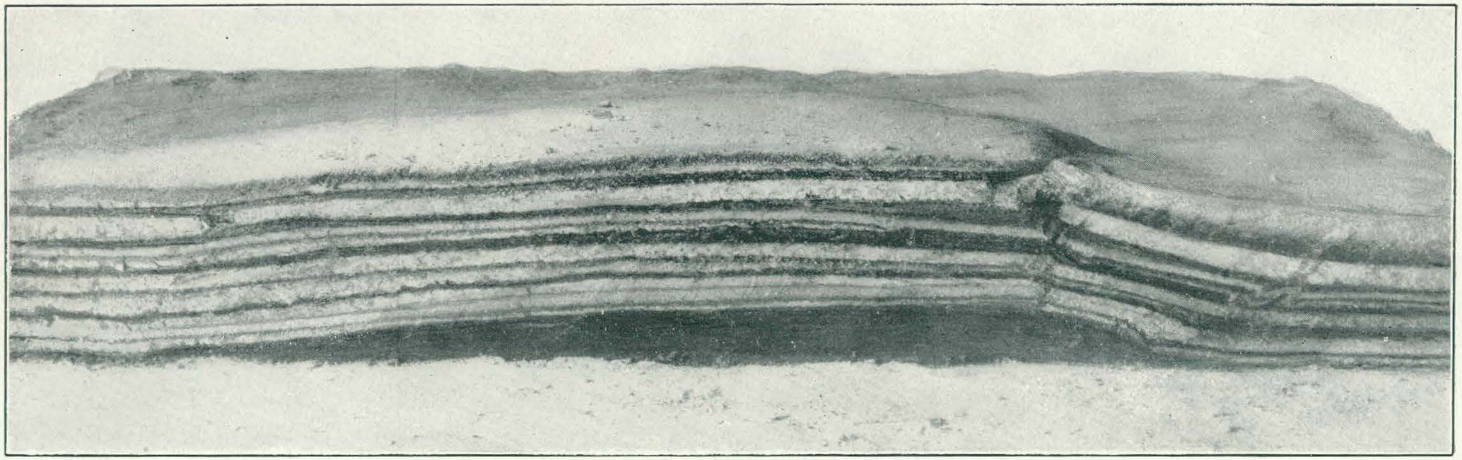
Ground plan.—The plan of the intrusion was roughly elliptical with the conduit at one of the foci (fig. 102). About the other focus was a region of coal dust into which the plaster had not intruded, apparently having flowed about it.

EXPERIMENT II. SYMMETRICAL LACCOLITH.

Process.—The results of the second experiment were in marked contrast to those of the one just described. The greater regularity in the form of the intrusion was in a large measure due to the nature of the sediments, there being more and thinner plaster layers than in the first series, and also thinner coal layers, the strata being therefore uniformly thin bedded and flexible. The result was that the pressure brought to bear on the overlying beds by the intruding magma was



A. UNSYMMETRICAL LACCOLITH, SURFACE OF MODEL, AFTER INTRUSION WITHOUT LOAD.



B. CROSS SECTION OF UNSYMMETRICAL LACCOLITH.

uniformly distributed and transmitted with little or no loss by lateral deformation to the very top of the column. In the first experiment the overlying coal layers were so thick and so loosely compacted that the upward pressure expended itself solely in compressing the strata, or in pushing aside and rearranging the individual grains of coal. The conditions of intrusion were the same in both experiments, but in Experiment II injection was accompanied by a gentle doming about the center, with resulting radial fractures.

Section.—A section of this model is shown in Pl. XLIII. The symmetry of the laccolith and the relation of the overlying beds to it are well shown, and were almost as diagrammatic in the original as they are in the figured section. One interesting point was the horse of plaster which was carried up from the basement layer of plaster and floated in the magma (compare Dome Mountain, Pl. XXI, section D–E; also Carriso Mountains, fig. 81, p. 210). The following is the order in which the sediments were deposited, the total thickness being about half an inch:

10. Sand.	6. Sand.	3. Plaster.
9. Plaster.	5. Plaster.	2. Coal.
8. Coal.	4. Sand.	1. Plaster.
7. Marble.		

The remaining experiments were all performed by means of the special apparatus.

EXPERIMENT III. EXTRUSION, SILL, AND LACCOLITH.

Process.—The conduit plate with the single slot was in place and the bottom of the tank was covered with plaster to make a smooth surface flush with the plate, and the tank was partly filled with water. The following series of sediments were then deposited to the depth of about 2.5 inches:

12. Sand.	8. Sand.	4. Sand.
11. Marble.	7. Marble.	3. Marble.
10. Coal.	6. Coal.	2. Coal.
9. Marble.	5. Plaster.	1. Plaster.

Previous to the deposition of the sediments the cylinder had been filled with a mixture of beeswax, paraffin, and ozokerite. It was found that thirty minutes were required to melt this mixture.

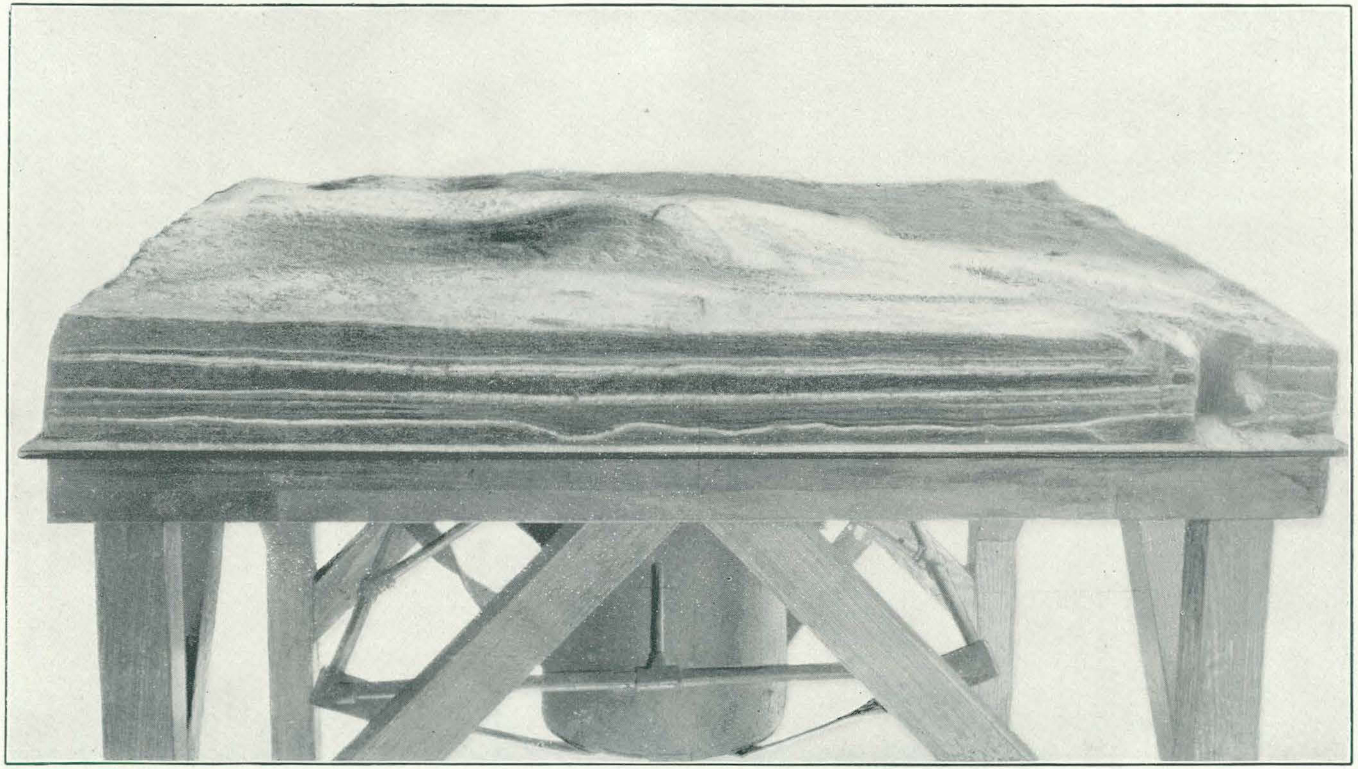
After the sediments had been allowed to dry for forty-eight hours the wax was melted and injection started. The piston was advanced 4 inches in fifteen minutes, at the end of which the whole model was gently domed. Several radial fractures had developed about the center, and part of an encircling fracture was also formed. The piston being advanced farther two-fifths inch, wax began to flow from the intersection of one of the radial fractures with the encircling fracture. The eruption continued for about five minutes, a small wax cone being formed, and the excess of wax flowing off in four or five well-defined streams. A further slight advance of the piston started the wax again, and after it had stopped flowing for the second time the whole mass was allowed to cool and solidify for twenty minutes. At the end of this period the piston was advanced 1½ inches in twenty minutes. By this time the wax had become extremely viscous, and the result was a small steep dome directly over the conduit, accompanied by circular fracturing.

Sections.—When the wax had thoroughly cooled, sections of the model were made, the most typical one being through the top of the dome and cutting the conduit through which the wax had risen to the surface and had overflowed. This section (sec. 3, Pl. XLIII) showed that the wax first intruded had entered the lowest layer of coal dust, had spread out as a sheet or sill, and had broken up through certain fissures, saturating the absorbent layers of coal and sand locally; on reaching the surface it flowed out, forming a miniature volcano. The second intrusion did not rise above the first sill, but lifted it and the first plaster layer, fracturing the beds above, but not causing any break in the sill. The effect of wax coming through the fissure-like conduit was to give the base of the laccolith a somewhat elliptical outline, the longest diameter being in line with the conduit. This experiment brought out in an interesting manner the tendency of a magma when extremely liquid and rapidly injected to form sheets or sills, and when more viscous to form laccolithic bodies. Two distinct types of fracturing in the overlying sediments were noted, the one of fractures concentric about the center of the dome, the other of fractures radiating from the center of the dome. Fracturing according to the first type will begin in the beds immediately above the intrusive at the point where its surface is concave and where the sediments are being folded into an encircling monocline. Fracturing according to the second type will begin at the apex of the domed sediments.

EXPERIMENT IV. UNSYMMETRICAL LACCOLITH.

Process.—In Experiment IV the conduit plate having six holes was used with two conduits extending above the level of the plate. One was vertical, while the other was inclined at an angle of 60 degrees with the horizon in the direction of the first—i. e., its walls dipping away from the first. The bottom was covered with sand until its surface was flush with the top of the conduit plate, then water was introduced and the sediments were deposited in the following order:

20. Sand.	13. Marble.	6. Plaster.
19. Plaster.	12. Sand.	5. Marble.
18. Sand.	11. Plaster.	4. Sand.
17. Coal.	10. Sand.	3. Plaster.
16. Plaster.	9. Coal.	2. Sand.
15. Marble.	8. Plaster.	1. Plaster.
14. Sand.	7. Coal.	



DOMED SURFACE OF MODEL; INTRUSION UNDER LOAD.

Superficial doming.—The injection in this experiment was very slow, one complete turn of the wheel being made in three minutes. There was no apparent doming at the surface until after the piston had been advanced 4 inches, but from this point on a very well-defined unsymmetrical dome began to form. As will be seen in *A* and *B* of Pl. XLIV, there is a gentle upward slope from the left, which continues well past the center of the model, while to the right the rise to the summit is very abrupt. The high angle of this slope was accentuated by the fracture indicated in sec. 4 of Pl. XLIII. The strata to the left of this fracture were lifted by the force of intrusion and made a well-defined fault scarp, which was very striking during the process of injection, but which soon became obscured by the sifting in of dry sand at the surface. This main fracture was the only one noted during the intrusion, but several other minor ones were discovered on cutting the model.

Sections.—Pl. XLIV, *B*, and sec. 4 of Pl. XLIII, illustrate fairly well most of the interesting points of this experiment. In all the other experiments the wax spread out in a layer of coal dust, corresponding to shales in nature, but in this case the main intrusion was in the horizon of sand over the first plaster layer. Just above the inclined conduit in the colored section a peculiar mushroom-shaped body of wax is seen, and another, not shown in the diagram, was found over the second conduit. Evidently the upper edges of the conduit tubes were somewhere in the middle of the first marble-dust horizon when injection was started, and the wax, finding the intrusion difficult in the closely-packed marble dust, flowed downward and spread out in the underlying sand layer, and subsequently lifted all the overlying beds. These projecting conduit tubes are necessarily artificial in their relations to the sediments and are unlike anything in nature. A number of small dikes occurred, filling local fractures, but the main intrusion was purely laccolithic. One characteristic which this experiment shares in common with the first is the mashing of the marble dust at the extreme right of the laccolith. The plaster immediately below has been fractured and the right-hand portion has been faulted upward half an inch above its original position, but the plaster layer next above has not been involved in this movement. The intervening layers of coal and marble dust, because of the lack of cohesion of their individual particles, have been pushed aside and have not transmitted the force coming from below to the overlying beds. The point to be particularly noted in this experiment is the asymmetry of the dome and its relation to the inclined conduit. A magma rising through an inclined conduit tends to form an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical. Such an inclined conduit corresponds with the case of inclined dikes following Algonkian lamination upward to the Cambrian unconformity (see Chap. II, pp. 203–204).

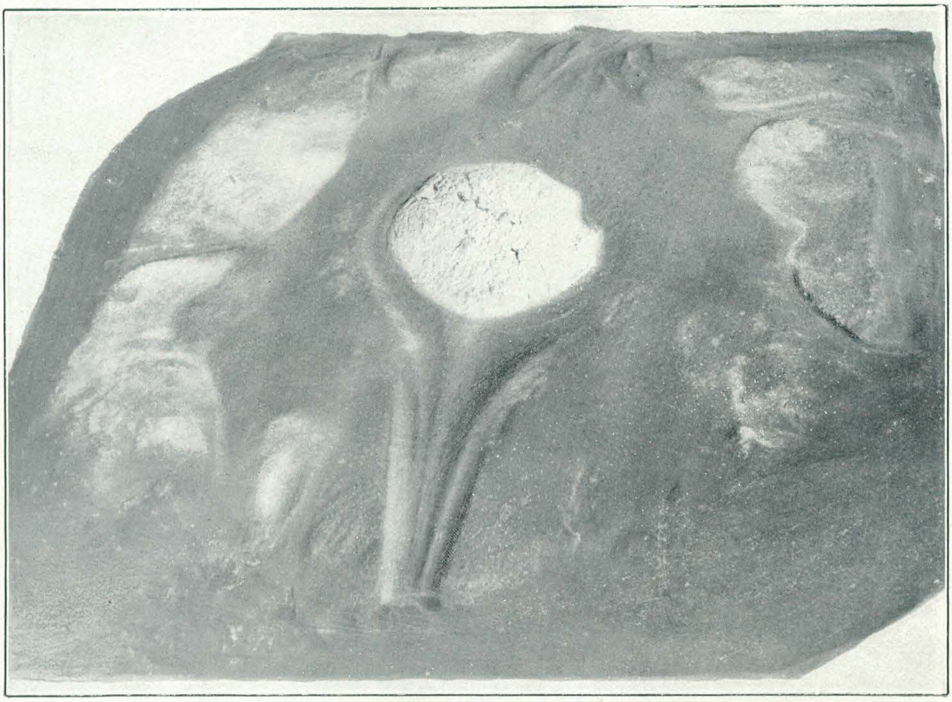
EXPERIMENT V. EFFECT OF LOAD AND OF EROSION.

Intrusion.—As it was intended to try the effects of artificial erosion on the laccolith formed in this experiment, special arrangements were made to facilitate the transfer of the model from the injection apparatus to the erosion tank. The conduit plate having six holes was used, all the holes but the central one being closed. This was left as a simple circular opening without any projecting tube. When this plate had been bolted in place sand was added, as usual, until it was level with the top of the plate. A sheet of zinc 35 inches square, having a hole in the center to correspond with that in the boiler plate, was then laid in place. The purpose of this sheet of zinc was to supply some sort of support for the model while it was being slid from the injection apparatus to the board on which it was carried to the erosion tank. The zinc having been placed in position, water was added, and the sediments were deposited as follows:

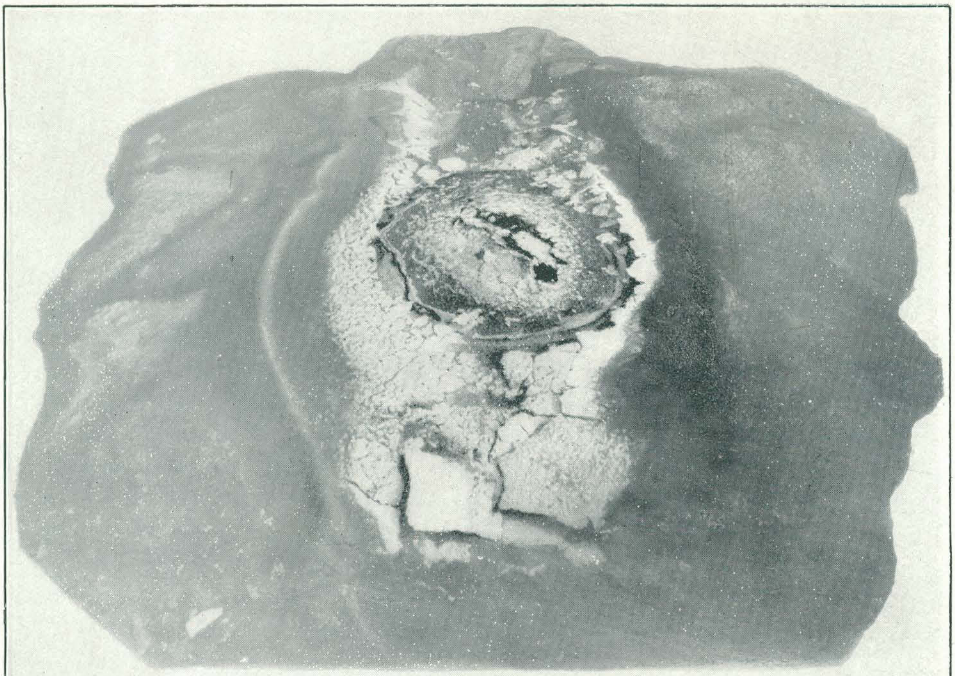
23. Sand.	15. Sand.	7. Coal.
22. Marble.	14. Plaster.	6. Plaster.
21. Plaster.	13. Marble.	5. Marble.
20. Marble.	12. Coal.	4. Coal.
19. Sand.	11. Marble.	3. Marble.
18. Marble.	10. Sand.	2. Sand.
17. Coal.	9. Plaster.	1. Plaster
16. Marble.	8. Marble.	

After the sediments had dried somewhat, a cloth was placed over them and 300 pounds of shot, to simulate load of superincumbent sediments, were evenly distributed over the surface. The wax was then melted and allowed to cool for forty-five minutes before injection was started. This was to insure viscosity. The piston was then advanced 5 inches, the speed averaging 1 inch in fifteen minutes. At the end of the injection the wax had become very hard and it was impossible to force any more into the model. When the shot was removed it was found that a very symmetrical dome had been formed (Pl. XLV), with one distinct fracture crossing the dome at its summit.

Erosion.—The model was then transferred to the erosion tank, great care being taken not to cause any further fracturing of the sediments. A few fractures indeed developed at the sides and corners, but they were not of sufficient importance to affect in any way the process of erosion. The erosion tank, 6 feet square and 1 foot deep, had a special flood gate by means of which the water level might be kept constant or changed at will. The water which was to accomplish the erosion was supplied in the form of a fine mist. By means of a small perforated nozzle, several jets of water were thrown with some force against a fine-meshed sieve, with the result that a large part of the water passed through and became atomized. As a certain amount of drip from the sides of the sieve accompanied the process, it was found



A. EROSION OF EXPERIMENTAL LACCOLITH (FIRST STAGE).



B. EROSION OF EXPERIMENTAL LACCOLITH (SECOND STAGE).

necessary to place the spraying apparatus at one side of the model instead of directly over its center. The shower was arranged so that the bulk of the water fell at the center of the model, but some particles of water were carried beyond, while others fell short, the result being that there was a zone of maximum rainfall extending from one side of the model to the other and passing over the dome. This necessarily influenced the drainage. As shown in Pl. XLVI, *A* and *B* representing an earlier and a later stage of degradation, two main streams developed in the line of maximum rainfall, flowing in opposite directions from the dome, and in a very short time after erosion commenced they had captured all the drainage, which, as shown in Pl. XLVI, *A*, was initially radial. Several small streams consequent upon the initial slope flowed from the dome and united near its base to form the four encircling master streams. Two of these master streams on each side united and formed the two trunk streams which drained the whole region. The action of frost and the disintegration of rock due to the chemical action of surface water could not be imitated, but similar results were brought about by the impact of the fine particles of water on the various layers of sand and plaster and coal. The force of the descending mist was indeed sufficient to cause a breach at the summit of the first plaster layer exposed, long before the streams had cut into the plaster on the flanks. Notwithstanding these unnatural conditions, revet hills were formed which were not unlike those found in nature. By the time that the first layer of plaster had been removed a dike was exposed at the left of the summit (Pl. XLVII, *A*), which had risen through the main fracture shown in Pl. XLVI, *A*. This dike of wax was not acted upon by the water and served to protect the left-hand side of the dome, deflecting a large part of the drainage to the right. The result is shown in Pl. XLVII, *A* and *B*.

Sections.—Sec. 5 of Pl. XLIII shows the form of the intrusive in this experiment, which was in many ways the most interesting. The laccolith proper was intruded into a layer of coal dust, as was the sheet which rests above the main intrusion to the right. In the body of the laccolith are three horses of plaster which belong to the horizon resting above the intrusive. It seems likely that in the early stages of intrusion fracturing occurred in the immediate neighborhood of the fragments of plaster, and that the wax rose above these and entered the main fissure, forming the dike, first following an encircling fracture and later a radial one.

SUMMARY OF EXPERIMENTS.

I. Variations dependent on the passive agents.

1. If the strata immediately above the intrusive are lacking in rigidity and are of considerable thickness, they will not transmit to the overlying beds the deforming force of the intrusion, but will themselves be locally deformed and will cause this force to expend itself laterally.

2. The converse is also true. If the overlying sediments are comparatively rigid they will tend to transmit the deforming force of the intrusion uniformly in lines normal to the surface of the intrusive.

3. The least coherent strata are the ones in which intrusion is most likely to occur.

4. Thick beds of incoherent material favor the production of intrusive bodies of irregular form.

5. For the same viscosity of magma (Experiments IV and V, Pls. XLIV, *A*, and XLV) it is probable that the domical curvature of a laccolith, other things being equal, varies with the load, and hence with the thickness of superincumbent strata. That is, a greater load produces a higher dome of smaller ground plan for the same volume of intrusive material (see paragraph below, numbered 3.)

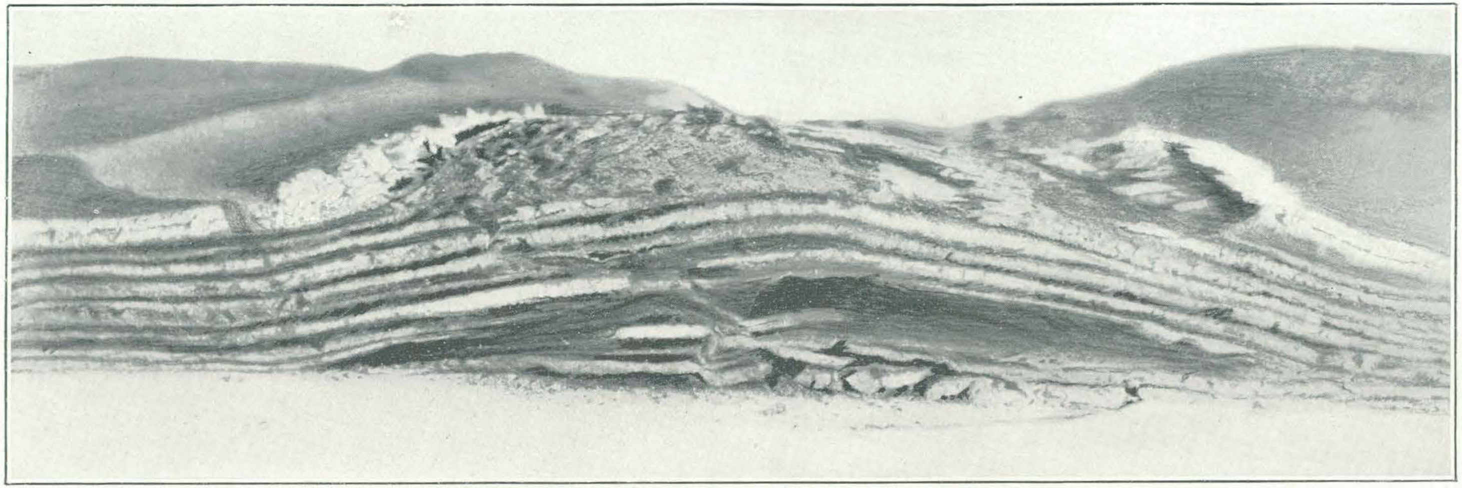
6. Any stratigraphic obstacle to horizontal spreading (Experiment I, fig. 2 of Pl. XLIII) may cause a sill to thicken locally into domes, the loci of these domes being determined by points of weakness in the overlying beds. The thinner and more flexible portions of the superjacent competent stratum under coal dust are the points of greatest doming in model 1 (sec. 2 of Pl. XLIII).

7. A magma rising through an inclined conduit tends to form an unsymmetrical laccolith whose thickness is greatest in the direction in which the conduit is inclined from the vertical (sec. 4 of Pl. XLIII).

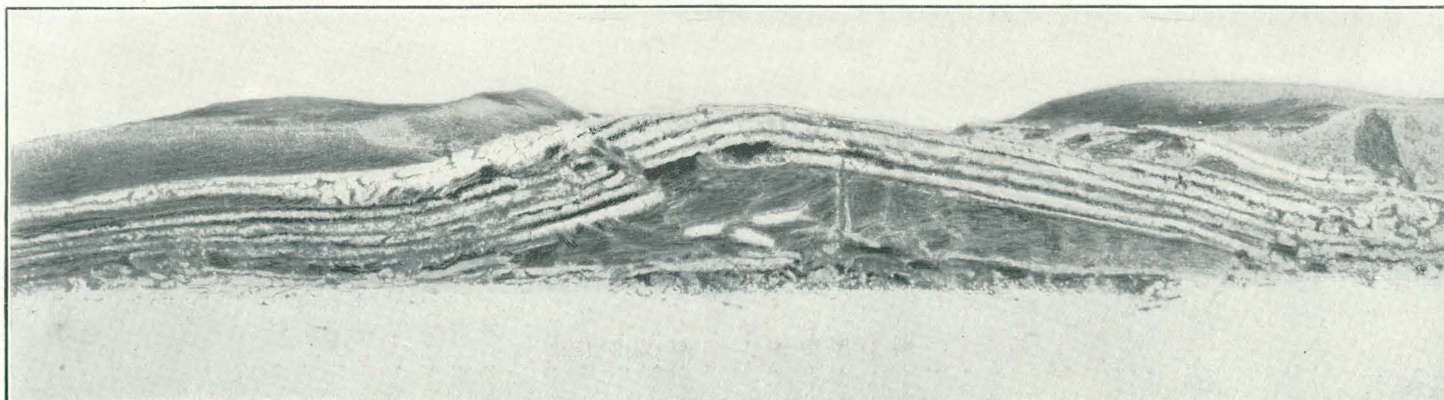
8. Fractures initially radial and secondly concentric tend to form in frangible strata over a symmetrical dome, the radial fractures gaping upward and the concentric ones downward. Hence the latter are the first to give passage to the intrusive, which, through them, forms peripheral sills, or, in connection with the radial fractures, dikes. Over an unsymmetrical dome, overthrusting and escape of magma to higher horizons will take place in the direction of greatest thickness of the dome (Pl. XLIV, *B*, and sec. 4 of Pl. XLIII).

II. Variations dependent on the active agents.

1. If the magma is in a condition of considerable fluidity it will tend to spread as a thin sheet in some stratum of least resistance (sec. 3 of Pl. XLIII), and, conversely,



A. CROSS SECTION OF ERODED DOME.



B. SECOND SECTION OF DOME SHOWN IN *A.*

2. If the magma is viscous it will tend to form a true laccolith, with its horizontal extension restricted and its thickness increasing toward the center.

3. For the same load (Experiment III) it is probable that the domical curvature of a laccolith, other things being equal, varies with the viscosity (see paragraph numbered 5, above). That is, a more viscous magma produces a higher dome of smaller ground plan for the same volume of intrusive material (sec. 3 of Pl. XLIII).

4. A viscous magma injected rapidly probably tends to form a dome of smaller radius, other things being equal, than when injected slowly (Experiments III and IV).

In the experiments described the injected wax was permitted to break its way into the sediments. The analogies to be drawn from these experimental illustrations should therefore be confined to cases of deformation directly due to the intrusive (see Chapter I, pages 187–188). No attempt was made in the experiments to imitate concomitant regional deformation.

THE IRON-ORE DEPOSITS OF THE LAKE SUPERIOR REGION

BY

C. R. VAN HISE

CONTENTS.

ILLUSTRATIONS.

THE IRON-ORE DEPOSITS OF THE LAKE SUPERIOR REGION.

By C. R. Van Hise.

INTRODUCTION.

ACKNOWLEDGMENTS.

For the material used in the preparation of this paper I am indebted to a large number of men. First, my acknowledgment is due to Maj. J. W. Powell, former Director, and to C. D. Walcott, present Director of the United States Geological Survey, for ample opportunity to study the iron-bearing districts of the Lake Superion region. Next, I am indebted to the late Prof. Roland D. Irving, my former chief, and to a number of men who have worked with me. Among them W. N. Merriam, W. S. Bayley, J. Morgan Clements, H. L. Smyth, and C. K. Leith have done important work. I have drawn upon the various special reports of these men on the different districts. Finally, I am indebted to the owners, superintendents, and engineers of the Lake Superior iron mines; with one or two important exceptions, for many years they have placed at my disposal information in their possession concerning the individual districts and properties. To mention all from whom I have received assistance would be to give a catalogue of the principal mining men of the Lake Superior region. However, four men have turned aside from their professional duties to give special assistance. In my early studies in the Penokee-Gogebic district, where I obtained the first clews as to the development of the ore bodies, the underground work was done for me by J. Park Channing, who, under my direction, obtained plats of the various mines of the district, and furnished a vast amount of accurate information. It was the data furnished by Mr. Channing that enabled me to work out my theory as to the relation of the ore deposits to dikes. A service precisely similar to that of Mr. Channing was rendered for the Marquette district by James R. Thompson. As a result of the exact information as to underground phenomena which he gave me, I was

able to see that essentially the same principles controlled the deposition of the ores in that district as in the Penokee-Gogebic district. Since Mr. Thompson did this work he has moved to the Penokee-Gogebic district, where he has charge of the Newport and Bonnie mines. Mr. Thompson has given me information which I use in this paper concerning faulting in the Gogebic district. W. J. Olcott has given me similar information concerning some of the mines of the district. This information in reference to faulting was the final structural data necessary in order to fully elucidate the development of the ores of the Penokee-Gogebic district. In our work on the Mesabi district Mr. Olcott and J. U. Sebenius have given valuable assistance which is more fully referred to on a subsequent page.

The statements as to the ore production are taken from reports by John Birkinbine,[1] or from data furnished by him, except the shipments for 1900 and the totals for the ranges, which are taken from the Iron Trade Review.

From my own writings I have taken without quotation such material as I could advantageously use.

IMPORTANCE OF LAKE SUPERIOR IRON ORES.

The production of iron ore in the United States as a whole, and in the Lake Superior region for the ten years from 1891 to 1900, inclusive, was as follows:

Production of iron ore in United States and in Lake Superior region, 1891 to 1900, inclusive.

Year.	United States.	Lake Superior.
	Long tons.	*Long tons.*
1891	14, 591, 178	7, 621, 465
1892	16, 296, 666	9, 564, 388
1893	11, 587, 629	6, 594, 620
1894	11, 879, 679	7, 682, 548
1895	15, 957, 614	10, 268, 978
1896	16, 005, 449	10, 566, 359
1897	17, 518, 046	12, 205, 522
1898	19, 433, 716	13, 779, 308
1899	24, 683, 173	17, 802, 955
1900	25, 979, 393	19, 121, 393

The total product from the Lake Superior region since shipment first began, in 1850, to 1900, inclusive, is 171,418,984 long tons.

From this table it appears that while the production of the Lake Superior region in the early years of the past decade was somewhat

[1] Twentieth Ann. Rept. U. S. Geol. Survey, Pt. VI, Mineral Resources, 1898-99, pp. 27-37.

more than half of the total production of the United States, in the years 1897, 1898, 1899, and 1900 the Lake Superior production was respectively about 70, 71, 72, and 74 per cent of the total for the United States. In the years 1899 and 1900 the Lake Superior production was considerably greater than the total production of the United States for 1897.

It is also to be remembered that the Lake Superior ores are of higher grade than those from other parts of the United States, and this makes it clear that the actual amount of iron produced in the Lake Superior region is about four-fifths of the total of the United States.

The maximum product of Great Britain, the greatest of the iron-ore producers with the exception of the United States, was in 1882. In that year 18,031,957 long tons were produced.[1] The production of the Lake Superior region alone for the year 1900 surpassed this maximum; and the ore, being of much higher grade, contained much more iron than the product of Great Britain's best year.

It is therefore evident that the Lake Superior region is by all odds the most important single factor in the world's production of the metal which is more important to man than all others.

[1] Monthly Summary of Commerce and Finance for August, 1900; Bureau of Statistics, Treasury Department, p. 201.

CHAPTER I.

GENERAL DISCUSSION OF PRINCIPLES.

GENERAL STRATIGRAPHY.

The iron-bearing districts of the Lake Superior region have been the special subjects of study of the Lake Superior division of the United States Geological Survey. This division was organized in 1883. From 1883 to 1888 it was in charge of the late Prof. Roland D. Irving, I being one of his assistants. Since 1888 the division has been in my charge.

Since 1883 the work of the division has been largely restricted to two main lines of investigation; first, general studies of Lake Superior stratigraphy; and, second, detailed studies of the various districts which yield iron ores, leading to the preparation of monographic reports upon these districts. At the present time the work is sufficiently far advanced to determine the general stratigraphy of the region south of the Canadian line to a reasonable degree of certainty. Disregarding comparatively late formations, this structural study shows that there are in this region five unconformable series from the top downward, as follows:

(1) The Cambrian, which in the Lake Superior district is mainly represented by the Lake Superior sandstone.

(2) The Keweenawan or copper-bearing series, consisting of two divisions, the rocks of the lower division being largely igneous, but containing interstratified sediments, and those of the upper being wholly sedimentary.

(3) The Upper Huronian, mainly a sedimentary series, but locally containing great series of volcanic rocks, and cut by intrusives of Upper Huronian and Keweenawan ages.

(4) The Lower Huronian, consisting mainly of sedimentary rocks, but in certain districts including volcanics. This series is cut by intrusive rocks of Lower Huronian and later ages.

(5) The Archean or Basement complex, composed mainly of ancient igneous rocks, both plutonic and volcanic, but apparently including subordinate amounts of sediments. Into these very ancient igneous rocks later igneous rocks of many kinds have been intruded at various times.

These series are separated from one another by great unconformities. It is not the purpose of this paper to describe the formations of each of these series nor to give evidence as to their structural relations.

These matters have been discussed by Irving and myself in various papers, to which reference can be made by anyone desiring fuller information on this part of the subject.[1]

The Lower Huronian and Upper Huronian series together constitute the Huronian for the Lake Superior region. These series are called Huronian because they are believed to be equivalent to the Upper Huronian and Lower Huronian of the original Huronian district north of Lake Huron. Within these Huronian rocks the great majority of the workable iron-ore deposits of the region occur, although a number of very important deposits are found in the Archean. Frequently, in papers on these series, the term Iron-bearing series will be used in apposition to Huronian series, precisely as the term Copper-bearing series is found in apposition to Keweenawan.

It is well known that within the Lake Superior region of the United States there are six iron-bearing districts. These are the Marquette, the Crystal Falls, the Menominee, the Penokee-Gogebic, the Mesabi, and the Vermilion. At the present time the Lake Superior division

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[1] R. D. Irving: Divisibility of the Archean in the Northwest: Am. Jour. Sci., 3d series, Vol. XXIX, 1885, pp. 237–229. Is there a Huronian group?: Am. Jour. Sci., 3d series, Vol. XXXIV, 1887, pp. 204–216, 249–263, 365–374. Preliminary paper on an investigation of the Archean formations of the Northwestern States: Fifth Ann. Rept. U. S. Geol. Survey, 1885, pp. 175–242. On the classification of early Cambrian and pre-Cambrian formations: Seventh Ann. Rept. U. S. Geol. Survey, 1888, pp. 365–454.

C. R. Van Hise: An attempt to harmonize some apparently conflicting views of Lake Superior stratigraphy: Am. Jour. Sci., 3d series, Vol. XLI, 1891, pp. 117–136. Correlation papers—Archean and Algonkian: Bull. U. S. Geol. Survey No. 86. Principles of North American pre-Cambrian geology (with Appendix by L. M. Hoskins): Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. I, 1896, pp. 573–874.

The foregoing papers render it unnecessary for me here to take up the general stratigraphy of the Lake Superior region. However, our work north of Lake Superior, in northeastern Minnesota and Canada, has upon two points modified our published conclusions as to succession and correlation. Those who compare this paper with earlier papers will note two important modifications. First, the Archean has heretofore been supposed to be composed wholly of igneous rocks; no sediments have been recognized in this division of the pre-Cambrian. The north-shore work, however, makes it very probable that certain of the sedimentary iron-bearing formations must be included in the Archean. As examples of such are the productive iron formations of the Vermilion and Michipicoten districts. This modification is important from a theoretical point of view, since it will make changes necessary in my general definition of the Archean and of the Algonkian. The Algonkian has been defined to include all pre-Cambrian sedimentary rocks. The Archean has been defined to include all pre-Algonkian rocks, and has been supposed to contain igneous rocks only. These definitions must be modified so as to include in the Algonkian all pre-Cambrian series which are dominantly of sedimentary origin, or equivalent in age with those which are dominantly of sedimentary origin. The Archean must be defined to comprise the rocks older than the Algonkian, which are dominantly of igneous origin, but which may include subordinate amounts of sediments. Recent work in northwestern Europe, and especially in Scotland, Scandinavia, and Finland, where the ancient rocks are best exposed in Europe, shows that these modifications in the definitions of the Archean and Algonkian are also there applicable. The changes are quite in line with what might be expected; for in recent years no one feature in geological advance has been more significant than the sweeping away of sharp dividing lines between the various periods.

Second, the iron-bearing formations of the Vermilion and similar districts I have heretofore regarded as Lower Huronian. In placing these formations in the Archean I recognize three series in which productive ore formations are found, the Upper Huronian, the Lower Huronian, and the Archean.

The evidence upon which these modifications of my opinion concerning Lake Superior stratigraphy are based can not be here presented in detail. It will be fully given in a monograph upon the Vermilion district, to be published later. In general it may, however, be stated that our work in the Vermilion district of Minnesota and on the Canadian side of the international boundary has convinced us that bands of sedimentary iron-bearing formation are interstratified with the upper part of the oldest series of the Lake Superior region, composed of greenstones, greenstone-schists, and tuffs, although the thick productive belts of the Archean appear to rest upon the greenstones and greenstone-schists.

of the United States Geological Survey has published monographs upon the Penokee-Gogebic,[1] the Marquette,[2] and the Crystal Falls districts,[3] and a special folio upon the Menominee district.[4] The field work upon the Menominee and Vermilion districts is completed, and monographs upon these districts are being prepared by W. S. Bayley and J. Morgan Clements. The detailed geological field work in the Mesabi district was begun by C. K. Leith in July, 1900. Spurr[5] has prepared a report upon this area which gives his view of the succession of formations and the relations of the iron ores; and the Minnesota geological survey has lately published a somewhat detailed account of the range.[6] At the present time, therefore, it is possible to make a general statement as to the stratigraphical positions and origin of the iron-bearing formations in the Lake Superior region and to summarize the principles which control the deposition of the ores. This is the purpose of the present paper, which is adapted from a partly prepared manuscript upon Lake Superior geology, to be later published as a monograph by the United States Geological Survey. In this paper it is not my intention to discuss each mine. Individual mines will be mentioned only as illustrative of the manner of occurrence of the ores. The selection of mine plats for figures is based upon the excellence with which they illustrate the principles of occurrence of ore rather than upon the relative importance of the mines.

THE IRON-BEARING FORMATIONS.

ROCKS OF THE IRON-BEARING FORMATIONS.

The iron ores of the Lake Superior region all occur within or are associated with certain formations which have been called the iron-bearing formations. The chief varieties of rocks of the iron-bearing formations are (1) cherty iron carbonates, (2) ferrous silicate rocks, (3) pyritic quartz rocks (confined to the Archean), (4) ferruginous slates, (5) ferruginous cherts, (6) jaspilites, (7) amphibolitic and magnetitic schists and rarely pyroxenic and chrysolitic slates or schists, (8) iron-ore deposits, and (9) detrital ferruginous rocks derived from the foregoing varieties. There are gradations between all of the different varieties of the iron-bearing formations. Gradation varieties also

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892.

[2] The Marquette iron-bearing district of Michigan, by C. R. Van Hise and W. S. Bayley, including a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey Vol. XXVIII, 1897. With atlas.

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

[4] Geologic Atlas U. S., folio 62, Menominee Special, 1900.

[5] The iron-bearing rocks of the Mesabi range in Minnesota, by J. E. Spurr: Bull. Geol. Nat. Hist. Survey Minnesota, No. 10, 1894, p. 268.

[6] Geology of Minnesota, Chaps. XIII-XX, by N. H. Winchell and U. S. Grant: Geol. Nat. Hist. Survey Minnesota, Vol. IV, 1899.

exist between the rocks of the iron-bearing formations and those of the associated formations. For the purpose of the present paper it is not necessary to consider these gradation varieties.

The cherty iron-bearing carbonates are the chief original sedimentary rocks of the iron-bearing formations. These are the rocks from which the other varieties of the iron-bearing formations and the iron ores have been mainly produced by various metamorphic and sedimentary processes. In the Mesabi district it has been held that the source of the iron can be traced to glauconite.[1] But work thus far done by the United States Geological Survey seems to indicate that hydrous ferrous silicate and iron carbonate are the important sources of iron ore in that district. The iron silicate is not glauconite, since analyses by Steiger show that it contains no alkali. In the Michipicoten district of Ontario pyrite and marcasite occur rather plentifully within the original iron-bearing carbonates, and also very abundantly with quartz in associated rocks. Pyritic quartz rocks also occur in the Vermilion district in subordinate quantity. The iron sulphide to some extent has undoubtedly been a source of the ores. But however one may emphasize the importance of ferrous silicate and iron sulphide as a source of the ore bodies, it still remains true that the iron-bearing carbonates are the dominant original sedimentary rocks out of which the iron-bearing formations and ore bodies have been produced. The iron-bearing carbonates vary from nearly pure siderite to dolomite. Thus the different varieties might be called siderite, ankerite, parankerite, and ferriferous dolomite. Between these definite minerals there are undoubted gradations. The amount of chert which was present in original rocks of the iron-bearing formations varies from an insignificant quantity to a predominant amount. On account of the great variability in the compositions of the original rocks the general term cherty iron-bearing carbonates rather than any definite mineralogical term is preferred.

In the present paper it is not my purpose to enter into a full discussion of the origin of the cherty iron-bearing carbonates, the ferrous silicates, and the pyrite-quartz rocks. This is an interesting and difficult subject, the adequate discussion of which would require a paper. It is, however, my belief that the iron for the iron-bearing formations was largely derived from the more ancient basic volcanic rocks of the Lake Superior region. When the individual districts are taken up it will be seen that a greenstone, often ellipsoidal, in many places porous and amygdaloidal, in many places schistose, and rich in iron, is the most characteristic rock of the Archean, and that similar rocks occur abundantly in the Huronian. Where these igneous rocks were adjacent to the seas they would be leached by the underground water and the iron transported to the adjacent seas. It is probable that

[1] The iron-bearing rocks of the Mesabi range, by J. E. Spurr: Bull. Geol. Nat. Hist. Survey Minnesota, No. 10, 1894, pp. 227-248.

to some extent this leaching process also went on below the waters of the sea. The iron was probably transported to the water mainly as carbonate, but to some extent as sulphate. The carbonate would there be thrown down by oxidation and hydration as limonite, and the sulphate in part as basic ferric sulphate. Much of the sulphate was probably directly precipitated as sulphide by the organic material. The limonite would be mingled with the organic matter which was undoubtedly present, as shown by the associated carbonaceous and graphitic shales and slates. When deeply buried the organic matter would reduce the iron sesquioxide to iron protoxide. By the simultaneous decomposition of the organic matter carbon dioxide would be produced, which would unite with much of the protoxide of iron, producing iron carbonate. The sulphate of the basic ferrous sulphate would be reduced to the sulphide by the organic material, thus producing the pyritic carbonates. Where the iron was brought to the water mainly as sulphate the direct reduction of this salt by organic matter would form iron sulphide with little or no carbonate. Simultaneously with the production of these substances chert was formed, probably through the influence of organisms.[1] Some of this silica would unite with a part of the iron protoxide, producing ferrous silicate. More or less mechanical sediment would also be laid down. Thus the original rocks—the cherty iron carbonates, the ferrous silicate rocks, and the pyritic cherts—would be produced.

It has chanced that at three different periods in the history of the Lake Superior region these processes of the development of the original rocks of the iron-bearing formations have occurred extensively. While this might at first be thought remarkable, there is no good reason for thus regarding it. At some time during each of the Archean, Lower Huronian, and Upper Huronian periods the quiescent conditions of chemical and organic sedimentation have occurred, and since the iron-bearing volcanic rocks were each time available for the work of underground waters and sea waters, naturally iron carbonate and the other original rocks have been produced. In each period the source of the material and the process of its formation were essentially the same.

Alterations of the rocks of the iron-bearing formations.—The alterations of the original rocks of the iron-bearing formations have been along two general lines, depending upon whether the iron-bearing carbonate or ferrous silicate or pyrite when altered was at the surface or at considerable depth. Where the rocks were altered at or near the surface, so that oxygen-bearing waters were abundant, ferruginous slates, ferruginous cherts, and ore bodies were produced. Where the iron-bearing carbonate was deeply buried when altered,

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 246–253.
Fossil Medusae, by C. D. Walcott: Mon. U. S. Geol. Survey Vol. XXX, 1898, pp. 17–21.

and especially where altered in connection with igneous rocks so that the temperature was rather high, the rocks which were produced were amphibolitic and magnetitic slates or schists. The formation of the ferruginous slates and ferruginous cherts from the iron-bearing carbonate is usually a process of liberation of carbon dioxide and of oxidation and hydration of the iron. Where oxidation takes place with little hydration, jaspilites may be formed. Where pyrite is also present the process is that of oxidation of both the sulphur and iron and partial hydration of the iron. Where ferrous silicate is present the process is that of separation of the silica and partial hydration of the iron oxide. Ordinarily the rearrangement of the iron and chert emphasized the original sedimentary banding.

The formation of the amphibolitic and magnetitic schists and the pyroxenic and chrysolitic schists from the iron-bearing carbonate is a process of decarbonation, silication, and partial oxidation. The driving off of the carbon dioxide leaves the protoxide free.[1] The union of silica with iron protoxide alone forms grünerite or fayalite; with iron and magnesium, cummingtonite, chrysolite, or hypersthene; with iron, magnesium, and calcium, actinolite; with these substances and various earthy impurities, hornblende. The excess of iron of the carbonate and sulphide is oxidized to magnetite. Where the original rock was strongly pyritic much of this mineral usually remains. Where a part of the original material was hydrated ferrous silicate, grünerite, or fayalite forms from it by simple dehydration and recrystallization. It is only where the metamorphism has been of the most profound character, as at the west end of the Gunflint iron formation, that rhombic pyroxenes and chrysolite have been produced. (See p. 409). The reactions producing this line of products are those of the deep-seated zone.[2]

For the development of jaspilite further alterations are commonly required. The first stage ordinarily forms ferruginous slate or ferruginous chert at or near the surface, as above described. These rocks when later deeply buried by sedimentation and subsequently folded are altered in the deep-seated zone in which dehydration is one of the characteristic reactions. The hydrated iron oxides of the ferruginous slates and ferruginous cherts are changed to hematite. This gives the rocks the blood-red appearance of jasper. The jaspilites therefore differ mainly from the ferruginous slates and the ferruginous cherts in the nonhydrated condition of the iron oxide.

During any of the above processes of alteration the iron oxides may be more or less concentrated. The concentration may result in bands

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[1] Metamorphism of rocks and rock flowage, by C. R. Van Hise: Bull. Geol. Soc. America, Vol. IX, 1898, pp. 277–286.

[2] Some principles controlling the deposition of ores, by C. R. Van Hise: Trans. Am. Inst. Min. Eng. Vol. XXX, 1900, pp. 77–78.

Metamorphism of rocks and rock flowage, by C. R. Van Hise: loc. cit., pp. 279–286.

Geology of Minnesota, Vol. IV, 1899, pp. 459, 476–477.

Contact metamorphism of a basic igneous rock, by U. S. Grant: Bull. Geol. Soc. America, Vol. XI, 1900, pp. 506–509.

of nearly pure iron oxide between the leaner portions of the rock. It may result in the concentration of the iron oxide in veins. It may result in the concentration of the iron oxide in large masses under peculiar conditions, as fully explained below, and thus produce ore bodies. The ores are mainly somewhat hydrated hematite, but limonite and anhydrous hematite (either earthy or specular) occur plentifully. Magnetite is also found, but is very subordinate in quantity. The great mass of the iron ore of the Lake Superior region is iron sesquioxide.

It appears from the foregoing that the original rocks of the iron-bearing formations, notwithstanding the facts that they appear to be in three unconformable series and that their deposition must have been millions of years apart, are remarkably similar. Moreover, while the original rocks of the iron-bearing formations have undergone a very wide variety of changes, the alterations for the three formations followed substantially the same courses. The reasons for this are that the original materials are essentially the same, and that they were largely transformed to other varieties of rocks at the same time. The particular transformations are extremely variable in different districts or in different parts of the same district, but the end results are similar for each formation when the conditions of metamorphism were similar. Consequently one who has worked for a brief time in the Lake Superior region, even if he can not describe and name the individual varieties of each iron-bearing formation, soon learns to recognize the chief kinds of rocks characteristic of these formations, and especially to recognize the associations of the different kinds of rocks with one another and the general appearance of the formations as a whole. Hence, while the iron-bearing formations are lithologically extremely variable, their common origin and common methods of metamorphism and the peculiar relations of the different varieties to one another make it easy to recognize them.

HORIZONS AT WHICH THE IRON-BEARING FORMATIONS OCCUR.

The iron-bearing formations occur in three series, reckoned from the base upwards as follows: (1) A nondetrital iron-bearing formation in upper portions of the Archean, (2) a nondetrital iron-bearing formation in the Lower Huronian series, (3) iron-bearing formations in the Upper Huronian series. The iron-bearing formations in the Upper Huronian series are at two horizons. These are (*a*) a basal detrital ferruginous formation of the Upper Huronian where in contact with the iron-bearing formation of the Lower Huronian; (*b*) a largely nondetrital iron-bearing formation in the Upper Huronian. Within these formations or adjacent to them exploration is warranted. Beyond their confines exploration for iron ore is a useless expenditure.

In most districts these formations have been given local names. This has been done, first, because at an early stage of our work it was not certainly known which of the formations of one district were equivalent to those of another; and, second, because the miners in a district prefer a name derived from that district rather than one from another district. The Archean iron-bearing formation of the Vermilion district has been called the Soudan formation. The Lower Huronian iron-bearing formation in the Marquette and adjacent areas has been named the Negaunee formation. The Upper Huronian iron-bearing formation in the Penokee-Gogebic district has been called simply the Iron-bearing member in previous reports of the Geological Survey. It is here named the Ironwood formation, from the principal town in the district. The productive iron-bearing formation in the Menominee district has been named the Vulcan formation, and in the Crystal Falls district the Groveland formation. The Upper Huronian iron-bearing formation in the Mesabi district has not heretofore received a distinctive name. It will be called the Biwabik formation. The Upper Huronian iron-bearing formation in the Animikie series of Canada we have decided to call the Gunflint formation, from Gunflint Lake, where the formation is finely exposed. Iron-bearing formations which are not producers are not given names nor has the iron-bearing formation of the Michipicoten district been named.

The iron ores may occur at any position within the iron-bearing formations. However, other things being equal, they are likely to occur in middle or lower strata rather than in high strata in the formations.

GENESIS OF THE ORE DEPOSITS.

GENERAL STATEMENT.

In another place I have somewhat fully discussed the general subject of the deposition of ore deposits by underground water.[1] It is there held that deposits so produced constitute by far the larger group of ore deposits. To this group of ores the iron-ore deposits of the Lake Superior region will be shown to belong. In the paper referred to I have shown that ore deposits produced by underground water are commonly found where there have been trunk channels of circulation.[2] It will be seen upon subsequent pages that this generalization is applicable to the Lake Superior region. I have divided ore deposits produced by underground waters into three main classes: (1) Ores which at the place of precipitation are deposited by ascending waters alone; (2) ores which at the place of precipitation are deposited by descending waters alone, and (3) ores which receive a first concentration by

[1] Some principles controlling the deposition of ores, by C. R. Van Hise: Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 27-177.

[2] Loc. cit., pp. 82-91, 123-125, 158-161, 166-169.

ascending waters and a second concentration by descending waters.[1] It will be seen upon subsequent pages that iron ores of the Lake Superior region belong to the second class.

STRUCTURAL RELATIONS OF THE IRON-ORE DEPOSITS.

Small iron-ore deposits are found where orogenic movements have produced faulting, close plication, brecciation, or combinations of two or all of these phenomena in the iron-bearing formations. Such movements furnish zones or areas where percolating waters are converged into trunk channels, and thus favor the concentration of the iron oxides.

Large ore deposits occur at contacts between different members of the iron-bearing formations or at the contact of the iron-bearing formations with other formations. These contacts are favorable places for the concentration of ore, because they are horizons along which important slipping or differential movement has occurred during the folding of the Lake Superior region. Whenever beds are folded there must be differential movement between them. This is well illustrated by the slipping of the leaves of a flexible book over one another when the book is bent. In nature the contact planes between formations of a different character are always places of weakness; hence, at such places the major movements take place. These movements are sure to make the formations porous, and thus produce main channels of percolating water, and hence the frequent presence of ore bodies at the contact planes.

The iron-ore deposits of the first order of magnitude occur on relatively impervious formations, which are in such position as to constitute pitching troughs. A pitching trough may be made by a slate underlying or interstratified with an iron-bearing formation; by a quartzite formation underlying an iron formation; by a limestone formation underlying an iron formation; by an igneous rock, whether intrusive or extrusive, underlying or within an iron formation; or by any combination of these rocks. The most frequent combinations are those of sedimentary or volcanic rocks with subsequent intrusive rocks. The essential thing in this connection is that somehow an impervious basement shall be in such a position as to constitute a pitching trough.

The combination of two or all of the favorable conditions, viz, strong orogenic movements, contact planes, and pitching troughs with impervious basements, is more favorable than any one of them. Where such a combination is found the largest ore deposits may be expected. Such are the conditions at a number of the great mines of the region. However, it can not be too strongly insisted upon that an essential condition for the development of a great iron-ore body in an

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[1] Loc. cit., pp. 173-174.

iron-bearing formation in the Lake Superior region is the production in some way of a pitching trough made by a formation which is relatively impervious. Where the impervious pitching troughs are large and continuous, as, for instance, at the end of a great synclinal fold (see Pls. LIV, LVI, LVII, LIX), the ore deposits are almost sure to be large. Where the pitching troughs are small, irregular, or broken, the ore deposits are likely to be small.

The forms of the ore deposits at first sight might be thought to be exceedingly irregular, but when the above relations are understood they are seen at once to have orderly forms. To illustrate, the main mass of an ore deposit on an impervious basement is likely to be at the bottom of the trough, but from this main mass a considerable belt of ore may follow the limbs of the trough to a much higher altitude than in the center of the trough (see Pl. LIX). The ore bodies in cross section thus frequently constitute a U, which is very thick at the bottom, the center of the U being occupied by the iron-bearing formation which has not been transformed to ore.

ORE DEPOSITS LARGELY SECONDARY.

The relations of the ore deposits (see Pls. L, LIV, LVI, LVII, LIX) are such as clearly to show that the iron ores in troughs must have been deposited in their present positions after the troughs and other structural features of the region were formed. No igneous or sedimentary rock as originally produced has such forms as those exhibited by the ore bodies. They clearly are not original sedimentary rocks, such as the iron formation as a whole, but the iron-ore deposits grade into the other rocks of this sedimentary formation. The ore-bearing rocks are clearly not igneous rocks. No igneous rocks ever grade by imperceptible stages into sedimentary rocks, such as the various members of the iron-bearing formations. Nor do igneous rocks ever have such uniformly definite relations to troughs. If the iron ores were deposited in their positions after the development of the present structure of the Lake Superior region, as the foregoing facts seem to show beyond question, they must have been produced by the work of underground circulating waters.

Bearing upon this conclusion is the fact that at the present time there is an undoubted relation between abundant underground circulation and the ore deposits. This is so well known that the miners understand the empirical relation even if they do not apprehend the causal one. When an explorer, in sinking a test pit or shaft, finds abundant water he regards this as a favorable indication. When, upon the other hand, he does not get much water, unless he is on high ground he fears that if he discovers an ore deposit it will be small. The exploitation of large ore deposits has frequently necessitated the handling of large volumes of water. In places where the amount of water is comparatively small, it is highly probable that in pre-Glacial time, before the valleys were filled, the circulation was much more abundant. The great quantity of water found in connection with the ore deposits is positive evidence, independent of all theory, that the ores are located at trunk channels of underground circulation.

IRON-ORE DEPOSITS PRODUCED BY DESCENDING WATER.

The question next arises as to whether the waters were ascending or descending when the ore deposits were formed. The positions of the great bodies of ores in pitching troughs bottomed by impervious basements rather than in pitching arches topped by impervious roofs is conclusive evidence that these ores were concentrated by descending rather than by ascending water. Descending waters would be converged into pitching troughs with impervious basements, whereas ascending waters would be converged into pitching arches having impervious roofs. This generalization is fully discussed elsewhere.[1]

The structural relations of the ores which are confined to the contact planes and to places of strong orogenic movement do not always enable one to determine whether the concentrating waters were descending or ascending. Since, however, as already noted in the larger ore deposits, these features are combined with troughs, it can hardly be doubted that the waters which formed the ore deposits at contact planes and places of orogenic movement were also descending.

In this connection it is also to be remembered that the ores are mainly iron sesquioxide, usually more or less hydrated—that is, they belong to the class of oxidized and hydrated ores. The products were therefore produced under conditions favorable to oxidation and hydration, and if secondary concentrates they must have been precipitated by water charged with oxygen. Such waters are usually descending, hence the character of the deposits makes it probable that the waters producing the ores were descending rather than ascending.[2]

CHEMICAL PROCESS OF CONCENTRATION.

The next question to be considered is the chemical process of concentration of the ores. For places where waters from different sources are converged, this process has been fully given in Monographs XIX and XXVIII of the United States Geological Survey.[3] In this paper the discussion will be only summarized. A part of the iron oxide of the ore was deposited in its present condition as an original sediment

[1] Some principles controlling the deposition of ores, by C. R. Van Hise: Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 27-177.

[2] Loc. cit., pp. 72-74, 138.

[3] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 534.

The Marquette iron-bearing district of Michigan, by C. R. Van Hise (with W. S. Bayley and H. L. Smyth): Mon. U. S. Geol. Survey Vol. XXVIII, 1897, pp. 608. With atlas of 39 plates.

containing silica and other impurities. However, the nature of the sediment may have been changed; that is to say, it may have been deposited in part as iron carbonate, or in small part as iron sulphide or iron silicate, and later transformed to iron oxide in situ. The lean material originally deposited where the ore bodies now are has been enriched by secondary deposition of iron oxide. Briefly, the process of enrichment is believed to have been as follows:

The source of the iron for the enrichment of the ores is believed to have been mainly iron carbonate. Meteoric waters are charged with oxygen. As they enter the soil they would be dispersed through innumerable minute openings. The waters, which early in their journey come into contact with iron carbonate, would have their oxygen abstracted. Such waters would be likely to be those following circuitous routes. The deoxidation of the waters by the iron carbonate would produce ferruginous slates and ferruginous cherts. In this alteration the carbon dioxide would be liberated, and would join the descending waters. Thus carbonated waters free from oxygen would be produced. Such waters are capable of taking a considerable amount of iron carbonate and some iron silicate into solution. Large quantities of these solutions would be converged upon the sides or at the bottom of the pitching troughs, or in other places where there were trunk channels for water circulation.

After an iron-bearing formation was exposed to descending waters for a considerable time, a large part of the iron carbonate adjacent to the surface would be transformed to ferruginous slates and ferruginous cherts. This change would take place most extensively where waters were abundant and a somewhat direct course led to the trunk channels. After this process was completed at such places, the waters now following this direct route would pass only through the ferruginous slates and ferruginous cherts, and would reach the trunk channels charged with oxygen. There the solutions bearing iron carbonate and those bearing oxygen would be commingled. Iron sesquioxide would be precipitated. Therefore, the iron oxide of an ore body consists in part of iron compounds originally deposited in situ, and in part of iron brought in by underground waters. The material deposited in situ may have been originally detrital iron oxide, or it may have been derived from iron carbonate, iron sulphide, or iron silicate, which was oxidized in place, or from two or all of these sources. It has been assumed that the part brought in by underground waters was mainly transported as carbonate, although a portion may have been transported in some other form. Of the two sources of iron ores, the original material and that added by underground water, the latter is upon the average probably more abundant. But in some exceptional cases, where there is a large amount of detrital iron oxide, the material added by underground waters may be subordinate. However, in all cases it may be said that were it not for the secondary enrichment by underground waters, through the addition of iron oxide, the material would not be iron ore. The evidence of this lies in the fact that the ore bodies are universally confined to the places where underground waters have been converged into trunk channels.

The ore deposits contain upon the average a less quantity of silica than does the average of the iron-bearing formations. It follows therefore that silica must have been dissolved. This doubtless was largely the work of the great volume of water converged into the trunk channels. It has been seen that the waters which carried iron carbonate to the ore deposits were carbonated. The precipitation of iron oxide from carbonate liberated more carbon dioxide, so that the waters were very heavily charged with carbonic acid. In some of the districts basic igneous rocks occur within the iron-ore deposits or as basements to them. In all such cases these basic rocks are found to have lost a large part or all of their alkalies. These must have passed into the solutions. Hence the waters moving along the trunk channels would in some cases contain alkalies besides being rich in carbon dioxide. It is well known that such solutions are capable of dissolving silica. Therefore, the conditions which result in the precipitation of iron oxide also furnish conditions favorable to the solution of the silica. Silica is thus largely dissolved from the ore bodies and transported elsewhere. The removal of the silica is ordinarily only less important in the development of the ores than the addition of the iron. In many cases the abstraction of the silica proceeded further than the deposition of the iron oxide, thus making the rocks very porous, and further rendering the conditions favorable for abundant circulation.

WHAT BECOMES OF DESCENDING WATER?

Another point which needs to be considered in connection with the above theory is to answer the question, What becomes of the descending water? In order to produce great masses of ore, such as the iron-ore deposits, the circulation must have been long continued. The volume of water which circulated through the ore deposits must have been many thousand times, probably hundreds of thousands of times as great as the volume of ore. It is certain that as depth increases the rocks become more and more compact, until finally the zone of rock flowage is reached, into which it can not be assumed the water passes. We, therefore, must conclude that the water converged into the trunk channels, represented by the pitching troughs or other forms, must again somewhere reach the surface. This conclusion is merely an application of the principles of underground water circulation discussed by me in a paper already referred to.

INFLUENCE OF TOPOGRAPHY ON ORE DEPOSITION.

The majority of the large iron-ore deposits of the Lake Superior region are located upon the slopes of hills or bluffs, often upon their upper parts. But there are some notable exceptions to this, as, for instance, the great deposit of ore which is below the Lake Angeline depression in the Marquette district, the great Chapin mass, which was largely located below an area which was a swamp, and some of the deposits of the Mesabi district. However, the impervious basements of even these deposits rise to higher elevations immediately adjacent. These impervious formations would concentrate a large amount of water which would move downward toward the low lying sloping areas.

Underground water circulation is due to gravity. Therefore, water below areas of elevation is likely to be descending at least for some depth, and water below valleys is likely to be ascending. Furthermore, a small difference of head is sufficient to account for the circulation penetrating to a considerable depth. Thus the topographic locations of the ore deposits are explained. However, the theory of the concentration of the iron-ore deposits by waters which, upon the whole, are descending, does not require that all of the ore shall be deposited on high ground, nor that precipitation can not occur where a portion of the waters are ascending. The waters are believed to be largely descending where the ores are deposited. In order that this shall be the case, there must be higher feeding areas which shall furnish sufficient head to carry the water to a considerable depth below the ground, in many cases at least for several hundreds of feet below the lowest points of the valleys. But below the lower parts of the slopes the waters which have followed circuitous routes, and therefore bear iron carbonate, may have begun their ascent and met descending waters bearing oxygen. In this case the ore in the parts of the deposit low on the slopes might be precipitated by the mingling of ascending and descending waters. Notwithstanding this qualification, the undoubted position of the larger masses of the thick deposits directly upon the impervious basements, and their position below areas of elevation and on slopes, and their general absence or poor quality below valleys, seem to me to be conclusive evidence that the main work was accomplished by descending waters.

In this connection it is to be recalled that the topography of the iron-bearing districts of the Lake Superior region has been greatly modified by the ice incursions. The pre-Glacial crests have been lowered by glacial erosion; but more important than this, the valleys are filled, some of them to the depths of hundreds of feet, so that in pre-Glacial time, when the ore deposits were mainly formed, the relief was considerably greater, and therefore the head-driving underground circulation greater and much more effective. In many of those cases in which large ore deposits lie below low ground it is certain that there was still lower ground in the adjacent areas in pre-Glacial times.

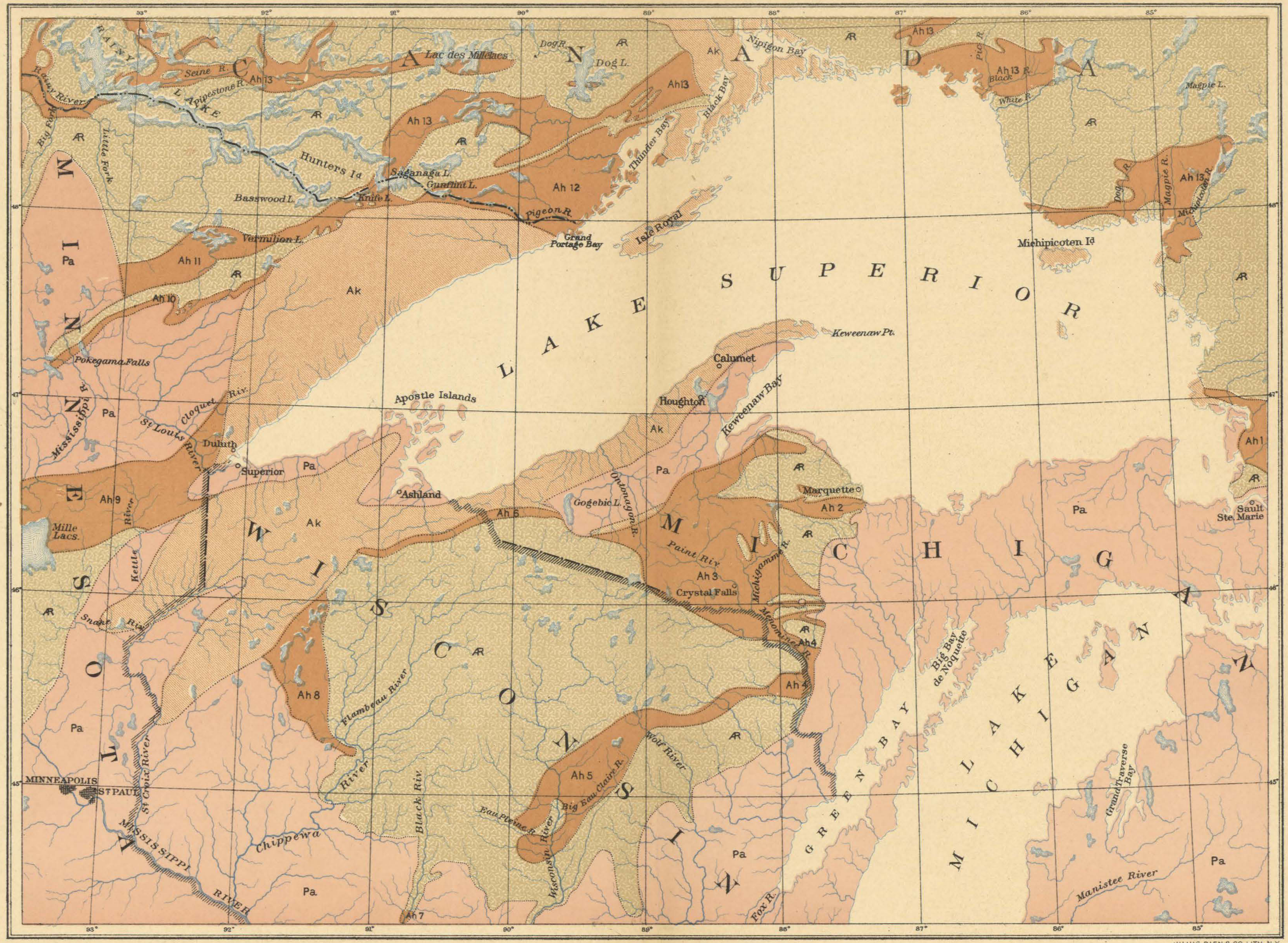
To the above statement the objection may be raised that the reason why ore deposits have been found mainly below elevations or slopes is that the low-lying areas are difficult to explore. This objection has some force. However, giving it all possible weight, it is not sufficient to explain the very great preponderance of discovered deposits on slopes and hills. Large iron-ore deposits are so valuable that if many existed below valleys a considerable number would have been found. Indeed, in many districts low-lying areas have been thoroughly explored, and yet in the majority of cases this work has not been rewarded.

INFLUENCE OF DENUDATION ON ORE DEPOSITION.

Nearly all, if not all, of the large ore bodies known in the Lake Superior region somewhere reach the solid rock surface. From the drift they may extend downward to variable depths. If the above explanation of the origin of the ores be correct, the iron ore of these deposits brought in by underground water must in large measure have been derived from those portions of the iron-bearing formation which were once above the present surface of denudation, but which have now been cut away by erosion. The ore deposits are therefore regarded as the result of the work of descending waters combined with progressive denudation. Contemporaneously with the development of the iron ores the ferruginous slates and ferruginous cherts were formed.

TIME AND DEPTH OF CONCENTRATION.

It has already been seen that the beginning of the processes of alteration of the original iron-bearing rocks occurred far back; indeed, in Archean and Lower Huronian times extensive changes took place in the iron-bearing formations during the erosions which followed those periods. These resulted in the transformation of large parts of the iron-bearing formations from iron-bearing carbonate to ferruginous slates, ferruginous cherts, etc. Thus the beginning of the processes of concentration for the Archean ores must be placed in early Huronian times, and for the Lower Huronian ores must be placed in the time between the two Huronian periods. Where at the base of the Upper Huronian rich ferruginous detritus was formed at the beginning of Upper Huronian time, the second stage of the process of concentration of the ores at this horizon took place. In certain places the iron-bearing formation within the Upper Huronian was exposed by erosion before Keweenawan time, and went through a set of changes in the time interval between the Huronian and Keweenawan similar to the Lower Huronian iron-formation in inter-Huronian time. Therefore the beginning of the



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

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

GEOLOGICAL MAP OF PART OF THE LAKE SUPERIOR REGION

SHOWING PRE-CAMBRIAN ROCKS

Compiled from Official maps of U. S. State, and Canadian Surveys

Scale

0 50 100 STAT. MI.

process of development of the ores at this horizon antedated Keweenawan time. While, therefore, it is plain that the beginning of concentration of the ores must be placed shortly after the different iron-bearing formations were deposited, if the theory advanced on the previous pages be correct, it is clear that the beginning of the final and most important enrichment of the ore deposits occurred in Algonkian time. Moreover, in those districts in which great masses of Keweenawan rocks were laid down upon the Huronian rocks this process could not have begun until the erosion period preceding Cambrian time, and it is rather probable that this limitation also applies to other districts. (See Pl. XLVIII.) Clearly the process in each district began when, as a result of the great orogenic movements and the attendant denudation, the iron-bearing formations were exposed to the weathering forces, and in the majority if not all of the districts this must have occurred in the great time gap represented by the unconformity between the Keweenawan and Cambrian. The process of enrichment has undoubtedly continued until the present time. It therefore appears that the circulating waters had eras of time in which to perform their work; indeed, a part of pre-Paleozoic and all of the Paleozoic, Mesozoic, and Cenozoic. In all of the districts since the beginning of final concentration many thousands of feet of strata have been removed by erosion. Therefore the main part of the deposits now being exploited must have been produced during the latter part of the work of weathering and denudation.

During the process of denudation the ore deposits for a given district would begin to form shortly after the iron-bearing formation was cut through. The ore deposits would long continue to increase in size. It is probable that after a sufficiently long time increase in size would practically cease, for denudation would finally remove the ores at the surface as fast as they formed below the surface. However, change would not stop. The ore deposits formed would continue migrating downward pari passu with denudation. On account of the pitch, lateral migration would accompany downward migration. At any given time the masses of ore would extend from the surface to the depth at which descending waters were effective. We therefore must conceive of the iron-ore deposits as slowly migrating downward through thousands of feet, at any given time being just in advance of the plane of erosion. As denudation goes downward a part of the ores would be carried away mechanically and thus lost. Another, but probably a relatively small part, was doubtless taken into solution and carried downward to be precipitated again at lower levels. However, as erosion extended downward and swept away the ore at the surface, the process of concentration also continued downward, so that the amount of ore existing at any one period through much of pre-Glacial time was roughly constant, although there was doubtless considerable variation depending upon topographic and climatic conditions. But I have little doubt that the amount of ore which existed at any one time was small as compared with that which has been produced in the past and has been carried away by running water.

For that portion of an ore deposit which now reaches the surface or is overlain by completely altered ferruginous slates or cherts, it is probable that there is little addition in iron oxide at the present time; for it has already been explained that the iron oxide for an ore deposit is mainly derived from that part of the iron-bearing formation which has been removed by erosion. However, it does not follow that the enrichment of an ore deposit by the abstraction of silica has not effectively continued after practically all of the iron was added. Indeed, there is every reason to believe that the solution of silica has continued to the present time, and, moreover, this process has probably been more effective in those parts of an ore deposit near the surface; for there the waters have been longest at work in abstracting the silica. It is a well-known fact that in many mines there is a tendency for the silica to run somewhat lower in the upper than in the lower levels of the deposits, and this is readily explained by the greater depletion of silica in the upper than in the lower parts of deposits. Also many of the ore deposits have a broken and porous character, and appear to have sagged, as if some compound or compounds had been abstracted. The material abstracted was doubtless mainly silica.

Furthermore, the ore deposits seem to have been rendered more valuable by the abstraction of the phosphorus compounds by the descending waters in a way precisely similar to the abstraction of the silica. The most notable published cases of this are the Pewabic mine, described by Brown,[1] and the Aragon mine, described by Larsson,[2] where the deposits near the surface are low phosphorus and those deeper down are high phosphorus ores. In general the phosphorus seems to be low where the iron is high and the ore porous, and therefore, where the water circulation was very effective. This is well illustrated in the Mesabi district, where, without reference to position in the mines, the porous ores high in iron are apt to be low in phosphorus, and where the yellow aluminous and relatively impervious slaty ores low in iron are high in phosphorus. The principle is also illustrated in the Gogebic district, where the porous ores are low and the very hard impervious ores adjacent to the dikes are high in phosphorus. The fact that phosphorus in many cases is relatively high at low levels has been explained by some mining engineers on the hypothesis that phosphorus abstracted above has been deposited lower down, but it seems to me that the more probable explanation is that the entire deposits

[1] Distribution of phosphorus and system of sampling at Pewabic mine, by E. F. Brown: Proc. Lake Superior Min. Inst., 1895, p. 49.

[2] Discussion of above paper by Per Larsson. Ibid., p. 55.

were once relatively rich in phosphorus, and that the variation in richness is generally that of relative depletion where the circulation was active, rather than that of abstraction above and deposition below.

In conclusion we may therefore say that the chemical processes have tended to make the ore deposits more valuable at the present time, although the additions of iron may have long since ceased.

While this general statement is true, it by no means follows that the processes of denudation and enrichment were uniform. At times the processes would go on rapidly; at other times would be stayed for long periods, depending upon the post-Keweenawan history of the Lake Superior region. The great steps of this history are (1) the great pre-Cambrian period of mountain making and erosion, (2) subsidence and Paleozoic sedimentation, (3) the post-Paleozoic uplift and denudation, (4) deposition of Cretaceous rocks upon parts of the region, (5) the post-Cretaceous uplift and denudation, and (6) the Pleistocene ice incursions.

(1) In the pre-Cambrian period of mountain making and denudation it is probable that the ore deposits reached their full development, and indeed they may during the later part of this ancient time have been of greater magnitude than they are at present, although possibly not so rich. This is shown by the Menominee district. In this district the Upper Cambrian sandstone and the Silurian limestone cap the Huronian formations, and even some of the ore deposits. The details of the relations are given under the description of the Menominee district (see p. 400). Since these ore deposits extend to the basal Cambrian, and the upward extension of the iron-bearing formation must have been removed before Upper Cambrian time, it is clear that the main additions of iron oxide for these deposits must have taken place in pre-Cambrian time. If, as is probable, as shown below, Cambrian and Silurian strata capped the other iron-bearing districts of the Lake Superior region, it is all but certain that ore concentration was equally advanced in these other districts; although where erosion has extended farther below the Paleozoic than in the Menominee district later events have had a more important influence upon the present condition of the ore deposits.

(2) After this period of denudation the Lake Superior region was encroached upon by the Paleozoic sea. Where the iron-bearing formations existed and were rich in iron oxide, detrital ores were formed at the base of the Cambrian. The entire region was deeply buried beneath the Paleozoic deposits. Probably so long as the region remained below the sea the processes of concentration practically ceased, and the mass of the ore deposits remained nearly stationary.

(3) When after Paleozoic time the region was again raised above the sea and denudation began, little enrichment would take place

until the major portion of the Paleozoic rocks was stripped from the region. Over much of the region these Paleozoic rocks were entirely removed, and the pre-Cambrian topography of the Huronian again emerged from below the Cambrian deposits. In the Menominee district and the southeastern part of the Crystal Falls district the Paleozoic deposits were not completely removed from the iron-bearing formations, and here are found considerable quantities of detrital ores at the base of the Cambrian. For most of the region erosion did not stop at the Paleozoic, but extended downward for a greater or less depth into the Huronian rocks, and so far as this took place it is presumed that the ore deposits migrated downward precisely as during the pre-Cambrian period of denudation.

(4) Erosion continued until the end of the Cretaceous period of base-leveling, when the area was again reduced nearly to an uneven plain and locally was overridden by the sea and capped by Cretaceous rocks, as in the Mesabi district. At the end of this period the processes of downward denudation and concentration were greatly diminished in speed.[1]

(5) During the period of post-Cretaceous uplift and erosion it is to be presumed that the main features of the present topography of the Lake Superior region were produced. During this time denudation and the migration of the ore deposits again went on, but to what extent is uncertain. In the Menominee district it is highly probable that the topography of the Huronian rocks is largely pre-Cambrian, and that the present depressions to a large extent are reexcavated pre-Cambrian valleys. The same is true for the Felch Mountain tongue of the Crystal Falls district. In the borders of the Marquette district, also, Cambrian deposits are found. However, it must always be a matter of conjecture as to how far the present topography is redeveloped pre-Cambrian topography and how far it is post-Cretaceous. For my own part, I am inclined to believe for several of the south-shore districts that it is probably in considerable measure exhumed topography, and therefore that a large part of the process of denudation and enrichment was in pre-Cambrian time, as already explained.

(6) The last great event in the development of the ore deposits was the glacial incursions of Pleistocene time. So far as the ore deposits are concerned the work was of two kinds, glacial denudation and glacial deposition. Commonly these two classes of work were very sharply separated from each other. Ordinarily the change from the ores to the drift is clean and sharp; in fact, as sharp as between the hard, grooved, and striated rocks and the overlying drift. In many places during the period of erosion the ore which was cut away by the moving ice sheets was transported elsewhere. Later, when the

[1] Geology of Minnesota, Vol. IV, 1899, p. 616.

glaciers receded and deposition occurred, the clean-cut ore bodies were covered to a greater or less depth by deposits of glacial drift. This may be seen to the best advantage in the great open pits of the Mesabi district. Here the soft, clean ore extends directly to the drift. It is overlain by sand and gravel, not derived from the ore but brought from the north. The contacts in many cases are of almost knife-like sharpness, there being practically no ore in the basal layers of the drift.

The quantity of ore which was removed during the first stage of Pleistocene time, that of glacial erosion, was very great. It is certain that the vast quantities removed have not yet been compensated for by concentration since Glacial time. In so far as the elevations in pre-Glacial time, upon which the ore now extends to the surface, were higher than at present, just so far have the ore deposits been truncated. Almost the entire zone of decomposed rocks which must have been adjacent to the ores has been removed. The ore deposits were certainly truncated to an equal depth. Not only so, but glacial erosion in many places cut deeper into the soft ore bodies than into the adjacent hard rocks, and thus produced subordinate valleys. This is finely illustrated in the Mesabi district. The abundant fragments of hard iron ore in the glacial drift furnish further evidence of the large amount of ore which has been removed by the glaciers. This material is so plentiful that it is clear that vast quantities of this hard ore have been swept away. If this be true, it is certain that still greater quantities of soft ore have been removed, although on account of its softness it has been broken into minute fragments, and therefore furnishes little evidence of its removal.

The foregoing considerations lead to the certain conclusion that the glacial truncation seriously reduced the amount of available iron ore in the Lake Superior region. While the process of concentration has continued since Glacial time, and has tended to enrich and deepen the deposits, I have no doubt that the gain since the glacial incursion is insignificant as compared with the loss of rich material during the Glacial period.

It appears from the foregoing that while the quantity of ore in the Lake Superior region has always been large since Cambrian time, there have been various vicissitudes in this history during which the quantity of ore alternately increased and decreased. On a priori grounds one might expect that there was a greater quantity of ore in the latter part of the period between the Keweenawan and the Cambrian than at any subsequent time; for in the early part of that period the variations in topography were probably greater than at any time since. If this were so, the descending water had greater head, and therefore penetrated to greater depths. Toward the close of the period denudation was probably slow, giving ample time for the process of concentration. Between this apparently most favorable period for ore development and the Pleistocene I do not venture to make any guess as to the times of increase and decrease in the quantity of ore. However, it will be seen (pp. 411–412) that the question of glacial denudation has a direct practical bearing upon the probable productiveness of various districts, and especially those north of Lake Superior.

As to the depth to which the enrichment has occurred, and therefore, ore deposits extend, it may be said that while the great majority of workings have not gone to a depth of 1,000 feet, some mines have gone to a depth exceeding 1,500 feet. The theoretical limit in depth is that to which the oxidizing and concentrating action of descending waters is effective. There is little doubt that at sufficient depth the ferruginous slates, ferruginous chert, and ore bodies, which are the result of alterations in the belt of weathering, will be replaced by the lean iron-bearing carbonates and silicates or by the deep-seated alterations of the same (see p. 32). The ore deposits are strictly the products of the work of descending meteoric waters in the belt of weathering and in the upper part of the belt of cementation.

CHAPTER II.

THE INDIVIDUAL DISTRICTS.

Thus far the statement has been general. I shall now take up the districts in succession, describe the phenomena characteristic of each, and give the explanation which seems in each case to be applicable. After this is done the features which are common to all the districts will be easily comprehended.

The various districts will not be considered in a geographical order, but rather in the order in which it is easiest to understand the relations and the development of the ore bodies.

THE PENOKEE-GOGEBIC DISTRICT.[1]

PRODUCTION.

The production of the Penokee-Gogebic district from 1891 to 1900, inclusive, was as follows:

Production of Penokee-Gogebic district from 1891 to 1900.

	Long tons.		Long tons.
1891	2,041,754	1896	2,100,398
1892	3,058,176	1897	2,163,088
1893	1,466,815	1898	2,552,205
1894	1,523,451	1899	2,725,648
1895	2,625,475	1900	2,875,295

The total production of the district from 1884, the first year of shipment, to 1900, inclusive, was 31,216,635 long tons.

CHARACTER OF THE ORES.

The iron ores of the Penokee-Gogebic range are soft red and somewhat hydrated hematite, with a very subordinate amount of hard steel-blue hematite. The iron content computed from cargo analyses of 1899 varies from 53.45 to 65.42 per cent, and averages about 61.32[2] per cent. The phosphorus content varies from .027 to .138 per cent,

[1] For a full discussion of this district see the Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892.

[2] These averages are made by multiplying the tonnage of any grade by the cargo analysis, adding these products, and dividing by the aggregate tonnage of all grades. In some cases data have not been at hand for determining the analyses of certain grades, and hence a small percentage of the tonnage is not accounted for. The figures given, however, are probably within a fraction of a per cent of the correct averages.

and averages about .044 per cent. The silica content varies from 3.14 to 15.05 per cent, and averages about 5.47 per cent. The water content varies from 8.14 to 13.65 per cent, and averages about 7.84 per cent.

LOCATION.

The Penokee-Gogebic district is a narrow belt south of Lake Superior, running about N. 70° E., from somewhat west of longitude 91° nearly to longitude 89° 30′. The belt lies between latitude 46° and 46° 30′. The eastern and most profitable third of the district is in Michigan; the western and less profitable two-thirds of the district are in Wisconsin. (See Pl. XLIX.) The more important mining towns of the district are Hurley, Ironwood, and Bessemer.

SUCCESSION OF FORMATIONS.

The succession of formations, in descending order, is as follows:

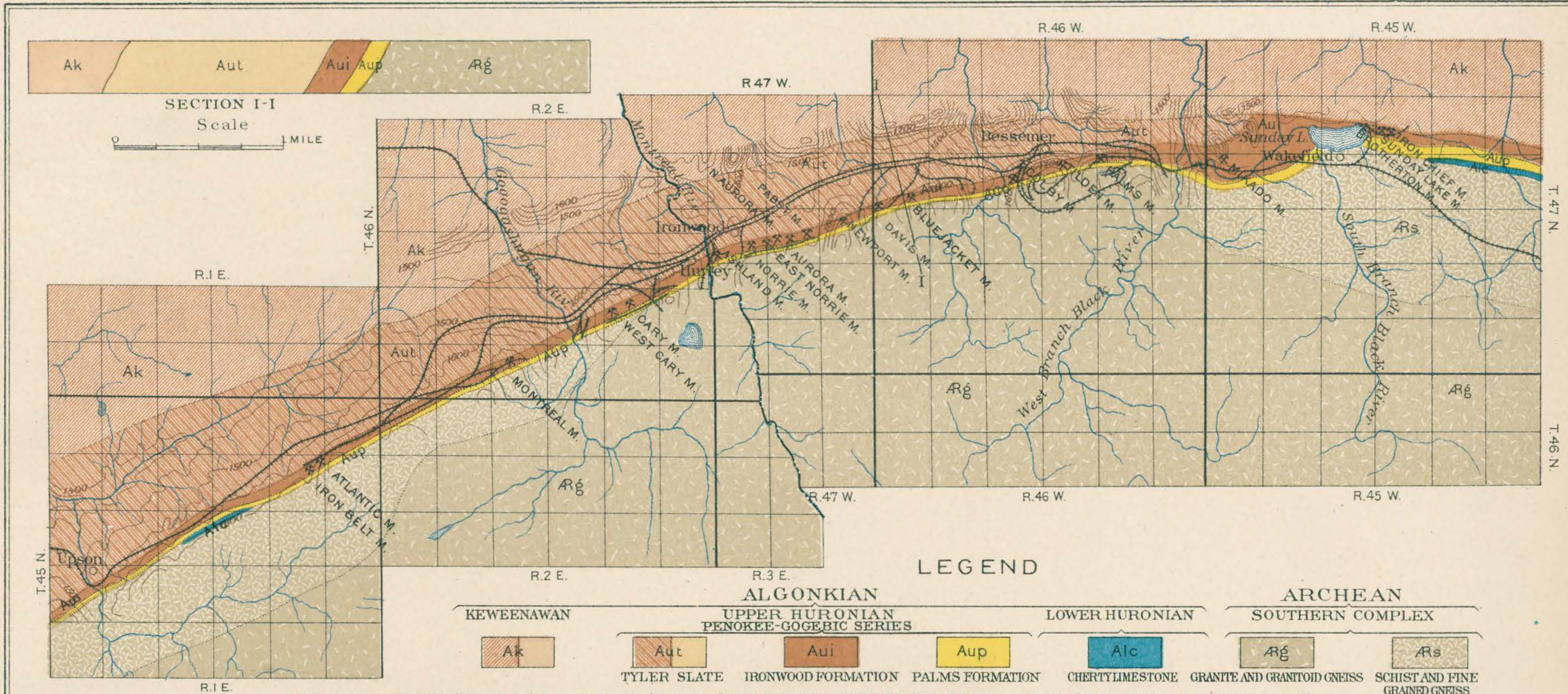
Succession of formations in Penokee-Gogebic district.

Cambrian	Lake Superior sandstone.
(Unconformity.)	
Keweenawan.	
(Unconformity.)	
Upper Huronian (Penokee-Gogebic series)	Tyler slate[1] (upper slate formation). Ironwood formation (iron-bearing formation). Palms formation (quartz-slate formation).
(Unconformity.)	
Lower Huronian	Bad limestone (cherty limestone formation).
(Unconformity.)	
Archean	Granite and granitoid gneiss. Schists and fine-grained gneiss.

STRUCTURE.

Between the Cambrian, Keweenawan, Huronian, and Archean there are great unconformities. There is also an unconformity between the Bad limestone and the Palms formation. This is regarded as the inter-Huronian unconformity. The Upper Huronian iron-bearing series has a northward monoclinal dip, varying from as low as 30° to as high as 80°. For the most of the district the dip is 60° to 70°. Superimposed upon the northern dips is a series of transverse minor rolls which gives the various formations wavy or crenulated outcrops. Also at various places there are cross faults. The most conspicuous of these is that at Penokee Gap, where the throw is 900 feet or

[1] The upper slate formation of the Penokee-Gogebic series is here called the Tyler slate, because excellent and typical exposures of the formation are found at Tylers Fork. The iron-bearing formation is called the Ironwood formation, because the city of Ironwood is partly located upon the formation and adjacent to this city are the most important mines of the district. The quartz-slate formation is called the Palms formation, because just south of the Palms mine, on the Palms property, are numerous typical exposures of the formation.



GEOLOGICAL MAP OF PART OF THE PENOKEE-GOGEBIC DISTRICT

BY R.D. IRVING AND C.R. VAN HISE

Scale

5 0 5 MILES

Contour interval 50 feet

Datum is mean sea level

JULIUS BIEN & CO. LITH. N.Y.

more. At Potato River is another cross fault, with a throw of at least 280 feet.[1] From faults of these magnitudes the cross faults vary in size to those in which the displacements are but a few feet.

Besides these cross faults, faults nearly parallel to the bedding occur. These faults have an important bearing upon the genesis of the ores and are discussed on pp. 344–348. The upper 50 feet of the quartz-slate member is quartzite. This quartz-slate member below and the upper slate member above are relatively impervious formations.

IRONWOOD FORMATION.

Extent, position, thickness, and character.—The iron-bearing formation extends as a continuous belt from about 6 miles east of Sunday Lake, in T. 47 N., R. 44 W., Michigan, to west of English Lake, in T. 44 N., R. 4 W., Wisconsin. The iron formation is also found both east and west of these limits, but is not traced continuously. The main belt of the iron formation has an average thickness of about 850 feet. The rocks of the iron-bearing formation comprise cherty iron-bearing carbonates, ferruginous slates, ferruginous cherts, jaspilites, ore bodies, and actinolite-magnetite-schists. Most of the ore is somewhat soft, partially hydrated hematite, but locally hard, blue slaty ore and, still more rarely, "needle" ore are found. All of these varieties of rocks, with the exception of the actinolite-magnetite-schists, occur in the central, i. e., the productive part, of the district. The actinolite-magnetite-schists are almost wholly confined to the eastern and western nonproductive parts of the district. In the productive part of the district the iron-bearing carbonates are abundant at high horizons, and the ferruginous slates, ferruginous cherts, jaspilites, and ore bodies are dominant at lower horizons.

Structural relations of the ores.—The productive part of the Ironwood formation extends from about 1 mile east of Sunday Lake in Michigan to within 4 miles of Potato River in Wisconsin, a distance of about 25 miles. (See Pl. XLIX.) Both east and west of these areas no workable ore deposits have been found. The absence of the ore deposits at the eastern and western ends of the district, and their presence in the central part of the district, are explained by the nature of the alterations which the iron-bearing formation has undergone. In Keweenawan time great masses of igneous rocks were intruded in a most complex way in the nonproductive eastern and western parts of the Penokee-Gogebic series. At the west end of the district these intrusives belong to the great basal gabbro of the Keweenawan. Consequent upon this intrusion the class of alterations occurred which has been described on page 321 as the deep-seated kind; the iron carbonate was almost completely decomposed, some of the protoxide of iron being

[1] Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 43, 441.

partly oxidized to magnetite. Another part of it with the calcium and magnesium united with the silica present, producing actinolite. The result was to transform the original cherty carbonate to a refractory actinolite-magnetite-schist, which meteoric waters were unable to handle so as to produce ore bodies when they were later transferred to the belt of weathering. The productive part of the iron-bearing formation, however, remained during Keweenawan time as a little-altered cherty iron carbonate, and when later the district was folded and deeply denuded so as to expose the formation to meteoric waters they found the readily transportable and alterable iron carbonate upon which to act. This material was therefore largely altered to ferruginous slate, ferruginous chert, and locally to ore bodies. During the metasomatic changes producing the ferruginous slates and ferruginous cherts the iron oxide and chert were in many cases concentrated to a large extent in alternate bands. Also the ore was partly concentrated into veins and irregular geode-like areas.

The iron-ore deposits, besides being confined to the central part of the Ironwood formation east and west, are further confined to its southern, lower horizon. No important ore bodies have been found more than 300 to 400 feet above the base of the formation.

All of the ore deposits except two lie against the steeply dipping quartzite at the top of the quartz-slate member. (See fig. 8 of Pl. L.) Two of the deposits, the Iron Belt and Atlantic, rest upon a black slate of considerable thickness interstratified with the iron-bearing formation. The quartzite is therefore the foot wall of most of the mines, but in two cases the foot wall is black slate. The ore deposits are thus bounded on the south by the steeply dipping quartzite or by black slate.

When the Huronian rocks were in a horizontal position they were cut by numerous dikes, presumably of Keweenawan age. These dikes are relatively impervious formations. They traverse the various sedimentary formations nearly at right angles. The positions of the majority of these dikes when intruded were such that when the iron-bearing series was tilted to the north at angles varying from 55° to 70° and erosion truncated the series, their strike was not the same as that of the layers they cut. Each dike is therefore somewhere exposed at the surface. From the places where the dikes reach the surface the majority of them pass under the surface with rather gentle easterly undulating pitches usually varying from 15° to 30°. However, some of the dikes are in such positions as to pass below the surface with westerly pitches, in some cases as high as 25°. Occasionally the dikes had such strikes that they now have nearly vertical pitches. The gently pitching dikes bound the ore deposits on the north and the bottom.

It follows from the relations above summarized that the quartz-

PLATE L.

PLATE L.

ORE DEPOSITS OF THE PENOKEE-GOGEBIC DISTRICT.

(Both ore exploited and ore now in mine are represented as ore, since the purpose of this plate is to show the manner of the development of the ore rather than the present stage of exploitation.)

FIG. 1. Vertical east-west longitudinal sections of Ashland mine, showing relation of ore deposit to eastward-pitching dikes and manner in which ore and a lower dike may make their way under a higher dike, there being rock capping between. As shown by the figures, the ore extends to the drift upon the upper dikes, but does not on the lower dikes. The bodies of ore resting upon the upper dikes are comparatively thin. The main body of ore is on a lower dike. Below the main mass of the deposit ore is found on still lower dikes. It is highly probable that the quantity of ore upon the upper dikes was far greater in pre-Glacial time than at present, and that a large amount has been lost through glacial erosion. Between the outcrops of the successive dikes are feeding areas. The water entering at one of these areas formed an ore deposit upon the dike below. This to the east passes below a higher dike.

Scale: 1 inch equals 200 feet. From plat furnished by W. J. Olcott.

FIG. 2. Vertical north-south cross section of Norrie mine at No. 7 shaft, showing relations of ore to adjacent rocks. This ore deposit is one of the greatest in the Gogebic district. As shown by the figure, the quartzite is the foot wall, a strong dike is at its base, and the ore-bearing formation constitutes the hanging wall. The figure shows that the ore extends to the drift.

Scale: 1 inch equals 400 feet. From Newett's Mines and Mineral Statistics of Michigan, p. 78, Lansing, 1896.

FIG. 3. Vertical north-south cross section of Colby mine. The Colby was one of the most important mines upon which the early prospectors in the Gogebic district based their belief that there existed separate "north" and "south" veins. At the Colby the "south vein," resting upon the foot-wall quartzite, and the "north vein," resting upon the dike, were both discovered at the surface; and it was only after considerable development that the two were found to come together and to constitute parts of the same ore deposit, the relations of which are typical for the district.

Scale: 1 inch equals 230 feet. From Mon. U. S. Geol. Survey Vol. XIX, Pl. XXXI, fig. 2.

FIG. 4. Vertical longitudinal east-west section parallel with the Gogebic range, showing the relations of the main dikes of the Ashland, Norrie, East Norrie, Aurora, Pabst, Newport, Davis, and Blue Jacket ore deposits. In all cases the ore deposits rest upon the dikes. From the Ashland to the Aurora the dikes pitch to the east. However, the upper Aurora dike forms a basin and takes a westward pitch, and when followed east contains the Pabst and Newport ore deposits. The figure clearly shows how an ore deposit on a dike below another dike always has a feeding area to the west or to the east; and therefore that the ore may make to as great a depth below other dikes as descending waters are effective. The ramifications of the dikes are very well shown in the Ashland mine. Also a number of the more important steeply inclined or vertical dikes are shown. In this sketch no attempt is made to represent the smaller dikes, of which there are many.

Horizontal scale: 1 inch equals 5,000 feet. From information furnished by W. J. Olcott and Jas. R. Thompson.

FIG. 5. Vertical longitudinal section of "north vein" of Pabst mine, showing bottom of basin of Aurora-Pabst-Newport dike where pitch changes from east to west.

Scale: 1 inch equals 400 feet. From Newett's report, p. 76.

FIG. 6. Vertical north-south cross section of Newport mine, showing vertical displacement of dike by faulting parallel to the bedding. The throw in this case is normal. It appears from figs. 6 and 7 that the maximum throw of the hanging side of the fault as compared with the foot-wall side is eastward and downward. Fig. 6 represents the vertical component; fig. 7 represents the horizontal component.

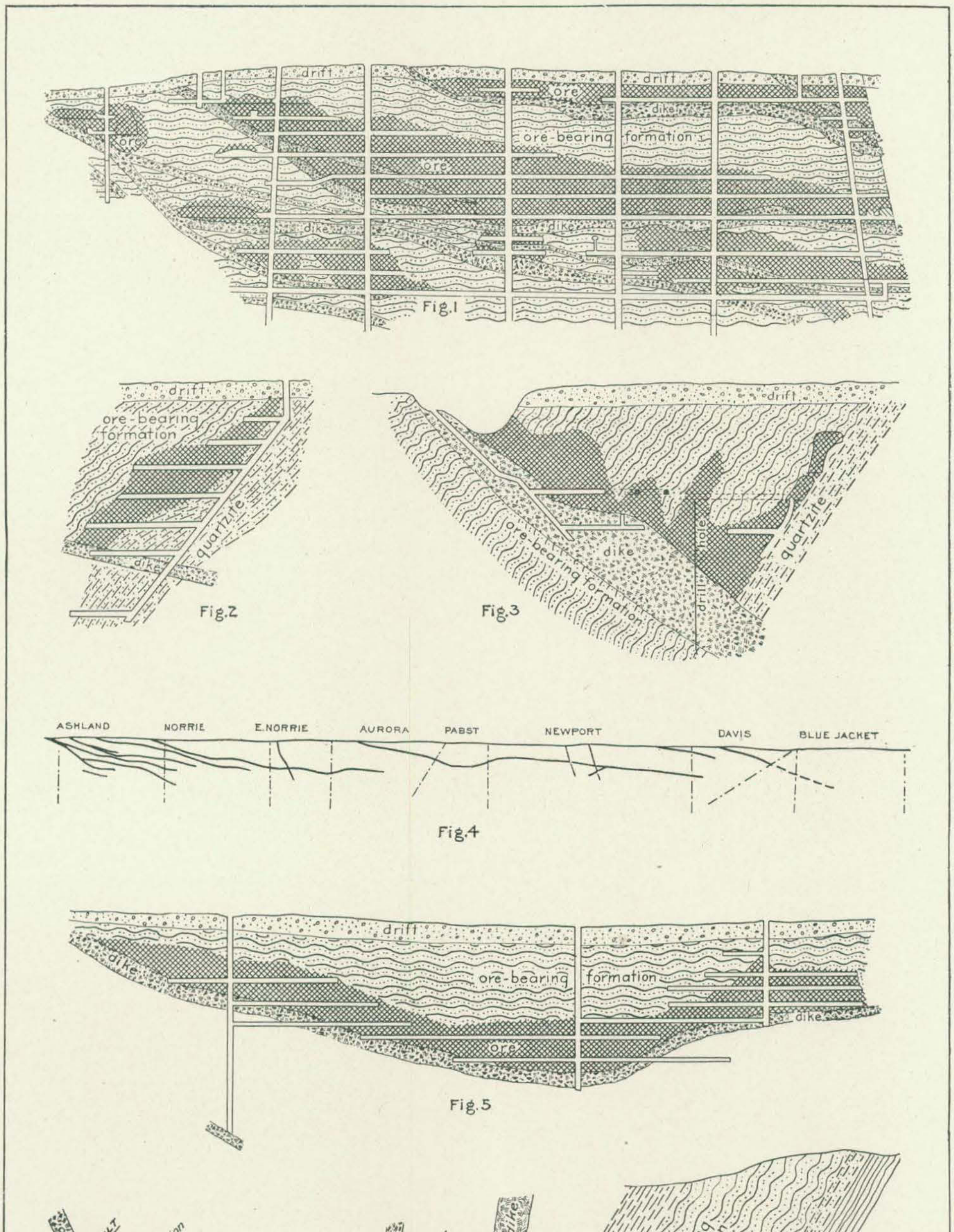
From information and sketch furnished by Jas. R. Thompson.

FIG. 7. Horizontal plan representing displacement of nearly vertical dike at Newport mine by faulting in the iron-bearing member parallel to the bedding. It would not have been possible to detect this horizontal displacement if it were not for the dikes. In this case the amount of horizontal movement is 400 feet.

From information and sketch furnished by Jas. R. Thompson.

FIG. 8. Theoretical north-south cross section designed to show manner in which ore deposits develop on dike basements and foot-wall quartzite.

Scale: 1 inch equals 1,400 feet.



ORE DEPOSITS OF THE PENOKEE-GOGEBIC DISTRICT.

slate member of the series and the dikes together constitute a set of impervious troughs, the majority of which pitch gently to the east. With two exceptions it is in these troughs that the ore deposits occur. In the case of the two exceptions similar troughs are composed of slate interstratified with the Ironwood formation and the dikes. Without exception all of the ore deposits are bounded by impervious quartz-slate or black slate formations on the south and by impervious dikes on the bottom and north. In the case of the Iron Belt and Atlantic mines, where the foot wall is the black slate, other troughs are produced between the black slate and the quartzite by the quartzite and the intersecting dikes. However, the iron-bearing formation between the black slate and the foot-wall quartzite at the Iron Belt mine is only about 150 feet in thickness, and apparently this thickness has not been sufficient to result in the concentration of important ore bodies, at least no such bodies have here been found below the black slate foot wall.

The ore deposits are usually sharply defined along the foot walls and the dike rocks, but often vary upward by imperceptible stages into the ferruginous cherts of the iron-bearing formation. Where there are a number of parallel dikes one below the other there may be several ore bodies one below the other, as for instance at the Ashland and Norrie mines. (See figs. 1 and 4 of Pl. L.) But all of the large ore bodies are bounded below by strong continuous dikes of considerable thickness, from which there may of course be branches. The main Norrie dike is over 30 feet thick. The main Aurora-Pabst-Newport dike varies from 20 to 25 feet in thickness. The main Colby dike is over 90 feet thick. Where a strong dike breaks into many stringers at some depth, as in the Colby mine, the ore body is also likely to be broken up and become small and perhaps worthless.

An ore deposit is likely to have its maximum depth in the apex of a trough, but from this apex a belt of ore may extend to the north along the dike and to the south along the foot wall. In many instances the ore bodies follow the foot walls almost exclusively, as at the Norrie mine. (Fig. 2 of Pl. L.) Usually where the deposits follow both the quartzite and dikes, the former is larger and more continuous than the latter. Where an ore deposit follows both it may divide before reaching the surface into two parts separated by rock, called the south and north veins of the mines, but where such deposits are traced below the surface they unite into a single body. (See fig. 3 of Pl. L.) The ore grades above or laterally into the ferruginous chert, and this into ferruginous slate.

These general statements are best illustrated by that part of the Gogebic range extending from the Ashland mine, near the Montreal River, east to the Davis and Blue Jacket mines. (See fig. 4 of Pl. L.) Beginning at the Ashland mine, we find a number of approximately parallel dikes, all pitching to the east and some of them forking in a curious way. The lowest of these dikes is at the surface near the west end of the property, and from this point passes underground to the east in consequence of the pitch. Eastward is a succession of dikes, each one in vertical section above the dike next to the west at the surface and below the dike next to the east at the surface, and all pitching east. (See fig. 4 of Pl. L.) The two upper and most easterly dikes of the Ashland mine carry a small amount of ore on this property, and then pass to the Norrie properties, and there carry the great ore body of these mines. The upper of these has been known as the main Norrie dike. The pitch of the upper of these dikes gradually flattens in the Norrie mines, and becomes very gentle upon the Aurora property, still carrying a large amount of ore. At the Aurora, however, another higher dike appears which is at the surface a short distance from the west line of the Aurora. This dike extends across the Aurora property upon the Pabst property, where it flattens out, and then takes a westerly pitch, so that it rises and again reaches the surface on the Newport property. (See fig. 5 of Pl. L.) Therefore the great mass of the Aurora ore, that of the Pabst, and that of the Newport, rest upon the same main dike. The eastward pitch of its western portion and the westward pitch of its eastern portion, combined with its flat center, make here a great canoe-like basin. East of the Newport is the Bonnie mine, which has an easterly-pitching dike; east of this is the Davis, with another easterly-pitching dike; and east of this is the Blue Jacket, with a third easterly-pitching dike. These gently pitching dikes are cut by steeply inclined or nearly vertical dikes at a number of places, as for instance in the Norrie, Pabst, and Newport mines. It therefore appears that the main bodies of ore which have yet been exploited in the Ashland mine rest upon several dikes, in the Norrie mines upon two dikes, in the Aurora mine upon two dikes, and in the Pabst and Newport mines upon one dike. Exploration has shown that some ore exists below these dikes, but as yet development has not gone far enough to show that the deeper dikes carry ore deposits comparable in richness and magnitude with those upon the dikes already mentioned comparatively near the surface.

So far as known, the great canoe-shaped dike carrying the Aurora, Pabst, and Newport deposit is unique. However, east of Bessemer the main dike in the Tilden mines has an eastward pitch, and the main dike in the Palms mine has a western pitch. As yet I have been unable to ascertain whether or not the dikes of these mines are the same, but if they are, this would be another case of a great canoe-shaped basin.

The remaining important structural feature in connection with the Penokee-Gogebic deposits is the faulting. It has already been stated that the structural study of the district has shown faulting across the series and faulting parallel to the bedding, or nearly so, at various localities. The latter class of faults is of importance in connection with the ore deposits. The best known of these faults in the iron-producing area is that on the Pabst and Newport properties. The hade of this fault is apparently nearly parallel with the foot-wall quartzite or with the strata. Its throw is nearly horizontal, and amounts to about 400 feet. While its displacement would be scarcely discoverable if the sedimentary formations were alone concerned, it is clearly shown by the pitching and vertical dikes. The north side of the fault has moved eastward relatively to the south or foot-wall side. Since at the Pabst and Newport the pitch of the dike is to the west, at a given cross section the displacement causes the dikes on the north side of the throw to be deeper than they are on the south side of the throw. (Fig. 6 of Pl. L.) At places where the dikes pitch to the east a fault with a similar throw would cause just the reverse relations in a cross section. Where the dikes are vertical the displacement on a horizontal section is represented by fig. 8 of Pl. L. One of the most interesting effects of the faulting where the dikes have a pitch is shown at the Pabst mine. The fault, here parallel to the strata, has cut the dike about 150 feet away from the foot wall. The ore, instead of stopping at the dike, follows down over the broken and displaced ends of the dikes toward another dike below. Upon the latter dike the Pabst mine has developed a large ore body. This lower dike may be the main Norrie dike. At the Bonnie, Palms, Blue Jacket, Montreal, and other mines there is also evidence of disturbances by faulting.[1]

[1] In connection with faulting in the Gogebic district and the relation of faulting to the ore deposits, Mr. James R. Thompson, superintendent of the Newport mine, has furnished me with full information. The following is extracted from a letter by him upon this subject:

"It is very evident, even upon a cursory examination of the underground workings of the Gogebic County mines, that there has been much movement within the limits of the iron-bearing member. Slickensided surfaces are found almost everywhere, and the siliceous portions of the formation are everywhere broken into small pieces by all sorts of cross joints and cracks, showing the strain which this material has everywhere undergone. These phenomena are so universally present, and usually so vague and indefinite in their indications, that they might easily be attributed entirely to the movements of accommodation were it not for other undisputed evidences of genuine faulting. The local evidences of known faults are in places so obscure, owing to the character of the formation, and isolated phenomena of faulting which can not be worked out and traced are so numerous, that I have been forced to the conviction that, in addition to known faults, many faults with moderate movement, say from 10 to 30 feet throw, have taken place at many places on the range. Every ore body which I have examined has one or more places showing a disturbance of the original conditions, but in only a few cases is it possible to follow up the indications to a sufficient distance to define the break. The indications referred to are as follows: There are continuous slickensided surfaces of considerable extent. Portions of the foot wall vary considerably in direction from the regular course of the foot wall adjacent. These irregular portions are sometimes vertical, sometimes overturned—that is, dipping south—and sometimes the foot wall has been moved to form a regular bench. This same class of phenomena is observed in the dikes, only to a greater extent. Often a portion of a dike is broken into detached pieces, which are out of place, while the other part of the dike keeps its regular course. Sometimes a few brecciated fragments, either of chert or dike, are found in the ore. All of the above observations apply to places where it is evident that there have been considerable movements, but where it is impossible to determine the extent and direction of the movements, or to determine the relation of such movements to the ore bodies further than to observe that the two usually are associated.

Aside from these rather indeterminate faults, there are others well determined and, in favorable places, well defined. With one exception these faults are all of small movement; and with this exception I would characterize the range as one much broken by many faults of small throw.

There seems to be a series of cross faults running due north and south, of about 25 to 35 feet throw. Three are known on the Newport property, two fault planes being occupied by cross dikes. The

Topographic relations of the ores.—In the general part of this paper it has been pointed out that there is an important connection between the topography and the ore deposits; viz, the ores generally are found below elevations or slopes rather than below valleys. This general principle is well illustrated in the Penokee-Gogebic district. (See Pl. XLIX.) Beginning at the westend of the district, and proceeding eastward, the Iron Belt and Atlantic are upon a prominent hill, with a valley immediately to the west. The next important mine west of the Montreal River in Wisconsin is the Montreal, and this is located on a large hill.[1] One other mine of importance west of the Montreal River is the Germania, and this also is on a hill. East of the Montreal River in Michigan are the great mines of the district. These are all located on the crests or the upper slopes of the elevations, with the exception of the Pabst, which is in a subordinate depression between the Aurora and Newport; and here, it is to be remembered, is the only certain case of a canoe-shaped basin. The Norrie and Aurora are each

fault planes are nearly vertical, and the east side of the fault in each case is thrown north, so that there is a dislocation of the footwall of about 25 to 35 feet. In two of the three cases at the Newport the direction of throw is nearly horizontal; the third is not yet determined. I suspect the occurrence of other faults similar to these at certain points, but have not had the opportunity to prove my suspicions are correct.

Another fault occurs on the Newport property at K shaft, the old Bonnie shaft. The strike is W. 28° N.; the fault plane is nearly vertical, but gains to the southwest 10 feet with every 100 feet in depth. A small ore body has so far followed the intersection of this fault plane with the foot wall, regardless of the occurrence of dikes. The southwest side of the fault is apparently elevated about 25 feet relative to the northeast side.

The only fault of large movement which is known among the mines is a large longitudinal or strike fault. Its plane is roughly the bedding plane of the formation, but it apparently has a somewhat steeper dip, 75° to 80°. Its throw is practically horizontal and 400 feet in extent. The north side has moved east relative to the south side. At the Newport mine a single observation has been made of a parallel fault some distance north with a similar throw of about 30 feet. My own personal information and observation show the main fault to continue through the Newport, Pabst, and Aurora properties, with a reasonable certainty of its further continuance to the Ashland mine. Besides, there are good reasons for believing that similar faulting is shown at the Montreal, Atlantic, and Iron Belt mines in Wisconsin. The lack of intelligent observation directed to this point accounts for the uncertainty as to the extent of the fault. I believe the same fault extends east to the Colby, but I have not been able to determine it at the Palms. In fact, at the Newport tunnels have penetrated the fault plane at points which gave absolutely no indication of its presence. Finally, while there is no direct evidence to prove it, there is at the same time no reasonable doubt that this large strike fault or a similar one extends nearly the whole length of the productive part of the range.

The relations of these faults to the ore deposits are mostly those which may be reasoned out in connection with your theory of the deposition of the ores. They have certainly greatly facilitated underground drainage and in places have greatly modified the course of the underground trunk channels. In places the ore bodies are unusually large on one side of the faults and abruptly disappear on the other side. In places the ore follows the breaks. Two different illustrations may be interesting. The Aurora dike, carrying the original main ore bodies of the Aurora, Pabst, and Newport mines in a longitudinal projection of its intersection with the foot wall, is lower in the center than at the two ends, but carries ore throughout its length. At the point of lowest depression, however, where cut by the great strike fault referred to above, the ore seems to pour over the rim of the dike and drop straight down to another dike, precisely the same as a large current of water would have done under the circumstances. This ore was obviously formed by downward-flowing waters.

At K shaft of the Newport we have found a place where a large volume of water was rising on a small dike until the dike was cut by the fault, after which the water took the fault plane as a channel and continued its way toward the surface. The ore body at that point is evidently formed by rising waters."

[1] Mon. U. S. Geol. Survey Vol. XIX, Pls. VII and VIII.

on large independent hills. The Newport is on another large hill; the Colby on a prominent hill above Bessemer; the Tilden and Palms on large hills east of Bessemer. The Tilden property extends across an entire section, with a central valley, and it is notable that where this depression occurs the ore deposit disappears.[1] The only important deposits east of the Black River are the Mikado, Sunday Lake, and Brotherton, and these are again all on the crests or the slopes of hills. In short, it may be stated that every large ore deposit of the Penokee-Gogebic range is located below high ground and that no important ore deposit has been found under an important cross valley. The Pabst is located below a subordinate cross depression, but to this mine a special explanation is applicable. (See pp. 349–350.) Notable examples of cross valleys with no ore deposits are those of the three branches of Black River, the Montreal River, and the West Branch of the Montreal River. Between Sunday Lake and the Palms mine one of the branches of Black River follows along the iron-bearing formation, and another branch crosses it. For 3 miles the only ore deposit found is at a place where the river swings far enough to the south so that a considerable hill occurs, and upon this is the Mikado. In short, no mine in the district has been found to extend under any cross line of drainage large enough to carry a distinctly marked river or creek. In this connection it is interesting to note that Mr. T. F. Cole says "it is his experience that the ore in the low ground on the Gogebic range is apt to be considerably split up, the formation being more irregular than upon high elevations."[2] However, the reason assigned by Mr. Cole for the change is that the dikes are more irregular, although for this statement no evidence is given. Since the connection of the dikes with the ore is so well known, it is natural for Mr. Cole to suppose that where the ore bodies become small and irregular the dikes undergo the same change, but it would be very strange indeed if the dikes which were injected into the Penokee-Gogebic series before the beginning of the development of the present topography should have such a relation to the topography as that suggested.

While no ore deposit is found below any distinctly marked cross line of drainage, the converse of this proposition—that is, that every hill contains an important ore deposit—can not be made, although from the Palms to the Ashland mine the only exceptions to this are the two hills between the Colby and Newport, upon which the Davis, Blue Jacket, Puritan, Ironton, and Federal mines are located, none of which have as yet developed large bodies of ore.

The apparent absence of large ore deposits below these hills may be due to the absence of large, continuous, well-developed dikes; but also

[1] Mines and Mineral Statistics of Michigan, by George A. Newett, Ishpeming, 1899, p. 167.
[2] Newett, op. cit., p. 167.

it may be that more thorough exploration in the future will develop large ore deposits in connection with these hills.

Development of the ores.—The position of the ore bodies in reference to the foot-wall quartzites, to the diabase dikes, and to the topography is to be explained by the general process described on pages 323–336. This process will here be considered only in so far as the local conditions give it a more definite application.

The upper portion of the Ironwood formation, where it dips under and is protected by the Tyler slate, now consists largely of residual iron-bearing carbonate. (See fig. 8 of Pl. L.) Not only is this so at the present time, but it may be presumed that the same conditions obtained at any given stage of denudation. The waters which fell upon the iron-bearing formation at high horizons were dispersed through many minute openings. These waters took iron-bearing carbonate into solution through the reactions explained on page 327. These solutions made their way downward until they came into contact with a dike, when they were diverted southward and eastward or westward, depending upon its pitch, until they reached the foot-wall quartzite bounded by the impervious slate below, or an impervious layer within the iron-bearing formation. Other waters which fell upon lower horizons passed only through the ferruginous slates and cherts which had already been formed from the iron-bearing carbonate when the surface was at a higher level than at present. The commingling of the waters from these two different sources at the apexes and along the limbs of the troughs resulted in the precipitation of iron oxide. As already pointed out, silica was also abstracted.[1] Chemical analyses show that the diabase dikes below the ore bodies, which were originally rich in the alkalies, are now almost devoid of these elements. The dikes in the slate member, and also those in the iron formation not associated with the ore bodies, are oftentimes but little altered, and these still contain much alkali. The work of alteration must therefore have been done by the waters which produced the concentration of the ore; and thus these waters became alkaline. It has been shown (pp. 327–328) that the waters were heavily carbonated by the decomposition of a portion of the iron carbonate. It is well known that waters which are rich in alkaline carbonates and carbon dioxide are capable of dissolving silica; and such were the waters following the troughs in the Penokee-Gogebic district. The Penokee-Gogebic ore deposits are therefore explained in small part by the oxidation of iron carbonate in place; to a much larger degree by the oxidization of iron carbonate brought to the troughs; and finally by the solution of the silica once present in the troughs. Contemporaneously with the development of the ore bodies the ferruginous slates and ferruginous cherts were formed. The process here outlined is much more fully

[1] Mon. U. S. Geol. Survey Vol. XIX, 1892, p. 284.

given in Monograph XIX of the United States Geological Survey, pages 285–290.

The ore deposits are in general below elevations or the upper parts of slopes, because these would be the places where descending waters are effective; whereas valleys are places where the waters are ascending, and, so far as known, important ore deposits were not produced. In applying this theory to the Penokee-Gogebic district the following facts are to be remembered. The greater extents of the ore deposits are east and west, following along the east-west pitches of the dikes, showing that the lateral direction of flowage was mainly east or west. Furthermore, it is to be remembered that the iron-bearing formation plunges under an impervious slate formation to the north. Therefore the waters could not be expected to escape in this direction, although the slate belt to the north is generally a low-lying area. The actual position of the ores below the elevations, their longitudinal extent east and west, and the impervious slate above, all point to the conclusion that the waters must have ascended and escaped at the cross valleys. Corresponding with this conclusion is the fact that in general at these places no ore bodies have been found.

It may be objected to this theory that the pitch of the dikes to the east is greater than the surface slope, and therefore that the underground waters when passing under a valley would be prevented from escaping by the overlying impervious dikes. However, this difficulty is explained by the faulting which has been mentioned as a general phenomenon, the displacements of which make passages available for ascending waters. (See figs. 6 and 7 of Pl. L.)

After this explanation was written, Mr. Thompson wrote me that at one shaft in the Newport mine a place was found "where a large volume of water was rising on a small dike until the dike was cut by the fault, after which the water took the fault plane as a channel and continued its way to the surface." This observation furnishes a complete confirmation of the theory that the ascending water is enabled to reach the surface by following faults which cut and displace the dikes, and therefore furnish passages through the impervious strata.

The only additional difficulty which has occurred to me that can be urged against the theory of circulation given is furnished by the great Aurora-Pabst-Newport deposit, which rests in a basin formed by the quartzite and a common dike. (See fig. 5 of Pl. L.) This, indeed, would have presented a great difficulty had not the fault described on pages 344–346 been discovered at the very bottom of the basin. This has so displaced the dike as to allow the waters descending from the east and from the west to escape below to a lower level. That the water has escaped in this direction is shown beyond any reasonable doubt by the relations of the ore, which makes completely over and under the ends of the dike, as described on page 345. Underground drainage has then run eastward from the Aurora and westward from the Newport into this depressed portion of the trough and has there flowed out of the trough over the edge of the dike where the fault had cut it, practically in the lowest part of the basin, and has then dropped vertically until the current struck other dikes directing its flow. Thus the faults parallel to the bedding which displaced the dikes and which in the early days of their discovery were regarded with alarm furnished one of the necessary conditions for the concentration of many of the large ore deposits.

The foregoing facts seem to me to show beyond reasonable question that, in the Gogebic district at least, we have the concentration of the ores somewhat fully worked out. The descending waters on the higher elevations worked to the east or west along the dikes to the north-south intersecting drainage. During this journey the ores were collected and deposited. Below the valleys the waters were ascending and escaping. Of course, in pre-Glacial time, when the main part of the ore deposition was done, many of these drainage lines were much deeper than at present, for the valleys are filled, in some cases at least, to the depth of many feet.

Time and depth of concentration.—Since the Penokee series is overlain by the Keweenawan series, and for the most part the iron formation was deeply buried during Keweenawan time, the process of concentration for the greater part of the district did not begin during this period. After the Keweenawan series was deposited and the great Lake Superior syncline was formed, as a result of which the Penokee series was changed into a northward monocline, the rocks were in a position in which concentration could begin. After denudation had cut through the Keweenawan and the Tyler slate of the Penokee series concentration would begin. This was at the time interval between the Keweenawan and the Cambrian. The beginning of ore deposition, therefore, occurred in pre-Cambrian time. It is to be supposed that by the time the Cambrian deposits were laid down in the Lake Superior region large ore deposits were formed, but how far these were above the present surface of the country is unknown. Since the beginning of ore deposition, so far as downward denudation has gone on, the ore deposits have also migrated downward, as explained on pages 330–331.

As to the depth to which concentration will be found to extend, I am unwilling to make definite predictions.

If deep exploration be made at any given mine below the dikes which are basal to the present known ore deposits, other dikes will undoubtedly be found. Exploration has extended below the so-called main dikes of a number of mines, and ore has been found. This is natural, since the deeper dikes may be the ones which, on account of the pitch, reach the surface east or west and near the surface bear the main ore deposits of other mines. How deep descending waters can be effective in the concentration of ores with a head of a few hundred feet can never be answered theoretically. The presence of one dike above another does not prevent concentration, since between the outcrops of two dikes which vertically are at different depths is an area at which meteoric waters can enter and concentrate ores on the dikes. (See Pl. L, figs. 1 and 4.) Moreover, since it has been shown that faulting exists parallel to the strata, it is certain that it is possible for water to make its way upward at valleys through the dikes. Therefore there is no reason to suppose that the ore deposits of the Penokee-Gogebic district may not extend to as great a depth as in other districts of the Lake Superior region.

At the present stage of development nearly all of the ore which has been exploited has been taken from above the 1,000-foot level. This is shown by the depth of the lowest level of some of the deeper workings, as given by the managers and superintendents in June, 1900. These are as follows: Aurora, 920 feet; Newport, 900 feet; Tilden, 600 feet; Palms, 600 feet; Norrie, 670 feet; Mikado, 565 feet; Brotherton, 700 feet; Sunday Lake, 700 feet; Atlantic, 840 feet; Montreal, No. 1 shaft, 1,020 feet.

THE MESABI DISTRICT.

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

The Mesabi district is treated somewhat more fully than the other districts because of its startlingly rapid development and its present preeminence as an ore producer. Further, the United States Geological Survey up to the present time has published no report on this district, and the reports already published by the Minnesota survey contain interpretations of the geology and the origin of the ores with which we are not in agreement. All of the detailed field work has been done by the junior author. The preparation of the accompanying map (Pl. LI) in its present form is also wholly his work. However, this map is based upon, but modified from, a private map in the possession of the Lake Superior Consolidated Iron Mines Company, which the president of that company, F. T. Gates, allowed to be placed at our disposal. This excellent private map was made by J. U. Sebenius, mining geologist, under the direction of W. J. Olcott, superintendent of mines. Without this map as a basis it would have been impossible for the junior author to have published the accompanying map at the present time. This account of the range is preliminary to a monograph upon the district, to be published by the junior author. This monograph is to be accompanied by complete maps of the entire district.

Our detailed information concerning the district is derived from several sources. The reports of the Minnesota survey by J. Edward

Spurr,[1] U. S. Grant, and N. H. Winchell[2] have been utilized. The most important source of our information is, however, the mining men who have developed the district. W. J. Olcott and J. U. Sebenius have kindly furnished us a vast amount of information concerning the area, including copies of detailed maps, as already noted, and several thousand locations of test pits and exposures. E. J. Longyear and H. B. Hovland have given us the results of extensive exploratory work; and, in fact, almost every mining man in the district has furnished us valuable information. The topography for the United States Geological Survey has been done by E. C. Bebb.

PRODUCTION.

The production of the Mesabi district for the years 1892 to 1900, inclusive, is as follows:

Production of Mesabi district from 1892 to 1900.

	Long tons.		Long tons.		Long tons.
1892	29, 245	1895	2, 839, 350	1898	4, 837, 971
1893	684, 194	1896	3, 082, 973	1899	6, 517, 305
1894	1, 913, 234	1897	4, 220, 151	1900	7, 809, 535

The total production for the district from 1892, the first year of shipment, to 1900, inclusive, was 31,933,958 long tons. Opened up in 1892, in 1900 the output was considerably greater than the combined totals of any other two districts, being 41 per cent of the total for the Lake Superior region. The next largest producer, the Marquette district, in 1900 shipped 18 per cent of the total of the region.

LOCATION AND TOPOGRAPHIC FEATURES.

The Mesabi district lies wholly in northern Minnesota, northwest of Lake Superior, between latitude 47° and 48°. It extends continuously from Pokegama Falls on the Mississippi River in a direction about N. 60° E. to Birch Lake, a distance of 100 miles. Its general trend for this distance is roughly parallel with that of the Marquette, Penokee-Gogebic, and Vermilion districts. West of the Mississippi the Mesabi formations undoubtedly continue, but they are so deeply buried by the glacial deposits that they have not been traced. East of Birch Lake to the middle of range 5 west are a few small isolated patches of Mesabi rocks close to the northern periphery of the great Keweenawan gabbro mass of northeastern Minnesota. These have no economic value and are of so little importance that they are here ignored. From the center of range 5 eastward through Gunflint Lake

[1] The iron-bearing rocks of the Mesabi range in Minnesota, by J. Edward Spurr: Bull. Geol. Nat. Hist. Survey Minnesota, No. 10, 1894.

[2] Final report of the geology of Minnesota, by N. H. Winchell: Geol. Nat. Hist. Survey Minnesota, Vol. IV, 1899.

into Canada the equivalents of the Mesabi series reappear in a continuous belt, where they are known as the Animikie series. The portion of the Animikie series between the center of range 5 and Gunflint Lake is iron-bearing and has been called the Gunflint formation. This is described in the section on the Vermilion district, pages 408–409.

The formations of the Mesabi series lie along the south slope of a ridge known as the Giants or Mesabi (Chippewa for *giant*) Range. (See Pl. LI.) This ridge, while extending in the general direction above indicated, has several gentle bends, and near the center of the district, in the vicinity of Virginia, Eveleth, and Sparta, a relatively sharp bend, known locally as "The Horn," carries the ridge, and consequently the iron-bearing rocks and their associates on its slopes, about 6 miles to the south. The elevation of the range is seldom more than 400 feet above the level of the surrounding country. These higher elevations are found mainly in the central and eastern portions of the district. Toward the west the elevations gradually decrease. The south slopes of the ridge are gentle, while the northern ones are relatively steep. The distance from the low ground on the south to the low ground on the north of the ridge varies from 3 to perhaps 10 miles. In addition to these general topographic features, the range has numerous minor irregularities, due on the upper slopes mainly to normal erosion in the rocks of the ridge, and on the lower slopes to normal erosion greatly modified by the presence of a heavy and irregular mantle of glacial drift.

SUCCESSION AND STRUCTURE.

The succession of formations in the Mesabi district appears in the following table:

Succession of formations in Mesabi district.

Cretaceous.	
(Unconformity.)	
Keweenawan	Great basal gabbro and granite, intrusive in all lower formations.
(Unconformity.)	
Upper Huronian (Mesabi series)	Virginia slate (upper slate formation). Biwabik formation (iron-bearing formation). Pokegama formation (quartzite and quartz-slate formation).
(Unconformity.)	
Lower Huronian	Granite, intrusive in lower formations. Slate-graywacke-conglomerate formation. (Equivalent to the Ogishke and Knife formations of the Vermilion district.)
(Unconformity.)	
Archean	Greenstones, hornblende-schists, and porphyries.

The core of the Giants Range—mainly its northern portion—is composed of igneous rocks, consisting of Archean greenstones and hornblende-schists and Lower Huronian and post-Huronian granites, against which, in some places with eruptive contact, and in some places with normal erosion unconformity, rest the Huronian sedimentary rocks of the district, both the iron bearing and noniron bearing, the oldest appearing closest to the core rocks and the youngest farthest from them to the south. The rocks on the range are well exposed only on the upper slopes, where they are mainly igneous, though partly older sedimentary. On the lower slopes, where the rocks are sedimentary, the exposures are few because of the thick covering of glacial drift.

ARCHEAN.

The Archean forms the basement upon which the Huronian sediments rest. It is represented in the Mesabi district mainly by greenstones, sometimes spheroidal, and by very subordinate quantities of acid porphyries, each of these rocks showing both massive and schistose aspects in different places. Probably also certain hornblende-schists are Archean. The greenstones and greenstone-schists have their best development in the higher parts of the area northwest, north, and northeast of Virginia; in the "Horn" between Virginia, Eveleth, and McKinley; and thence east to Embarrass Lake. East of Embarrass Lake there are no Archean rocks in the part of the district here described. The Archean porphyries are found only in three isolated areas in the "Horn." The hornblende-schists are best exposed north and northeast of Mountain Iron. North of Hibbing also hornblende-schists appear, but it is doubtful how many of them can be assigned to the Archean. Some are certainly metamorphosed Lower Huronian sediments, and it is possible that all are.

The greenstones and their associated hornblende-schists and porphyries have their exact counterparts in the Vermilion iron-bearing district. The jaspers and iron areas associated with these rocks in the Vermilion district, however, are not present in the Mesabi. The Mesabi ores are of later age, as will be shown below.

LOWER HURONIAN.

The sedimentary rocks of the Lower Huronian consist of beautifully banded graywackes and slates and conglomerates, standing in an approximately vertical attitude adjacent to the older igneous rocks of the higher parts of the range. The principal areas of the Lower Huronian sediments appear in a belt running from Eveleth northeast to Biwabik, and beginning again a little northwest of Mesabi station and continuing northeast to the Mallman camps, near the center of range 14 west. In small patches they are found next to the granite north of Hibbing; inclosed in the hornblende-schist north of Mountain Iron; bordering the greenstone in the northern part of sec. 31, T. 59 N., R. 17 W., north of Virginia; bordering the greenstone just north of Sparta in sec. 34, T. 57 N., R. 17 W.; in the NE. ¼ of sec. 34,

T. 59 N., R. 16 W.; in the NE. ¼ of sec. 1, T. 58 N., R. 16 W., east of Biwabik. The rocks of these small areas are usually much metamorphosed, but their sedimentary character is unquestionable.

The presence of a lower sedimentary series was recognized by the Minnesota survey.[1] The distribution of this series and the proof of the unconformities between it and the underlying and overlying series were worked out by the junior author.

It has already been noted that the Lower Huronian series is in nearly vertical attitude. If there is subordinate folding and reduplication of beds in isoclinal attitudes, as one would expect, evidence of this is not apparent. The bedding appears to correspond approximately with the secondary cleavage, and the strikes throughout the extent of the belts do not vary more than 10° or 15°. If the beds have nowhere been folded back on themselves, the thickness of the strata has a possible maximum of 10,000 feet. However, it is more than probable that in places where covered with drift the formation may be sharply folded, in which case this great thickness is only apparent. Probably 3,000 to 5,000 feet would be the greatest thickness that can safely be assigned to the formation.

Where the Lower Huronian sediments are in contact with the Archean rocks the relations are those of normal erosion unconformity. Near this contact in a number of places conglomerates containing pebbles from the Archean rocks are to be observed.

A coarse, gray granite in large areas is intrusive in the Lower Huronian sediments. Actual contacts may be observed at a number of places, near which the Lower Huronian sediments have been altered in many places to hornblende-schists, which are with difficulty recognized as sediments and distinguished from the hornblende-schists of the Archean. This granite extends along the entire length of the Mesabi district. It forms the higher parts of the Giants Range in but a few places—in the area from northwest of Mesaba station northeast to the Mallman camps, in the area northeast and north of Virginia, and in the area extending from north of Mountain Iron west to Hibbing. Where the Archean greenstone and hornblende-schists form the higher parts of the range, and where, as in the extreme eastern end of the range, a still later granite forms the higher part of the ridge, the Lower Huronian gray granite lies on relatively low-lying ground to the north of the range. It probably is continuous with the White-Iron granite of the Vermilion district.

That this granite was intruded in the Lower Huronian before the Upper Huronian was deposited is shown by the fact that pebbles of the granite are found in a number of places in the conglomerate at the base of the Upper Huronian.

[1] Geology of Minnesota; Virginia plate of the Mesabi iron range, by U. S. Grant: Geol. Nat. Hist Survey Minnesota, Vol. IV, 1898, pp. 372–374.

UPPER HURONIAN.

The Upper Huronian rocks comprise three distinct formations, conformable one with another. These are, from the base upward, the Pokegama formation, consisting mainly of quartzite and indurated shale; the Biwabik or iron-bearing formation; and the Virginia slate. The quartzite and indurated shale formation is called the Pokegama formation, following the Minnesota survey, because at Pokegama Falls, on the Mississippi River, are the best-known exposures of this formation in the district. The iron-bearing formation, known generally on the range as taconite, is called the Biwabik formation because the word *biwabik* is the Chippewa word for "a piece or fragment of iron," and the Biwabik mine is one of the earliest and larger of the mines located upon the formation. The upper slate formation of the Mesabi series is called the Virginia slate because the slate in typical form has been found in numerous test pits and drill holes west of the town of this name.

The relations of the Upper Huronian series with the subjacent Archean and Lower Huronian are those of unconformity. This unconformity is shown by the presence of basal conglomerates containing fragments of all the underlying formations, by the wide divergence in dip where the Upper Huronian and Lower Huronian are found close together, and by the manner in which the Upper Huronian laps over and cuts out the surface outcrop of the Lower Huronian.

Exposures of the Pokegama formation and a part of the Biwabik formation are fairly numerous well up on the slopes of the Giants Range; but the Virginia slate and a large part of the iron-bearing formation which occupy the lower slopes to the south seldom outcrop. For their distribution in this area the geologist must be dependent upon the records of drill holes and mines, which are numerous.

The Upper Huronian series constitutes a gently southward-dipping monocline, the dips being for the most part between 5° and 15°. The series is very gently folded in a direction transverse to the range. As a consequence of the flat dips of the monocline, these cross folds cause great undulations in the distribution of the surface outcrops of the series. Gentle cross synclines are likely to be associated with a considerable bowing of the surface outcrops of the series toward the north, while cross anticlines are likely to be associated with southward bends of the surface outcrops.

The varying width of the surface outcrops of the different formations to be observed on the map is due to several factors. First, considerable variation in thickness of the formations; second, the variations in dip, causing considerable variations in width of the surface outcrop of formations of the same thickness—a low dip gives a broader outcrop and a high dip a narrower one; third, variations in topography.

The formations dip to the south. Therefore, the greater the difference in elevation between the north and south sides of the surface outcrops of a formation the greater is the width of its surface outcrop. This factor of topography is important in proportion as the dips are flat and the differences in elevation great. With the low dips which obtain in the Mesabi district and with difference in elevations up to 400 feet, the topography has a considerable effect upon the surface widths of the formations.

The gentle cross folds of the Upper Huronian series seem to correspond roughly with similar undulations of the subjacent Lower Huronian and Archean rocks. This may be taken to indicate that these were depressions in the Lower Huronian and Archean formations at the time of the deposition of the Upper Huronian, and that the initial dips of the Upper Huronian rocks have determined the position of the cross folds, or that both the Upper and Lower Huronian series have been folded together, or it may indicate some combination of these. If a combination, probably the folding is the more important.

Below, the formations of the Upper Huronian series are separately described.

Pokegama formation.—The Pokegama formation varies from a fine conglomerate, through light-colored, vitreous quartzite with well-rounded quartz grains, to an exceedingly fissile and micaceous shale, containing coarse clastic mica plates lying parallel to the bedding. The conglomeratic varieties are generally at the base of the formation. The most abundant variety of rock is the quartzitic phase. The shaly phase of the formation is exceedingly difficult in some cases to distinguish from certain phases of the Lower Huronian graywackes in which secondary mica flakes have developed. Indeed, future work may show that it will be necessary slightly to shift the boundary line on the map between the two formations.

The Pokegama formation appears at the surface as a narrow belt bordering the Biwabik formation on the north. The belt is widest and best exposed in the western portion of the district. From Mountain Iron east the quartzite thus far found appears to be in narrow discontinuous belts as far east as range 13 west. For much of the district the mapping of the formation is based on somewhat meager data, and future work will show changes, but the formation has not been represented on the map far beyond places where at least some data show its presence. Where the boundaries of the formation are somewhat hypothetical, if they encroach in either direction it is upon the formations to the north rather than on the iron-bearing formation. Judging from experience, further exploratory work is likely to extend the limits of the Pokegama formation, making the areas wider and more nearly continuous than they now appear to be.

The thickness of the formation undoubtedly varies considerably, but it is not sufficiently well explored to show what the effect of the factors of changing dip and topography has been upon the apparent thickness. It is probable that the thickness seldom exceeds 450 feet, and from this the thickness may vary to zero. Mr. E. J. Longyear, of Hibbing, in one place (sec. 35, T. 58 N., R. 21 W.) drilled completely through the quartzite and found a thickness of 69 feet.

Biwabik formation.—The Biwabik or iron-bearing formation is a well-bedded formation resting in structural conformity on the Pokegama quartzite. In a number of places a film of fine conglomerate is at the top of the quartzite just as is the case at the corresponding horizon on the Gogebic range, but, so far as the study of the district has yet gone, this conglomerate has not been found to indicate any break of magnitude. The correspondence in strikes and dips shows the two formations to be essentially conformable. Yet the change from a coarse clastic formation to a fine-grained and largely nonclastic formation is astonishingly abrupt.

The iron-bearing formation appears as a continuous belt running from Grand Rapids on the west to Birch Lake on the east, and eastward from this point it is found in a few small isolated patches. Its breadth varies from less than a quarter of a mile, as near Biwabik, to 2 miles or more, as near Hibbing, Mountain Iron, Virginia, and Eveleth.

The thickness of the Biwabik formation undoubtedly varies considerably from place to place along the range. On the basis of average dips and widths of exposures, the thickness seldom exceeds 1,000 feet, and is seldom less than 500 feet. A record of a deep drill hole made by Mr. E. J. Longyear, in sec. 34, T. 59 N., R. 14 W., shows a thickness of 576 feet.

As one of the members of the Upper Huronian series, the iron-bearing formation was included in the gentle cross folding of the district. The synclines of these cross folds have had an important relation to the position and origin of iron deposits, as will be seen below.

The Biwabik formation presents such a wide variety of phases that they can be scarcely more than mentioned. Four widely differing varieties are: (1) A lean ferruginous chert, the chert and iron occurring in alternate bands or irregularly mixed; (2) iron-ore bodies; (3) ferrous silicate and carbonate rocks; (4) more or less ferruginous slates. All gradational varieties between these rocks are present, giving great lithological complexity to the formation. Variety 1 makes up the great bulk of the formation and usually is the one immediately inclosing the ore bodies. Variety 2 is, of course, the important one from an economic standpoint. Thin layers of paint-rock found associated with the ore bodies are probably the altered equivalents of the ferruginous slates. Varieties 3 and 4, while not so closely connected with the ores as variety 1, have had a part in the development of the ores. They usually are found in the southern part of the Biwabik formation close to the overlying Virginia slate. The ferruginous slates are also present at middle and lower horizons in the Mesabi formation eastward from Mesaba station to Birch Lake. The presence of these ferruginous slates in the Biwabik formation has been one of the puzzling features in the exploratory work of the district. In drilling, slates are found capping the iron-bearing material, or as layers in the Biwabik formation itself, or as a part of the solid black slate formation to the south, the Virginia slate. The slates within the Biwabik formation, as will be seen on pages 366 and 368, probably have an important influence on the location of ore deposits, and hence the discrimination of these slates is of vital importance to mining men. As yet data are not at hand for this discrimination on the map, but it is hoped that sufficient data may ultimately be collected to allow of the mapping of the patches of upper slate resting upon the iron-bearing formation, and of the slate horizons in the Biwabik formation itself. Indeed, this can already be done for limited areas.

The present productive part of the Biwabik formation lies between the center of range 22 west on the west and Embarrass Lake on the east, although the discovery of good ore in quantity is reported as far east as Mesabi station and as far west as the center of range 24 west. Indeed, it is reported that mining will shortly commence at the Stephens mine in sec. 26, T. 59 N., R. 15 W., east of Biwabik, and at the Diamond mine in sec. 15, T. 56 N., R. 24 W. The present productive portion of the district is thus the central part. In this respect the Mesabi district is similar to the Penokee-Gogebic district.

The Biwabik formation shows many interesting alterations due to the intrusion of great masses of igneous rocks both basic and acid. Of these the Keweenawan gabbro is by far the most important. The intrusives and their contact effects may be observed east of Mesaba station. The alterations are too complicated to be discussed in this paper, but one should be mentioned which concerns the economic value of the area. The iron oxide of the Biwabik formation west of Mesaba station is mainly hematite. In this part of the district, as above noted, are all the discovered workable ore deposits. The iron oxide east of Mesaba station is largely magnetite. The proportion of magnetite increases as the distance east of Mesaba station increases. In this part of the district no workable ore deposits have been discovered. The magnetite and intrusive rocks are present in the same area, and furthermore the amount of magnetite is great in proportion as the intrusives are approached. The magnetitic nature of the formation is due at least partly to the effect of the intrusives, as explained on page 409. The intrusives, however, are probably not entirely responsible for the apparent lack of workable iron-ore deposits. The slaty layers in the

Biwabik formation, and perhaps other differences in the original character of the iron-bearing formation may also have had their effect. If the main cause of the nonproductive character of this area has been metamorphism, due to the Keweenawan gabbro, this area is unproductive for essentially the same reason that the eastern and western portions of the Penokee-Gogebic district are barren.

Virginia slate.—The Virginia slate lies conformably above the Biwabik formation, with frequent interlaminations of the two formations near the contact. The slate is exceedingly dense, fine grained, of gray and black color, sometimes graphitic, and occasionally shows concretionary structures. The slate is found south of the Biwabik formation throughout its extent from Grand Rapids to Birch Lake. Outcrops, however, are exceedingly rare, because of its softness and because of the heavy covering of drift.

POST-HURONIAN INTRUSIVES.

Intrusive in the Upper Huronian rocks is a red granite with large purple quartz eyes. This forms the higher parts of the Giants Range through most of range 12 and part of range 13 west, near Birch Lake. An actual contact with the iron-bearing formation is exposed in the western portion of range 12, and here interesting metamorphic changes in that formation are to be observed. This granite is probably the equivalent of the red granite appearing at Embarrass, north of the Mesabi range, near the Duluth and Iron Range track. Also later than the Upper Huronian formations, and certainly intrusive in them, is the great Keweenawan gabbro. This overlaps the Mesabi formations, cutting across them diagonally from southwest to northeast, and near Birch Lake cutting them out altogether. To this also is doubtless partly due the almost complete absence of the Mesabi series for a long way east of Birch Lake, although pre-Keweenawan erosion probably was the major cause. Both the granite and the gabbro have had profound metamorphic effects on the iron-bearing formation, but just how much the present lithologic character of the Biwabik formation east of Mesaba station is due to the gabbro, and how much to the granite, and how much to differences in the original character of the formation, is not yet worked out. The age of the gabbro is certainly Keweenawan, and that of the granite probably so.

CRETACEOUS.

In a few places in the district are slightly consolidated Cretaceous sediments resting unconformably upon the older formations. These are for the most part made up of the débris of the underlying formations, principally the Biwabik formation, but sufficient fossil remains have been found to identify the sediments as Cretaceous. Probably the Cretaceous is much more widespread than mapped. So far, it has been found only in isolated test pits.

PLEISTOCENE.

The glacial deposits of the district constitute one of the most important formations. They form a heavy mantle overlying all of the other formations. The thickness of the drift varies from 0 on the upper parts of the slopes of the Giants Range, where the rock exposures are numerous, to 150 or more feet over the low-lying Virginia slate and part of the Biwabik formation. The thick mantle of drift over most of the area of the iron-bearing formation is a serious obstacle to exploratory and mining work.

IRON ORES IN BIWABIK FORMATION.

Topographic relations of the ores.—The majority of the ore deposits are on the gentle southward slope of the Giants Range, or on the westward or eastward slopes of the "Horn." In many cases they are well up on this general slope; in other cases the deposits are well down on the slope, or even extend to the flat-lying land characteristic of the Virginia slate. Usually the ore deposits pitch away from the high land adjacent, and in some cases the difference in elevation of the two ends of a deposit is 100 feet or more, though usually less.

Commonly the thickness of the drift covering the deposits is greater over the parts of the deposits farthest from the adjacent high land than it is over the parts close to it. This indicates that the surfaces of the deposits really have steeper slopes than appear at the drift surface. For this reason in places where the ore deposits apparently occur in flat-lying areas, the ore bodies themselves may have considerable pitches.

Structural relations of ores.—The Mesabi iron ores, following the flat dip of the rocks of the iron-bearing formation, form broad, shallow deposits. As a consequence they present considerable areas of exposure under the drift. In this feature they show a characteristic difference from the deposits of other districts of the Lake Superior region, where the dips of the rocks are steeper and the deposits have greater vertical and less horizontal components, and therefore present smaller surfaces of exposure. Because of the low dips also the Mesabi deposits have their long dimensions transverse to the trend of the range, in this feature differing from the Penokee-Gogebic deposits, where they are parallel to the range.

The Mesabi deposits have the shape they would have if deposited by water in broad shallow troughs, and indeed it will be shown below that they now rest in troughs formed by the cross folding to which the Mesabi series has been subjected and are bottomed by impervious substances. No intrusives are reported in the iron-bearing formation of the productive portion of the Mesabi district, and igneous rocks are thus not a factor in the formation of troughs.

The evidence of the existence of cross synclines or troughs where the ore bodies are found can be seen at almost any of the large open pits of the district. On either side of a pit the layers of the iron-bearing formation are found to dip gently toward the ore body. Where the rocks pass into ore the dips usually increase, in many cases rising to 20° or 30°, or even to 45° or 60°. The steep dips are found only a few feet from the transition places from rock to ore. In the ore and in the rock a few feet away from the places of transition the dips are low. In the few places where the change in dip is very sudden the rocks are much broken, and some of the more abrupt of these flexures may actually pass into minor faults, but the throws of the faults in most cases are not more than a few feet. The sudden downward flexures at the places of transition from rock to ore are probably partially due to the solution of material in the places now occupied by the ore. The underground circulation dissolved more material than was deposited, and this resulted in subsidence or the slump of the strata under the stress of gravity.

While chemical action has thus emphasized the synclines, and in a few places faults may have slightly emphasized them, we have no question that the trunk channels of underground circulation were mainly localized by original synclines belonging to the series of cross folds.

The largest and most complex of the cross folds are those between Biwabik and Mountain Iron. Here is one major cross anticline, to the east and west of which are major cross synclines. It is notable that this area is one of the two great productive ones of the district. The major anticline projects southwestward, and on it are the town and mines of Eveleth. This anticline is known as the "Horn." West of this anticline is a complex cross syncline, on which are located the towns and mines of Virginia and perhaps Mountain Iron. East of the "Horn" is a less marked syncline, on which are the towns and mines of Biwabik and McKinley. These major anticlines and synclines are composed of minor anticlines and synclines, and it is the cross synclines of the second order of magnitude which mark the position of the ore bodies. The other great productive area of the district is that adjacent to Hibbing. Here the cross folding as certainly exists as it does between Biwabik and Mountain Iron, but the folds are not of such magnitude, and it is probable that here the ore bodies rest in the cross synclines of the first order. Superimposed on the folds of the second order of magnitude are still smaller ones, which may be observed in any of the open pits of the mines. These minor folds are the rule and not the exception; it is rarely that the layers of the ore deposits can be seen to continue for any distance without variations in dip or pitch.

Accompanying the cross folding of the iron formation is a considerable amount of minor brecciation and faulting. In the open pits of the mines many such fractures are to be observed. In one or two places the relations of the formations are such as to suggest that possibly faults with considerable displacements are present. However, sufficient evidence is at hand to warrant the statement that for the district as a whole the faulting and brecciation are not so important factors in localizing ore deposits as the general gentle folding above described.

The bases of the ore deposits are more irregular than would be inferred from the above statement of their occurrence in troughs. Horses of rock are frequently found in the ores, and the bottom of any deposit never reposes on a single layer of the gently bowed strata, but rests upon many layers at different horizons. Indeed, it is common, in going from the center of the troughs toward the limits, to find the bottoms of the deposits ascending in series of steps.

The troughs in which the iron ores occur are and have been in the past trunk channels for the circulation of underground water. They are at the cross depressions where the movement of water must be downward, as shown on pages 367-369. As a matter of fact, the course of the flow can now be followed in most of the troughs on which mines are now working. The movement of the water down the formation is further shown by the fact that drill holes piercing the Virginia slate and entering the iron-bearing formation below frequently meet water under pressure, showing that water actually does flow down the dip of the iron formation under the impervious Virginia slate.

Character of ores.—The Mesabi iron ores are for the most part soft, somewhat hydrated hematite, although soft limonite ores are present in subordinate quantity. Their texture varies from exceedingly fine-grained "flue dust" to a fairly coarse, hard, and granular ore, breaking in parallelopiped blocks. In either case the ore needs but little blasting to allow the steam shovel to take it from the bed.

The fineness of many of the ores has prevented the use of large percentages of them in blast-furnace charges. For the finest ores 33 per cent is about as large an amount as it has been found practicable to use. The ores of medium coarseness have been used in amounts as high as 50 per cent. The coarsest grade has been used in percentages running from 60 to 75. Indeed, as large a percentage of the coarsest grade can be used in a mixture as it is ordinarily advisable to use of any one grade.

The iron content, when dried, computed from cargo analyses during 1899, varies from 58.97 to 64.85 per cent, and averages about 63.28 per cent. The phosphorus content varies from 0.025 to 0.080 per cent, and averages about 0.042 per cent. The silica content varies from 2.50 to 9.20 per cent, and averages about 3.38 per cent. The water content varies from 6.81 to 14.11 per cent, and averages about 10.78 per cent.

The ore as it lies in the deposits is beautifully bedded in layers ranging from a fraction of an inch to several inches in thickness. A single bed commonly shows considerable uniformity in composition and structure when followed out laterally, but when compared with the beds above and below it shows considerable differences. In other words, the change in texture and composition is between different beds and not between different parts of the same bed, although to this there are certain exceptions. The effect of these different colors and textures in different layers is to make the bedding very conspicuous. Standing in any of the open pits of the district, it is easy to follow the course of any layer or group of layers through their gentle flexures.

The differences in color are due mainly to differences in composition. The brownish, reddish, and black layers are mainly hematite. Some of the very bright-red layers are paint-rock. The yellowish layers owe their color to the limonite in them. Not uncommonly thin layers of white efflorescence emphasize the banding and add brilliancy to the coloring. Occasionally material of the same color is in a vertical zone across the layers, and such zone resembles an alteration along a joint, the alteration extending different distances in crossing different layers. Commonly such material crossing the bedding is yellowish limonitic material, and the beds through which it runs are brownish or reddish hematitic material. Veins of brecciated quartz also cross the beds.

In texture the variation is even more marked than in color or composition. Certain layers are continuous with many minor bends in them, while intervening layers are characteristically broken into small flat parallelopipeds whose greatest diameters vary from a fraction of an inch to several inches. These broken blocks in alternate layers are one of the most characteristic features of the deposits. Ordinarily the continuous layers are either soft paint-rock or exceedingly fine and soft hematite ore. The small joint blocks are commonly harder hematite. Not infrequently when textures apparently associated with these varieties are present in the bed a stroke of the pick will resolve the whole into a fine dust in which the materials of different textures are not to be discriminated.

These are the general obvious features which strike one in a casual examination of any of the mines. When the ores are studied in detail many interesting features appear. Many of these are not essential for the purposes of this paper, but others will be briefly mentioned.

The distribution of the limonite in the ore bodies is peculiar. It usually occurs in rather thick zones with more or less hematite mixed with it. These zones for each deposit have a tendency to be fairly well defined and persistent, but in different deposits they occur in different horizons. In some mines the limonitic layers occur near the tops of the deposit, in others in middle horizons, and in still others at the bottoms, and in others in two or more of these horizons. More are confined to the tops or bottoms than to the middle horizons, and those confined to the tops are far more common than those confined to the bottoms. Limonite has ordinarily been considered an alteration phase due to the influence of surface waters. If this is the case here, it is interesting to note that this alteration has not been confined to any particular zone of the deposits. Certain features indicate that the limonite in the Mesabi ore bodies may owe its position partly at least to original variations in the composition of the beds, as well as to the position with reference to the surface waters. It is seen, page 363, that the limonitic ores are frequently aluminous, and therefore they probably represent beds containing more than the usual amount of shaly material.

Another feature of interest is the constant association of limonitic ores with high percentages of phosphorus. This is well recognized by the mining men of the area. This common association has a bearing on the derivation and alteration of the ore deposits. It might mean that phosphorus was more abundant in the original beds from which the limonite has been derived; or, if no more abundant than in other parts of the formation, that the phosphorus has not been removed to the same extent, since in some cases the limonitic ores are less pervious, due to their content of shale; or it might mean that the conditions which resulted in the development of limonite were favorable also to the precipitation of phosphorus. This latter probability is indicated, for a part of the limonite at least, by an occurrence in the Oliver mine, where in one place a zone of limonite was, in 1900, to be seen cutting across the layers of hematite like a vein with sharp outlines. The differences of percentages of phosphorus just within the limonite and a few inches outside of it were very great.

The amount of pore space in the Mesabi ores due to chemical alteration and fracturing is shown by the figures used by the mining men in estimating tonnage. They allow 11½ to 13 cubic feet for a ton, depending upon whether the ore is mainly limonite or mainly hematite. The tonnage of hard specular ore is figured on the basis of 8 or 9 cubic feet to the ton. The space occupied by a ton of the Mesabi ore is thus great as compared with the space occupied by hard specular ore.

Kinds of rocks associated with the ore.—The ores, so far as they are now exploited, are in general in middle horizons of the Biwabik formation, though there are exceptions to this rule. Below the ore bodies drill work at numerous localities shows that a hard ferruginous chert exists (variety 1 above). Above the horizon at which the ore bodies occur are apparently similar ferruginous cherts and smaller quantities of carbonated and ferrous silicate rocks of the formation (variety 3 above), and particularly near the junction with the upper slate, slaty layers (variety 4). As already shown, slaty layers also appear in the horizon holding the iron ores. These slaty rocks at high horizons have a somewhat broad and irregular bedding. Frequently, when examined with a lens, they show numerous peculiar roundish greenish granules, giving a texture when altered resembling an oolitic texture. The nature of these granules has as yet not been fully studied by us. They are called glauconite by Spurr, but analyses by Steiger show that the material contains no alkalies, and therefore is not glauconite. It is a ferrous silicate. A portion of the rocks of the central horizon, that in which the ore exists, appears to consist of the altered equivalent of these ferrous silicate rocks. But also at various places associated with the ores are considerable quantities of very evenly banded rocks, ferruginous cherts, and ferruginous slates, the structures and textures of which are identical with the carbonated slates of the Penokee-Gogebic and Marquette districts.[1] While these rocks to some extent show the little oolitic granules, they are not prominent. In what respects the composition and texture of the nonproductive horizons below the ores differ from those in which the ores occur and from the rocks of the Biwabik formation above the ores has as yet not been ascertained.

At the bottoms of several of the larger mines are layers of paint-rock, sometimes associated with beds of considerable thickness of lean limonitic ores. The limonitic ores are frequently high in aluminum, and therefore the original rock contained a considerable amount of argillaceous material. The paint-rock is plainly an altered slaty phase of the Biwabik formation. The paint-rock may be a single fairly persistent layer from a fraction of an inch to 2 or 3 inches wide, or several or many thin layers through a zone of a few feet. The belts of argillaceous ore and paint-rock together constitute a relatively impervious basement. In other mines no limonitic ore and paint-rock are reported at the bottoms of the ore deposits, the ore appearing to rest upon a massive phase of the ferruginous chert. In such cases it may be that at some horizon below the ferruginous chert are impervious layers or beds. Such impervious strata may be within the iron-bearing formation itself or may be the Pokegama slate below the Biwabik formation. If the Biwabik formation below the ore body is in places exceptionally dense and cherty, such a combination of chert with an impervious stratum below would as certainly stop the downward course of the major part of the moving water as would a belt of aluminous slaty material immediately below an ore body.

At many places near the top horizon of the ore bodies and at some places interstratified with them are also layers of lean limonitic ores rich in aluminum. From the composition one would infer that these also were probably somewhat slaty phases of the iron-bearing formation, and, in fact, in some cases these ores have actually been traced into slate by J. U. Sebenius. The existence of these relatively

[1] See Pls. XVII and XIX of Mon. XXVIII of the U. S. Geol. Survey.

impervious strata at middle and higher horizons in the ore deposits has not prevented the concentration of the ores upon an impervious basement lower down. The development of the iron ores upon the impervious strata at different horizons is precisely analogous to the development of the iron ores upon dikes at different horizons in the Penokee-Gogebic district. In both cases the best ore deposits developed at the bottoms of thick belts of iron-formation material which are bottomed by relatively impervious strata.

Origin of the ore deposits.—The Mesabi district is the only one in that part of the Lake Superior region within the United States in which our detailed studies of the iron-bearing formation have not been completed. At the present time it is not possible to make as definite statements concerning the development of the ores as is desirable. However, our studies have gone far enough to justify certain conclusions. It is clear that pitching troughs underlain by slaty or other impervious layers of the Biwabik or other formations are below every ore deposit. It is equally clear that the brecciation of the formation accompanies the cross folding. These troughs do now, as in the past, serve as trunk channels for the circulation of underground water. In the unaltered parts of the iron-bearing formation we find ferrous silicate and siderite rocks, and in the altered parts textures and structures indicating the former existence of these rocks. Such rocks contain iron in a form favorable for its easy oxidation or solution by underground water.

All of these facts point to one explanation of the origin of the ore deposits. They are mainly secondary concentrations in pitching troughs with impervious basements by downward moving waters, and subordinately oxidations in place. The process is the one outlined below. Iron from carbonate and silicate, taken into solution by the descending waters, was carried to the pitching troughs, and there met other waters bearing oxygen more directly from the surface, resulting in the precipitation of the ore. The solution of the silica was a simultaneous process and was favored by the large quantities of water concentrated in these troughs. The ores are very porous, and, as already noted, they show decided indication of slump. This seems to be conclusive evidence that the silica has been dissolved more rapidly than the iron oxide was put into its place. While the chemical action had thus emphasized the synclines, there is no question that the trunk channels of underground water were localized by original synclines.

The meteoric waters, entering the pervious iron-bearing formation at the higher northern ground, followed the troughs transverse to the range down the general slope, and mainly issued on the low ground before passing below the impervious slate. The higher geological horizons of the Biwabik—i. e., the horizons near the overlying slates—were not in general transformed to ore deposits. When the ore deposits do approach the slate they are usually found to grow lean and thin. These were the places where the waters were ascending and issuing, and such waters were deficient in oxygen, and hence the circulations were not favorable for the development of large ore deposits of good quality.

The waters were confined below by impervious strata, probably mainly slates, at different horizons, although principally in horizons some little distance above the bottom of the formation. In some cases, as shown above, the presence of slaty layers has not prevented the concentration of ores upon an impervious basement lower down, since between the outcrops of two sets of relatively impervious strata there is a broad area where meteoric waters may enter. However, in most cases there is a considerable thickness of apparently barren iron-formation material below the iron-ore deposits, and the question arises why ore deposits have not been concentrated in these horizons either on impervious strata in the lower parts of the formation or on the underlying Pokegama quartzite. In the Penokee-Gogebic district all the ore deposits, with the exception of the Iron Belt and Atlantic, are at the bottom of the Ironwood formation and rest upon the Palms formation, and one might anticipate that the same condition of affairs would obtain in the Mesabi district, and that the ores would rest on the Pokegama formation. If such deposits had formed, they would pitch under most of the deposits now known, precisely as the deposit of one dike in the Penokee-Gogebic district pitches below the deposit upon a higher dike. The apparent absence of large ore deposits at the bottom horizon in the iron-bearing formations in the Mesabi district is probably explained in most cases by the fact that the part of the iron-bearing formation below the impervious layer, whether this layer be slate or impervious chert, was not sufficiently thick to furnish material out of which such ore bodies could develop. In some cases, however, it may be ascertained that the lower part of the Biwabik formation was originally of a different and somewhat less favorable character than the rocks rich in iron carbonate and ferrous silicate out of which the ore deposits developed.

The irregularities in the bottoms of the ore deposits above mentioned are probably due largely to the concentration of water in synclines, causing deeper penetration at the centers than toward the sides of the troughs. Thus at the centers of the troughs the water got down to impervious strata. But other factors probably have had their effect. The horses of rock commonly to be observed have a tendency to show flat joint sides and are not broken into little bits by numberless minute joints. It seems probable that the very numerous small joints which may be observed in the iron ores have had a considerable effect on the circulation of underground water, causing the waters to be deflected from certain places and concentrated in others, and thus causing differences in the amount of alteration in the original rock. The result is that in places where the fracturing is not complex the circulation of water has not been vigorous and horses of rock are left standing. Another factor explaining the irregular bottoms of the ore deposits may have been the original character of the rock. Where the original rocks varied, the alteration products now to be observed would vary in a corresponding manner.

Time of concentration.—As to the time of concentration, the same argument applies as in the Penokee-Gogebic district. The processes which formed the ore bodies were those of the belt of weathering. They therefore could not have begun to form until denudation had exposed the Biwabik formation to the action of the weather. The enrichment therefore occurred subsequent to the general folding which produced the Lake Superior syncline and subsequent to the long-continued erosion which removed the overlying Keweenawan, and after the iron-bearing formation was exposed to the agencies of weathering. The major part of the work was probably done before Upper Cretaceous time, and certainly in pre-Pleistocene time, but no exact limitations of the period of enrichment can be given. As in the Penokee-Gogebic district, the rich ores doubtless represent a concentration of iron, a large part of which at one time was at a higher position in the iron-bearing formation and the strata of which have been removed by the processes of denudation.

Depth of deposits.—The Mesabi district is new, and the depth to which the ore bodies have been opened up is not great. In June, 1900, the depths of the lowest levels of some of the mines were as follows:

	Feet.		Feet.
Adams	175	Hull	157
Burt	97	Rust	170
Duluth	92	Sellers	120

In November, 1900, further figures obtained from other mines are as follows:

	Feet.		Feet.
Biwabik	110	Auburn	213
Mahoning[1]	40–55	Genoa	175
Sparta	125	Fayal	170
Malta	110	Mountain Iron	150

These figures are for the most part measured from the surface of the drift.

While few of the mines have reached the bottom of the deposits, exploratory work shows beyond question that in most cases the ore deposits extend to no great vertical depths. In many cases the bottoms of the rich parts of the deposits are at depths less than 200 feet, and few deposits extend to a depth as great as 300 feet. It is clear that the Mesabi ore deposits are shallow as compared with

[1] Average depth 48 feet.

those of the other iron-bearing districts of the Lake Superior region. This is due to the very gentle pitch of the deposits as compared with the steep pitches of the deposits in the other districts. However, it must not be understood from this that the quantity of ore in the Mesabi district is less than that in the other districts, for the shallowness of the deposits is much more than compensated for by their extraordinary breadth and length. Probably the famous T. 58 N., R. 20 W., Minnesota, contains more high-grade iron ore than any other equivalent area in the Lake Superior region, and the Mesabi district as a whole has vastly more ore shown up than any other Lake Superior district.

Ease of mining Mesabi ore.—With the shallowness of the deposits and their great length and breadth goes ease of exploration and mining, giving the Mesabi district a considerable advantage in this respect over other districts. The common method in the district of stripping off the drift and loading the ore directly from the deposit onto the cars by steam shovels has been fully described by a number of mining engineers. The large open pits of the district, with trains threading in and out and steam shovels loading from the banks to the trains, are most characteristic sights in the district. The cheapness of the method as compared with that of underground mining is obvious. However, while this method is the most conspicuous one, there are many deposits to which it can not be applied, and as many or more mines are operated by underground as by open-pit work.

THE MARQUETTE DISTRICT.[1]

PRODUCTION.

The production in the Marquette district from 1891 to 1900, inclusive, was as follows:

Production in Marquette district from 1891 to 1900.

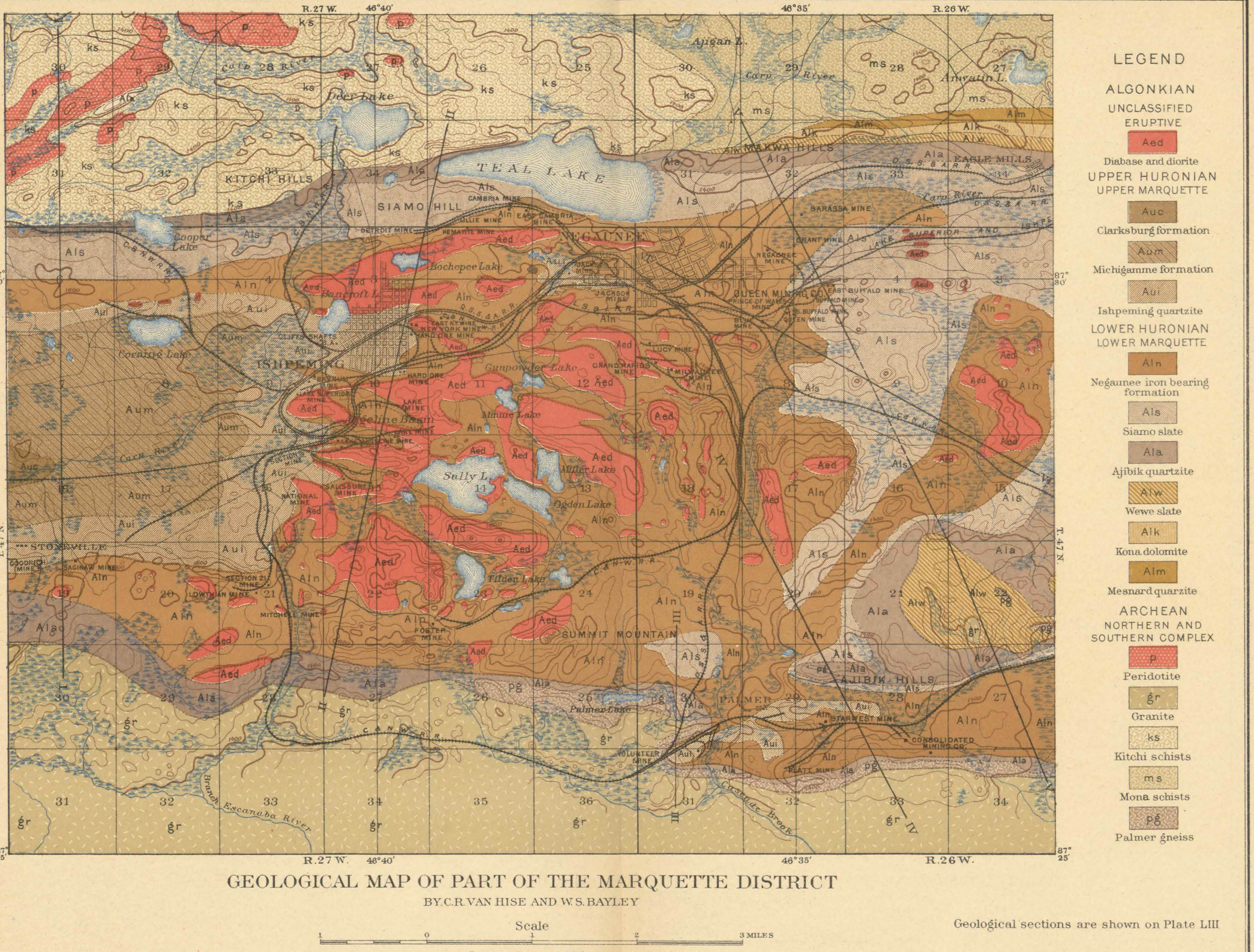
	Long tons.		Long tons.
1891	2,778,482	1896	2,418,846
1892	2,848,552	1897	2,673,785
1893	2,064,827	1898	2,987,930
1894	1,935,379	1899	3,634,596
1895	1,982,080	1900	3,457,522

The total production of the district from 1854, the first year of shipment, to 1900, inclusive, was 59,592,793 long tons.

CHARACTER OF THE ORES.

The iron ores of the Marquette district are mainly soft red hematites. Hard specular hematites are, however, important. Magnetite

[1] For a full discussion of this district, see The Marquette iron-bearing district of Michigan, by C. R. Van Hise, W. S. Bayley, and H. L. Smyth: Mon. U. S. Geol. Survey Vol. XXVIII, 1897.



GEOLOGICAL MAP OF PART OF THE MARQUETTE DISTRICT

BY C. R. VAN HISE AND W. S. BAYLEY

Geological sections are shown on Plate LIII

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and limonite are subordinate. The iron content computed from cargo analyses during 1899 varies from 39.985 to 69 per cent, and averages about 63 per cent. The phosphorus content varies from 0.016 to 0.610 per cent, and averages about 0.083 per cent. The silica content varies from 1.30 to 38.27 per cent, and averages about 4.8 per cent. The water content varies from 0.45 to 15.29 per cent, and averages about 5.40 per cent.

LOCATION.

The Marquette district is a comparatively small east-west belt running from about longitude 87° 20′ to 88° along the parallel of 46° 30′. The district lies wholly in the State of Michigan, and gets its name from the city of Marquette. The more important towns are Marquette, Ishpeming, Negaunee, Champion, and Republic. (See Pl. LII.)

SUCCESSION OF FORMATIONS.

The succession of the formations for the district from the top downward is as follows:

Succession of formations in Marquette district.

Cambrian	Lake Superior sandstone.
(Unconformity.)	
Upper Huronian (Upper Marquette series).	Michigamme formation (locally replaced by Clarksburg volcanic formation). One might divide the Michigamme sedimentary formation into three parts; (*a*) upper slate member, (*b*) iron-bearing member, (*c*) lower slate member. Ishpeming formation, consisting of two members; the Bijiki schist (in western part of district), and the Goodrich quartzite, containing detrital ores at its base.
(Unconformity.)	
Lower Huronian (Lower Marquette series).	Negaunee formation. (The chief iron-bearing formation.) Siamo slate, containing interstratified amygdaloid. Ajibik quartzite. Wewe slate. Kona dolomite. Mesnard quartzite.
(Unconformity.)	
Archean	Granite, syenite, peridotite. Kitchi schist and Mona schist, the latter banded, and in a few places containing narrow bands of iron-bearing formation. Palmer gneiss.

Various basic igneous rocks, mostly altered dolerites and having the mineralogical composition of diorite, cut the sedimentary formations.

STRUCTURE.

In a broad way the Marquette district is a great synclinorium. At the west end of the area the Republic tongue projects to the southeast as a subordinate synclinorium. The district is cross folded in a composite way, so that the distribution of the formations of the district is exceedingly irregular. (See Pl. LII.) A cross anticline in the eastern part of the district gives a westward pitch to the various formations in the most productive part. The sections of Pl. LIII give the essential facts. For a full discussion of the structures reference is made to Monograph XXVIII of the Survey.

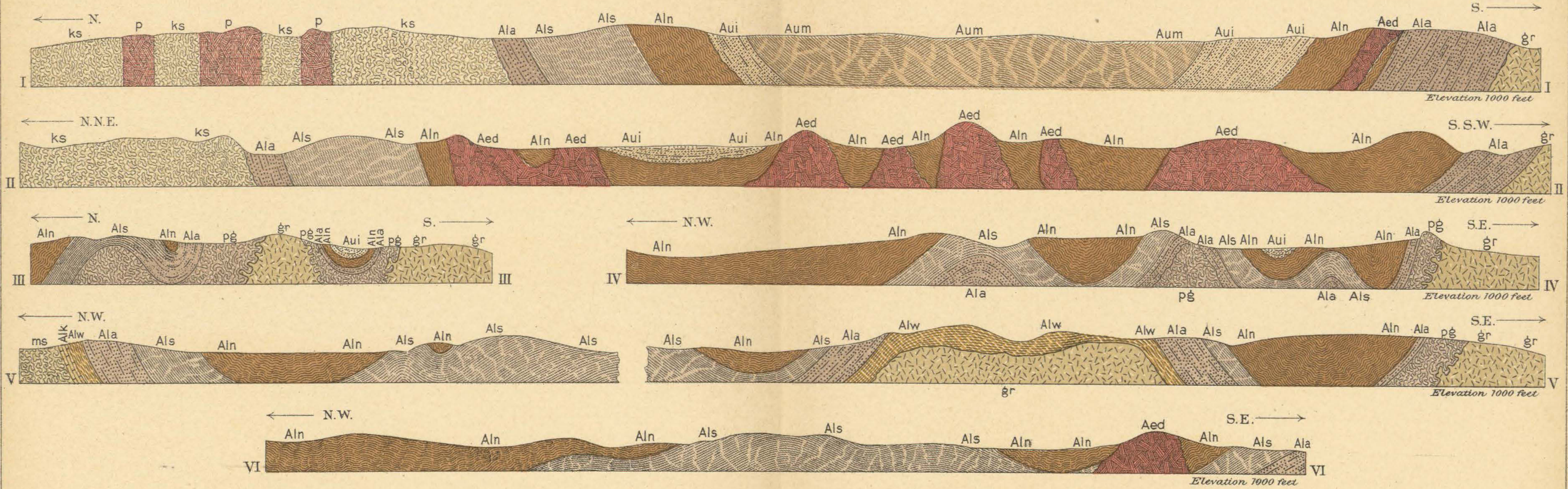
The iron-bearing formations of the Marquette district occur at all four of the positions at which ores are known in the Lake Superior region; viz, from the base upward, as follows: the Archean iron-bearing formation; the Negaunee formation of the Lower Huronian; and two iron-bearing horizons in the Upper Huronian, one at the base of the Goodrich quartzite and the other within the Michigamme formation.

The Archean iron-bearing formation so far as known is confined to a few localities, the more important being Marquette, the so-called Holyoke mine, and sec. 2, T. 48 N., R. 27 W. The materials comprise ferruginous slate, ferruginous chert, magnetite-grünerite-schist, and very small amounts of hematite. The only one of these localities which has ever produced iron ore is the Eureka mine in the Marquette area, and this has not produced ore for many years. Economically the Archean formation therefore has no importance in the Marquette district, and will here not be further considered; but from a scientific point of view the formation is significant, since it furnishes a parallel to the productive Archean of the Vermilion and Michipicoten districts.

NEGAUNEE AND GOODRICH FORMATIONS.

Extent, position, thickness, and character.—The chief iron-bearing formation of the Marquette district is the Negaunee. This covers an extensive area in the neighborhood of Ishpeming and Negaunee. (See Pl. LII.) From this area various short arms extend toward the east, and two arms extend westward to the west end of the district along both the north and south borders, and along the borders of the subordinate Republic fold.

The Negaunee iron-bearing formation at its maximum is somewhere from 1,000 to 1,500 feet thick. It bears ores at various horizons. Ores also occur at various places at the basal horizon of the Goodrich quartzite, where it rests upon and has derived débris from the Negaunee formation. However, these two horizons will be treated together. Small quantities of ore are also found in the Michigamme formation at various places. The rocks of the iron-bearing formations comprise



LEGEND

ALGONKIAN

ERUPTIVE	UPPER HURONIAN — UPPER MARQUETTE		LOWER HURONIAN — LOWER MARQUETTE				
Aed	Aui	Aum	Alk	Alw	Ala	Als	Aln
Diabase or diorite	Ishpeming formation	Michigamme slate	Kona dolomite	Wewe slate	Ajibik quartzite	Siamo slate	Negaunee iron-bearing formation

ARCHEAN

NORTHERN AND SOUTHERN COMPLEX

pg	ms	ks	gr	p
Palmer gneiss	Mona schist	Kitchi schist	Granite	Peridotite

GEOLOGICAL SECTIONS OF THE MARQUETTE DISTRICT

ON LINES I, II, III, IV, V, AND VI, PL. LII

BY C. R. VAN HISE AND W. S. BAYLEY

Horizontal Scale

1 ½ 0 1 MILE

Vertical Scale

1320 990 660 330 0 1320 2640 FEET

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cherty iron-bearing carbonates, ferruginous slates, ferruginous cherts, jaspilites, grüneritic magnetite-schists, detrital ferruginous rocks, and ore bodies.

The original rock of the Negaunee iron-bearing formation was a cherty iron-bearing carbonate, precisely as in the districts already described. Furthermore, at various places the iron carbonate approached very closely to a siderite. The metamorphism of the formation is less simple than in the districts already described, in that there have been two periods of alteration. In inter-Marquette time the erosion cut deep enough to expose the Negaunee formation. The upper part of this formation which was in the belt of weathering was largely transformed into ferruginous slates and ferruginous cherts. In early Upper Marquette time detrital material, largely derived from the Negaunee formation, accumulated, thus making a horizon at the base of the Upper Marquette series largely composed of iron oxide and quartz. Thereafter the original rock, the weathered products in situ, and the detrital material were buried under the Upper Marquette sediments and igneous rocks of that and Keweenawan time were intruded. While the rocks were deeply buried they were folded closely. Under these circumstances the original iron carbonate and the secondary material from it yielded very different products. Where original iron carbonate remained, and especially where it was intruded by abundant igneous rocks, it was partly transformed into a grünerite-magnetite-schist. The iron oxide of the ferruginous slates and ferruginous cherts was dehydrated, and these rocks were therefore changed to jaspilites. At the same time the detrital ores at the base of the Upper Marquette were transformed to hematite and jasper-bearing quartzites and conglomerates. Much later, but before Cambrian time, the region was again elevated above the sea and folded, and denudation cut through the Upper Marquette series and again exposed the Negaunee formation and adjacent rocks to the agents of weathering. A new set of transformations was then begun. Residual unaltered cherty iron carbonate was still abundant. Where this reached the surface it was transformed into ferruginous slates and cherts. The jaspilites and detrital ores also received a new contribution of iron oxide. It was at this period of alteration that the ore deposits were developed.

Structural relations of the ores.—Workable iron ores have been found at many places from east of Negaunee to Michigamme and Spurr on the northwest and to Republic on the southwest. In this respect the Marquette district differs from the Mesabi and Penokee districts, which have long stretches of iron-bearing formation which as yet have not been fruitful. It is notable in this connection that the basal Keweenawan gabbro is not found in the Marquette district, hence the deep-seated and profound metamorphism in connection therewith has not occurred. However, at various places intrusive igneous rocks are very abundant, and at such localities the iron formation is transformed into a grüneritic and magnetitic schist from which the circulating waters have not produced ore deposits.

The ore deposits of the Negaunee formation and the associated ores may be divided, according to position, into three classes: (1) Ore deposits at the bottom of the iron-bearing formation. (2) Ore deposits within the iron-bearing formation; these ores frequently reach the surface, but are not at the uppermost horizon of the formation. (3) Ore deposits in the top layers of the Negaunee formation and in bottom layers of the Goodrich quartzite. (Figs. 4 and 6 of Pl. LIV.) This last class of deposits runs past an unconformity. Some of these ore bodies are almost wholly in the Goodrich quartzite. Stratigraphically these deposits ought to be separately considered, but they are so closely connected genetically and in position with the Negaunee ore deposits that they are treated in connection with the deposits of that formation. The first two classes of ore are generally soft, and the adjacent rock is ferruginous chert or "soft-ore jasper," while those at the top of the iron-bearing formations are hard specular ores and magnetite, and the adjacent rock is jaspilite, also called "specular jasper" and "hard-ore jasper."

While the larger number of ore bodies can be referred to one or another of the three classes above given, it not infrequently happens that the same ore deposit belongs partly in one and partly in another. To illustrate: The inter-Marquette erosion may have cut so nearly through the Negaunee formation that an ore deposit may extend from the bottom of the formation to the top. However, in these cases the ore bodies are usually hard, and upon the whole are more closely allied to the third class than to the first. In many places, also, the upper part of an ore deposit may be at the topmost horizon of the iron-bearing formation and be a specular ore, while the lower part is wholly within the iron-bearing formation and is soft ore. In some places there is a gradation between the two phases of such a deposit, but in more instances the two bodies are separated by dikes, now changed to soapstone or paint-rock.

(1) The ore deposits at the bottom horizon (fig. 4 of Pl. LIV) can occur only where the lowest horizon of the formation is present—that is, they are confined to that part of the formation resting upon the Siamo slate or the Ajibik quartzite. Hence they are found along the outer borders of the Negaunee formation, and do not occur in the broad Ishpeming-Negaunee area. The best examples of these deposits are those occurring at the Teal Lake Range and east of Negaunee. Here are situated the Cleveland Hematite, the Cambria, the Buffalo, the Blue, and other mines. These ore deposits have as their foot wall the Siamo slate. A striking fact about these deposits is that all of

PLATE LIV.

PLATE LIV.

ORE DEPOSITS OF THE PENOKEE-GOGEBIC AND MARQUETTE DISTRICTS.

(Both ore exploited and ore now in mine are represented as ore, since the purpose of this plate is to show the manner of the development of the ore rather than the present stage of exploitation.)

FIG. 1. Vertical north-south cross section of Pittsburg and Lake Angeline mine in the Marquette district in trough of soapstone which grades downward into greenstone and upward into the ore-bearing formation.

Scale: 1 inch equals 210 feet. Mon. U. S. Geol. Survey Vol. XXVIII, Pl. XXVIII, fig. 5.

FIG. 2. Theoretical east-west longitudinal section in Penokee-Gogebic district designed to show manner in which ore deposits develop upon dike basements as a result of circulating waters. Below crests and the slopes of elevations the water moves downward, is concentrated near the dike and foot-wall quartzite, and there deposits the ore. Below the valleys the water ascends and escapes, and at these places no ore deposits are produced.

FIG. 3. Vertical north-south cross section of fig. 5, where ore deposit extends to the drift, showing that the basal synclinorium of slate consists of two subordinate synclines with an intermediate anticline.

Scale: 1 inch equals 210 feet. Mon. U. S. Geol. Survey Vol. XXVIII, Pl. XXIX, fig. 4.

FIG. 4. Generalized section in Marquette district, showing relations of all classes of ore deposits to associated formations. On the right is soft ore resting in a V-shaped trough between the Siamo slate and a dike of soapstone. In the lower central part of the figure the more common relations of soft ore to vertical and inclined dikes cutting the jasper are shown. The ore may rest upon an inclined dike, between two inclined dikes, and upon the upper of the two, or be on both sides of a nearly vertical dike. In the upper central part of the figure are seen the relations of the hard ore to the Negaunee formation and the Goodrich quartzite. At the left is soft ore resting in a trough of soapstone which grades downward into greenstone.

From Mon. U. S. Geol. Survey Vol. XXVIII, Pl. XXVIII, fig. 1.

FIG. 5. Vertical longitudinal east-west section of one of the mines of the Buffalo Mining Company, east of Negaunee, showing ore resting upon impervious foot wall of Siamo slate and pitching to the west under the ore-bearing formation, and grading into the latter through mixed ore. A large quantity of the ore extended to the drift.

Scale: 1 inch equals 210 feet. From Mon. U. S. Geol. Survey Vol. XXVIII, Pl. XXIX, fig. 3.

FIG. 6. Cross section of Section 16 mine, Lake Superior mines, in the Marquette district. On the right is a V-shaped trough made by the junction of a greenstone mass and a dike. The hard ore is beween these and below the Goodrich quartzite. On the left the hard ore again rests upon a soapstone which is upon and contains bands of ore-bearing formation. The ore is overlain by the Goodrich quartzite.

Scale: 1 inch equals 220 feet. Mon. U. S. Geol. Survey Vol. XXVIII, Pl. XXIX, fig. 1.

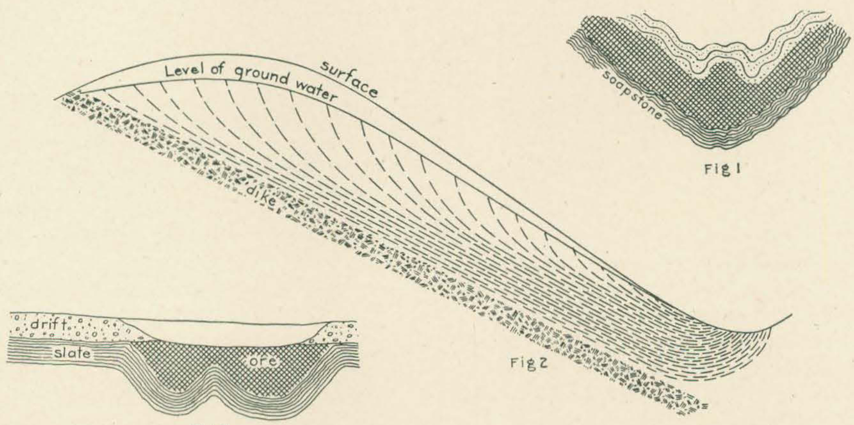


Fig 1

Fig 2

Fig 3

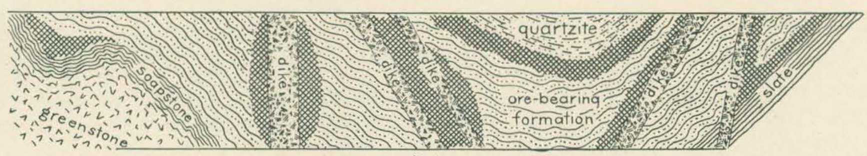


Fig 4

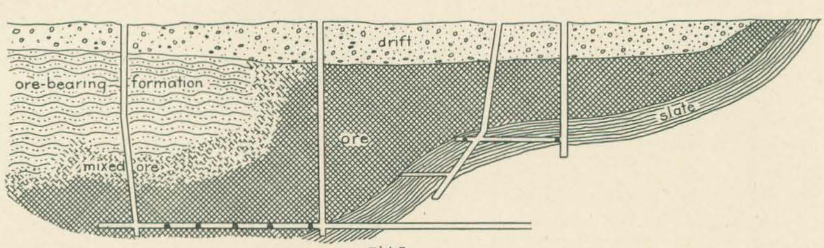


Fig 5

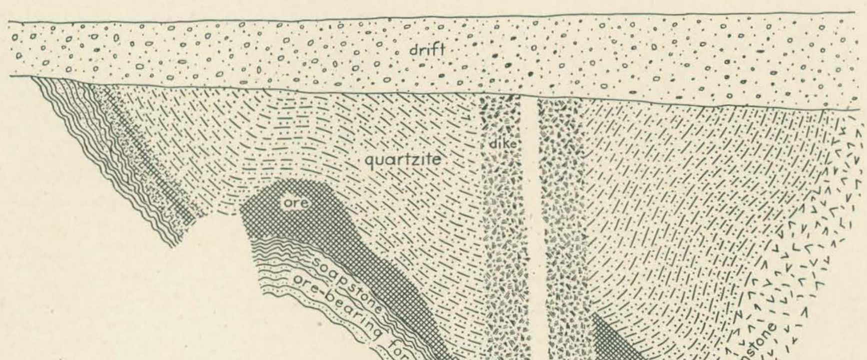


Fig 6

ORE DEPOSITS OF THE PENOKEE-GOGEBIC AND MARQUETTE DISTRICTS.

those mentioned, and all of those known, occur at places where the Siamo slate is folded so as to form a trough. All of the Teal Lake mines occupy a place where the iron formation curves to the north and then swings back to its original course, the ore deposits thus resting upon a southward-pitching trough of the slate. Still more striking is the occurrence east of Negaunee. Here the ore bodies occur at places where the slate is folded so as to furnish sharply pitching synclinal troughs which plunge to the west. (Figs. 3 and 5 of Pl. LIV.) It is further found, by an examination of the workings, that the iron-bearing formation is often cut by a set of steep or vertical dikes, and that the conjunction of these dikes with the foot-wall slate forms sharp V-shaped troughs. This is particularly clear in the case of the Cleveland Hematite mine, where the ore bodies are found between a series of vertical dikes and the Siamo slate.[1] By comparing this occurrence with the ore deposits of the Penokee-Gogebic district, it will be seen that they are almost identical, in each case there being on one side of each of the ore bodies an impervious sedimentary formation and upon the other an impervious dike, the two uniting to form a pitching trough.

(2) The typical area for the soft-ore bodies within the Negaunee formation is that of Ishpeming and Negaunee. Here belong such deposits as the Cleveland Lake, the Lake Angeline, the Lake Superior Hematite, the Salisbury, and many others. When these deposits are examined in detail it is found that the large deposits always rest upon a pitching trough composed wholly of a single mass of greenstone (Pl. LIII), or on a pitching trough one side of which is a mass of greenstone and the other side of which is a dike joining the greenstone mass (figs. 1 and 6 of Pl. LIV). The underlying rock is called greenstone, although immediately in contact with the ore it is known by the miners as paint-rock or soapstone. However, a close examination of numerous localities shows that the greenstone changes by minute gradations into the schistose soapstone, and this into the paint-rock, and that therefore these phases are merely parts of the greenstone which have been profoundly altered by mashing and leaching processes and strongly impregnated by iron oxide. Many of the thinner dikes are wholly changed to paint-rock or soapstone, or to the two combined. The larger number of these troughs are found along the western third of the Ishpeming-Negaunee area. By examining Pl. LII, the masses of greenstone may be seen partly inclosing several westward-opening bays, which are occupied by the iron-bearing formation. Conspicuous among these are the Ishpeming basin, the northern Lake Angeline basin, the southern Lake Angeline basin, and the Salisbury basin. In each of these cases the greenstone forms an amphitheater about the

[1] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 268–294.

rocks of the iron-bearing formation. Areas of iron formation open out to the west into the main area, and thus the troughs have a westward pitch. In the case of Lake Angeline, an east-west dike cuts across the basin south of the center, and this combined with the greenstone bluffs to the north and to the south forms two westward-pitching troughs. The northernmost of these has the greatest ore deposits of the Marquette district, containing many millions of tons of ore.

(3) The hard-ore bodies, mainly specular hematite, but in some deposits including much magnetite, occur, as has been said, at the top of the iron-bearing formation, immediately below and in the basal members of the Goodrich quartzite. (Figs. 4 and 6 of Pl. LIV.) As typical examples of mines of this class may be mentioned the Jackson mine, the Lake Superior Specular, the Volunteer, the Michigamme, the Riverside, the Champion, the Republic, and the Barnum. Also, as interesting deposits, giving the history of the ore, may be mentioned the Kloman and the Goodrich. In all of these deposits the associated rocks of the iron-bearing formation are jaspilite or grünerite-magnetite-schist, usually the former. These ore deposits, bridging two different geological series, can not be separated in description, for frequently they weld together the Upper Marquette Goodrich quartzite formation and the Lower Marquette Negaunee formation. As in the cases of (1) and (2), all of the large ore deposits belonging to this third class have at their bases soapstone or paint-rock. (Figs. 4 and 6 of Pl. LIV.) In those cases in which the soapstone is within the Negaunee formation it is a modified greenstone mass, or this in conjunction with a dike or dikes. Where the ore deposits are largely or mainly in the Goodrich quartzite the basement rock may again be a greenstone, but also it may be a layer of sedimentary slate belonging to the Goodrich quartzite. These different classes of rocks are, however, not discriminated by the miners, but are lumped together as soapstone or paint-rock. Also, as in the cases of (1) and (2), wherever the deposits are of any considerable size the basement rock is folded into the form of a pitching trough, or else, by a union of a mass of greenstone with a dike, or by a union of either one of these with a sedimentary slate, an impervious pitching trough is formed. Perhaps the most conspicuous example of this is at the Republic mine, but it is scarcely less evident in the other large deposits. However, a few small deposits of ore (chimneys and shoots) occur at the contact of the Negaunee and Ishpeming formations, where no soapstone has been found. As examples of ore deposits which are largely or wholly within the Upper Marquette may be mentioned the Volunteer, Michigamme, Champion, and Riverside. These are partly recomposed ores, and differ in appearance from the specular hematite or magnetite of the Lower Marquette in having a peculiar gray color and in containing small fragmental particles of quartz and complex fragmental pieces of jasper,

and frequently, also, sericite and chlorite are discovered with the microscope.

In any of these classes the deposits may be cut into a number of bodies by a combination of greenstone dikes or masses. A deposit which in one part of the mine is continuous, in another part of the mine, by a gradually projecting mass of greenstone which passes into a dike, may be cut into two deposits, and each of these may be again dissevered, so that the deposit may be cut up into a number of ore bodies separated by soapstone or paint-rock. In some cases the ore deposits have a somewhat regular form from level to level, but the shape of the deposits at the next lower level can never be certainly predicted from that of the level above. Horses of "jasper" may appear along the dikes or within an ore body at almost any place. The ore bodies grade above and at the sides into the jasper in a variable manner. As a result of the combination of these uncertain factors, most of the ore bodies have extraordinarily irregular and curious forms when examined in detail, although in general shape they conform to the above descriptions.

While these different classes of ore bodies have the distinctive features indicated above, they have important features in common. They are confined to the iron-bearing formations. They occur upon impervious basements in pitching troughs. The impervious basement may be a sedimentary or igneous rock, or a combination of the two. Where the ore deposits are of considerable size the plication and brecciation of the chert and jasper are usual phenomena. Frequently this shattering was concomitant with the folding into troughs or with the intrusion of the igneous rocks. When the passage of the ore bodies into the chert or jasper is examined in detail it is found that a siliceous band, if followed toward the ore, instead of remaining solid becomes porous and frequently contains considerable cavities. These places in the transition zone are lined with ore. In passing toward the ore deposit more and more of the silica is found to have been removed, and the ore has replaced it to a corresponding degree. An examination at many localities shows this transition from the banded ore and jasper to take place as a consequence of the removal of the silica and the substitution of iron oxide. In such instances the fine-grained part of the ore is often that of the original rock, while the coarser crystalline material is a secondary infiltration. It is not infrequently the case, however, that the ore deposits abruptly terminate along joint cracks or fractures.

Topographic relations of the ores.—The relations between the topography and the ore deposits are as clear in the Marquette district as in the Penokee-Gogebic and Mesabi districts. In general the portions of ore deposits which reach the surface are located on the middle or upper parts of slopes, although in some instances the ore deposits are entirely below low-lying areas; but in these instances the impervious basement material makes a surrounding amphitheater. Since Monograph XXVIII of the United States Geological Survey, on the Marquette district,[1] is accompanied by an atlas, to which the reader may refer, the relations of the topography and the deposits will be given for a number of the larger mines. (See also Pl. LII herewith.) Beginning at the west end of the district, the Michigamme and Spurr mines are on the southward slope of a bluff which rises to more than 1,700 feet at its highest points, and which descends to the level of Lake Michigamme, at an elevation of about 1,550 feet.[2] The Champion mine is located well up on the northward slope of a hill which rises to an elevation of 1,700 feet and descends to 1,550 feet. The Republic mine is located near the brow of a plateau-like area, the crest of which rises to an elevation of 1,700 feet. The elevation of the brow is about 1,600 feet. From the shafts of the mine a steep slope descends to Smith Bay, at an elevation of somewhat less than 1,500 feet.[3] About Ishpeming and Negaunee (see Pl. LII) the surfaces of a majority of the deposits are at about the 1,500-foot level. The valleys to the westward are mostly at about the 1,400-foot level. But the Jackson mine is located on a northward slope which descends into a glacial-filled valley only 40 to 60 feet below. About three sides of the majority of the ore deposits are amphitheaters of diorite which rise to altitudes of from 1,600 to 1,700 feet. Thus there are in this district collecting areas with impervious basements which converge abundant waters at the places where the iron-ore deposits reach the surface.[4] The mines at the base of the iron-bearing formation east of Negaunee are below the 1,400-foot contour and the drainage line to the southwest is only a little below the 1,300-foot level.[5] The Teal Lake mines are somewhat higher than 1,400 feet; but these mines actually dip to the south, while the drainage is to the north to Teal Lake. This is the only case in the district in which the pitch of the mines does not correspond with the drainage.

Development of the ores.—The facts given in the foregoing pages in reference to the iron-bearing formation and its origin, combined with the peculiar occurrence of the ores, indicate with certainty the main features of the development of the ore deposits.

While the ore deposits of the Negaunee formation have a greater variety of forms and relations than those of the Penokee district,[6] it is evident that the conditions governing their formation are much the same. In both districts the material immediately underlying the ore

[1] The Marquette iron-bearing district, by C. R. Van Hise and W. S. Bayley, with a chapter on the Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey Vol. XXVIII, 1897, pp. 608, with atlas of 39 plates.

[2] Op. cit., Atlas sheet V.

[3] Op. cit., Atlas sheet VI.

[4] Op. cit., Atlas sheets XXV, XXVI, and XXVIII.

[5] Op. cit., Atlas sheet XXXI.

[6] The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, pp. 280–290.

is relatively impervious to water. In the cases of the deposits resting upon soap-rock this lack of porosity is nearly complete. Most of the ore bodies are in troughs in both districts; the ore bodies in both, in longitudinal section, have a pitch; in both the many phases of material found in the iron-bearing formation are nearly the same; in both is found plenty of residual iron carbonate; in both the ore deposits are below elevations or slopes and pitch toward the valleys. It is therefore thought that the general explanation already applied to the Penokee district is applicable, with a few modifications, to the deposits of the Marquette district; although the larger number of the deposits of the latter belong to an older series.

All the facts bear toward the conclusion that the ore was secondarily enriched by the action of descending water, since the ore deposits occur at places where such waters are sure to have been concentrated. The greenstone and its altered form, soapstone, accommodated themselves to folding without extensive fractures, and, while probably allowing more or less water to pass through, acted as practically impervious masses along which water was deflected when it came in contact with them. It is a common opinion among miners that a few inches of soap-rock is more effective in keeping out water than many feet of the iron-bearing formation. On the other hand, the brittle, siliceous ore-bearing formation was fractured by the folding to which it was subjected, so that where this process was extreme water passes through it like a sieve. That the tilted bodies of greenstone, or soap-rock, especially when in pitching synclines or forming pitching troughs by the union of dikes and masses of greenstone, must have converged downward-flowing waters is self-evident. It is also clear that the weak contact plane between the Goodrich quartzite and the Negaunee formation was one of accommodation and shattering. Therefore, the plane of unconformity between the Upper Marquette and Lower Marquette series must have been a great horizon for descending waters.

It has been seen that the whole of the iron-bearing formation was probably originally a lean, cherty carbonate of iron, with some calcium and magnesium, and that from this rock the ferruginous cherts and jaspers developed. The general process of concentration described on pages 326–328 is therefore directly applicable. What proportion of the original iron carbonate still remained in the ore-bearing formation at the beginning of the concentration of the ore deposits is uncertain; but since it is still found in places sheltered from percolating waters, such as the deeper horizons of the iron-bearing formation, adjacent to and probably protected by greenstone masses, it is probable that the quantity was great. A part of the iron oxide of the ore bodies already existed in place before the post-Huronian erosion. This is especially true of the class 3, those at the top of the formation, where weathering decomposed the iron carbonate in inter-Marquette time, producing ferruginous slates and ferruginous cherts, and where detritus from these rocks was deposited at the base of the Upper Marquette series. This iron oxide in many cases is discriminated by its micaceous or specular character, caused by dynamic action and dehydration, from that subsequently added by infiltration.

At the time of enrichment the descending waters from different sources, some containing iron carbonate, some containing oxygen, were converged into pitching troughs or other trunk channels. The union of these currents precipitated the iron oxide mainly as more or less hydrated hematite; but where the oxygen of the oxygen-bearing waters was insufficient, as magnetite. The abundant waters in the trunk channels also slowly dissolved the silica, its place being taken by the ore. That this interchange actually has occurred has already been noted. (See p. 379.) For the solution of the silica the water in this district contained both carbon dioxide liberated by the decomposition of the iron carbonates and alkalies produced by the decomposition of the diabases when they were transformed into soap-rock.

The descending waters continued their work along the pitching ore bodies until they had passed below low ground. Here they began their ascent and escaped at the valleys. The difference in elevation of the entering and issuing waters in the Marquette district at the present time is upon the average not more than 100 feet, as shown by the figures given on page 380. However, it is to be remembered that the majority of the valleys are now filled with thick deposits of drift, and that the drainage lines in pre-Glacial times may have been on an average 100 feet lower than at present. The crests of the hills also may have been reduced an equal amount. This would give a difference in head between the entering and issuing waters of 300 feet, which is probably the maximum that can be assumed at the present time, although in pre-Pleistocene time the relief was more marked and in pre-Cambrian time far greater.

Time and depth of concentration.—The final concentration of the ores occurring at the contact of the Upper Marquette and Lower Marquette series must have taken place later than Upper Marquette time. This is shown by the fact that the unconformable formations are welded together at many places by the infiltrated iron oxide. The relations of the ore bodies within the ore-bearing formation to the greenstone masses and dikes give evidence that the concentration of this ore occurred subsequently to the intrusion of these rocks. It is certain that some of these igneous rocks were intruded during or later than Upper Marquette time, since they cut across the Goodrich quartzite. Others of them appear to have yielded fragments to the Upper Marquette series, and therefore antedate these rocks. Finally, if the hypothesis were accepted that the ore bodies were concentrated before the Upper Marquette folding and erosion, their invariable positions above the impervious formations would be inexplicable. The folding would perhaps have left them as often below as above these formations. The Upper Cambrian sandstone caps the eastern part of the district in places, and doubtless Paleozoic rocks once capped the entire district. Taking all the facts together, it is certain that the final concentration of all the ores occurred later than the folding and during the erosion subsequent to Upper Marquette time; it is probable that it had largely taken place before the end of the Paleozoic.

As given by the managers and superintendents, June, 1900, the lowest levels of some of the more important deeper mines are the following: Prince of Wales, 510 feet; Negaunee, 800 feet; Cleveland Hematite, 1,000 feet; Cambria, 706 feet; Lillie, 826 feet; Salisbury, 800 feet; Hard Ore Mine, 890 feet; Section 16 (Oliver Mining Company), 730 feet; Section 21 (Oliver Mining Company), 660 feet; Lake Angeline, 480 feet; Champion, 1,636 feet; Republic, 1,432 feet; No. 7 shaft (Oliver Mining Company), 885 feet.

From the foregoing figures it appears that, notwithstanding the fact that the difference in the head of the descending and ascending waters is not now great, the descending column of water carrying oxygen and ore locally certainly penetrated to a depth greater than 1,600 feet. But the difference in head of the descending and ascending waters may have been greater at the time these ore deposits were mainly formed than at present. (See p. 382.) However, making allowance for this, the depth to which the ores have formed in the Marquette district is strong evidence that descending water may be effective in the deposition of ores to a depth at least several times as great as the head which drives the entering waters. No clearer evidence could possibly be furnished of the correctness of the general theory of underground circulation expounded in the first chapter of this paper, on the deposition of ores.

MICHIGAMME FORMATION.

The fourth position at which ores occur in the Marquette district is in the Michigamme formation of the Upper Marquette series.

At a few localities in the Michigamme formation are found limonitic ores. These are associated with sideritic slates, ferruginous cherts, and grüneritic slates. The country rock is black carbonaceous and pyritiferous slate. The ore deposits in this slate appear to be small, and they have not been sufficiently developed to determine precise relations. However, in all probability they are derived from sideritic slate through processes of concentration similar to those which are applicable to the ores of the similar horizon in the Crystal Falls district, to be subsequently described. (See pp. 385-387.)

THE CRYSTAL FALLS IRON-BEARING DISTRICT, INCLUDING METROPOLITAN, COMMONWEALTH, FLORENCE, AND IRON RIVER AREAS.[1]

PRODUCTION.

The production in the Crystal Falls district, including the Metropolitan and Iron River areas in Michigan and the Commonwealth and Florence areas in Wisconsin, from 1890 to 1899 inclusive, was as follows:

Production in Crystal Falls district from 1890 to 1899.

	Long tons.		Long tons.
1890	1,048,746	1895	409,927
1891	766,257	1896	417,915
1892	1,059,073	1897	364,437
1893	463,851	1898	469,761
1894	247,512	1899	980,920

The figures for 1900 are included in the Menominee figures for that year.

The total production of the district from 1882, the first year of shipment, to 1899, inclusive, was 9,930,231 long tons.

CHARACTER OF THE ORES.

The ore obtained from the Crystal Falls district is chiefly a soft red hematite, although in places it is hydrated and graded as brown limonite. The metallic iron of the ores, calculated from cargo analyses of 1899, ranges from 54 to 63 per cent, and averages about 59 per cent. The phosphorus usually ranges from 0.049 to 0.7 per cent, averaging about 0.40. The silica ranges from 4 to 9 per cent and averages about 5.5 per cent. The water content varies from 3 to 9 per cent and averages about 7.5 per cent.

LOCATION.

The Crystal Falls district includes the broad area of Huronian rocks between latitude 45° 45′ and 46° 30′, and longitude 88° and 89°, with several eastward-projecting tongues between longitude 87° 30′ and 88°. It therefore comprises a broader area of Huronian rocks than any other of the districts of the Lake Superior region. The greater part of the district is in Michigan and the remainder is in Wisconsin. The chief towns of the district are Florence, Commonwealth, Mansfield, Crystal Falls, Amasa, and Iron River.

[1] For a full discussion of this district see the Crystal Falls iron-bearing district of Michigan, by J. Morgan Clements and H. L. Smyth; with a chapter on the Sturgeon River tongue, by W. S. Bayley, and an Introduction, by C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XXXVI, 1899.

SUCCESSION OF FORMATIONS.

The succession of formations in descending order is as follows:

Succession of formations in Crystal Falls district.

Cambrian	Lake Superior sandstone.
(Unconformity.)	
Upper Huronian	Michigamme formation, containing an iron-bearing horizon not separated in mapping for much of the district, but in southeastern part having as lower formations (*a*) the Groveland formation and (*b*) the Mansfield slate.
(Unconformity.)	
Lower Huronian	Hemlock formation. Negaunee formation (in northeastern part of the district). Randville dolomite. Sturgeon quartzite.
(Unconformity.)	
Archean	Granite.

Various gabbros, dolerites, and diorites are intrusive in the sedimentary formations.

STRUCTURE.

The structure of the district taken as a whole is very complicated and no attempt will be made to summarize it.

GROVELAND FORMATION.

From an economic point of view the district may be divided into two parts, a northern and a southern part. In the northern part of the district both the Lower Huronian Negaunee formation and the basal ferruginous horizon of the Upper Huronian occur. The iron-bearing formation within the Upper Huronian may also be present, but this is not certain. However, in this part of the district no workable ore bodies have been found. The productive part of the district is confined to the southern half—that is, to the area south of latitude 46° 15′. Here the only iron-bearing formation known is the Groveland, belonging within the Upper Huronian. This southern half may again be divided into two areas, an eastern and a western, which are separated by a broad area of Pleistocene deposits so thick that the underlying rocks can not be mapped.

In the eastern half of the southern portion of the district are two Huronian troughs, the Metropolitan trough on the south and the Sturgeon River trough to the north. The Metropolitan trough is about 1 mile wide. The descending Huronian succession is as follows: Groveland iron formation, Mansfield slate, Randville dolomite, and Sturgeon quartzite. The two lower formations are certainly Lower

Huronian; the upper formations were also placed as Lower Huronian in the Crystal Falls monograph. However, later work in the Menominee district makes it probable that the Mansfield slate is the base of the Upper Huronian, and that the Groveland formation belongs in the Upper Huronian. This iron-bearing formation is largely detrital. The detrital material is supposed to have been derived from a Lower Huronian iron-bearing formation, which has been wholly removed by erosion. The Sturgeon River trough is much wider than the Metropolitan trough. The Randville dolomite and the Sturgeon quartzite are there exposed, but the Pleistocene deposits hide all higher formations. Next above the Randville dolomite an ore formation was inferred, and recent exploration has shown that such a formation actually exists. Whether this iron-bearing formation is Negaunee or Groveland can not be stated at the present stage of the development of the trough.

In the western half of the southern portion of the Crystal Falls district the iron ores are confined to the Upper Huronian. They occur at various places, among which Florence, Commonwealth, Mansfield, Crystal Falls, Amasa, and Iron River are the more important. The ores are found in the Upper Huronian slate, either near or at a short distance above its base. The abundance of the glacial drift has prevented the ore-bearing rocks from being traced as a continuous formation in this district as in the Penokee-Gogebic and Mesabi districts, although they occur at essentially the same horizon. It appears that the ore-bearing formation in this district was somewhat localized. The nearest approach to continuity is that furnished by the row of mines north of Crystal Falls, running from the Claire mine, in sec. 19, to the Great Western mine, in sec. 21, a distance of about 2 miles.

The Groveland formation consists mainly of ferruginous slates and ferruginous cherts, with some cherty iron carbonate. These largely nonclastic sediments are, however, usually more or less intermingled with clastic, and especially argillaceous material. The slates immediately above and below the ore-bearing formation are usually carbonaceous.

In the area including Mansfield, Crystal Falls, and Amasa the Upper Huronian slates rest upon Lower Huronian greenstones—the Hemlock formation—so that in this part of the district it is easy to determine the base of the upper series. For this part of the area the Groveland formation occurs within the Upper Huronian slate at a short and somewhat variable distance from the volcanics, showing that the iron-bearing formation is a persistent horizon. The Mansfield is in a belt of slate adjacent to the Hemlock formation. But the relation is especially well illustrated in the vicinity of Crystal Falls. East of Crystal Falls the Hollister, Armenia, Lee Peck, and Hope mines follow along the western border of this same greenstone. Near Crystal Falls the various mines, including the Claire, Youngstown, Lamont, Paint River, Lincoln, Great Western, and Crystal Falls, are in a belt south of another Hemlock volcanic area. They are probably therefore at the same horizon as the mines east of Crystal Falls, although the folding is so complicated that this is not quite certain.

So far as the structural relations of the ores have been made out they indicate that they lie in pitching synclinal basins bottomed and capped by slate. In some places, as at Amasa, where the formations strike approximately north and south and dip steeply to the west, minor cross rolls furnish pitching troughs for the ore bodies. At Mansfield, while the structure is not certain, it is probable that there is a narrow, closely appressed synclinal trough. However, this can not be demonstrated until work has gone deep enough to find by what rock the ore is bottomed. The Crystal Falls area of mines is located in a complex synclinal basin, the anticlines being represented by the Hemlock volcanics. The local folds producing the mines in some cases are closely appressed, sharply pitching troughs, as for instance in the case of the Armenia mine. In some instances intrusive dikes may have helped to form the pitching troughs.

The iron ores at Commonwealth, Florence, and vicinity were the first to be discovered in this district. At Iron River and vicinity ore has been taken from various mines for a number of years. These ore deposits are very irregular in form. All of them lie in the Michigamme formation. In the vicinity of the mines the only formations aside from the iron-bearing formation are the Michigamme and some igneous rocks. One layer of the slate of the Michigamme formation looks like another, so that it is very difficult, if not impossible, to say at what horizon within the slate the ore bodies occur. But it is exceedingly probable that they are at substantially the same horizon as that in which the mines of Crystal Falls and vicinity are found. The structures of the deposits are uncertain; but doubtless when close investigations are made it will be found that these deposits, like the other deposits in the Upper Huronian slate, are in synclinal basins.

While the evidence is far from complete, there are many reasons for believing that the ores of the western area are secondary concentrates produced by descending waters converged into pitching troughs, the original source of material being iron carbonate.

THE MENOMINEE IRON-BEARING DISTRICT.[1]

PRODUCTION.

The production in the Menominee district from 1890 to 1899, inclusive, was as follows:

Production of Menominee district from 1890 to 1899.

	Long tons.		Long tons.
1890	1,225,446	1895	1,385,043
1891	1,089,867	1896	1,345,320
1892	1,343,122	1897	1,402,783
1893	1,099,198	1898	1,805,903
1894	1,007,743	1899	2,300,502

The figures for the Menominee district for 1900, not including the Crystal Falls district, are not available at this time. The figures for the Menominee and Crystal Falls districts, the latter probably but a small proportion, are 3,261,221 long tons.

The total production of the Menominee district since 1877, when mining began, to 1899, inclusive, was 20,809,906 long tons.

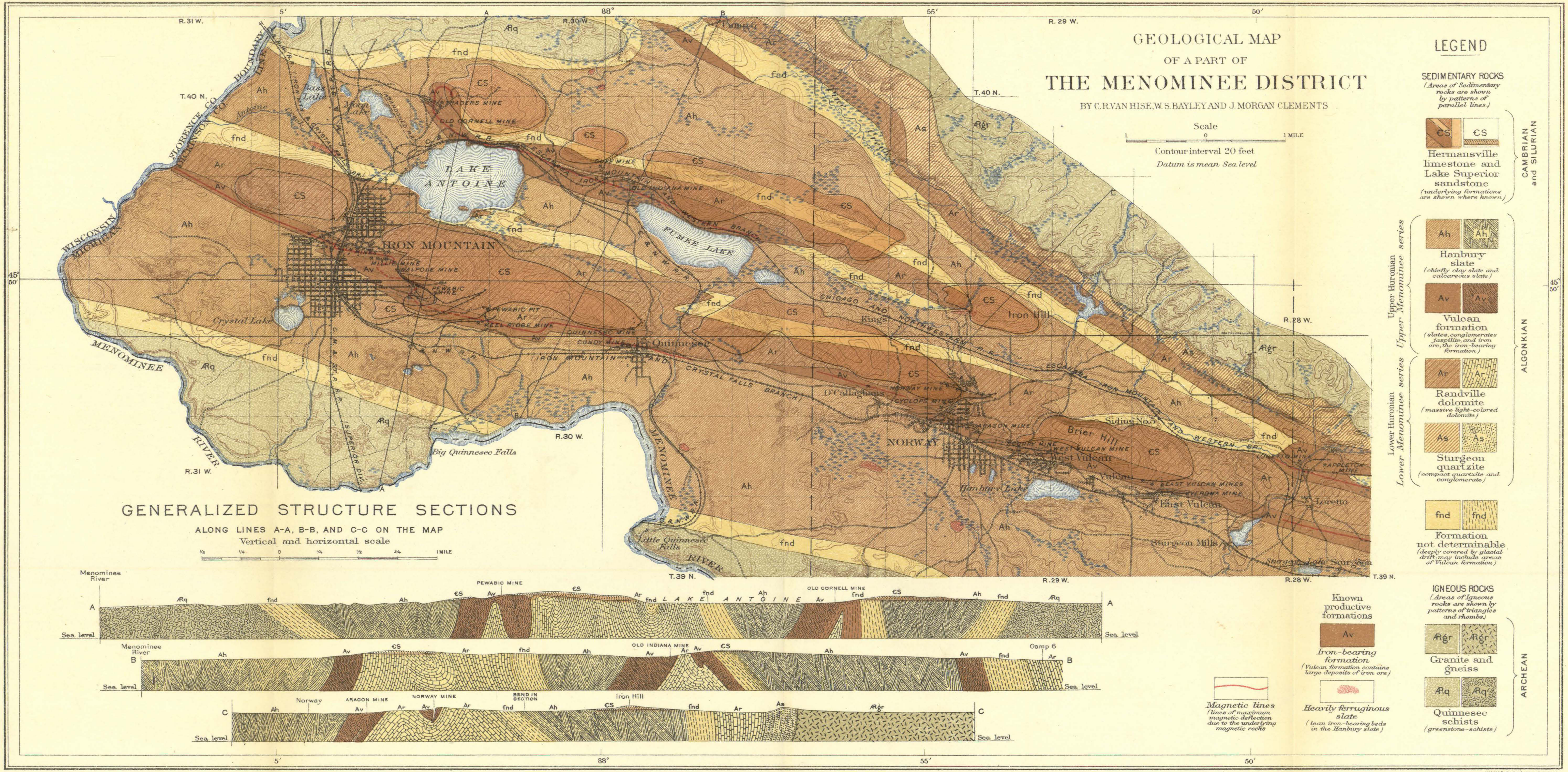
CHARACTER OF THE ORES.

The iron ores of the Menominee district are principally gray, finely banded hematite, and to a subordinate extent dense, flinty black hematites and siliceous, black and gray, banded hematites. The iron content, computed from cargo analyses during 1899, varies from 40.64 to 64.405 per cent, and averages about 56.6 per cent. The phosphorus content varies from .009 to .738 per cent, and averages about .083 per cent. The silica content varies from 2.97 to 39.10 per cent, and averages about 7.57 per cent. The water content varies from 2.18 to 11.20 per cent, and averages about 7 per cent.

LOCATION.

The Menominee district extends from the Menominee River in a direction about E. 60° to 70° S. It crosses longitude 89°, and lies between latitude 45° 45′ and 46°. The area which has been mapped is about 20 miles long and on an average about 6 miles broad. The Huronian belt has not been mapped farther to the east because it is capped by the Cambrian sandstone. It has not been mapped west of the Menominee River because of the overlying Pleistocene. The district considered lies wholly in Michigan. The more important towns of the area are Iron Mountain, Quinnesec, Norway, Vulcan, and Waucedah.

[1] For a rather full discussion of this district see Geologic Atlas U. S., folio 62, Menominee.



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SUCCESSION OF FORMATIONS.

[See Pl. LV.]

The succession of formations in descending order is as follows:

Succession of formations in Menominee district.

Silurian and Cambrian	Hermansville limestone. Lake Superior sandstone.
(Unconformity.)	
Upper Huronian (Upper Menominee series)	Hanbury slate, bearing in lower portions calcareous slates, etc., containing siderite and iron oxide. Vulcan formation, consisting in descending order of three members: (*a*) Curry member (iron bearing); (*b*) Brier slate; (*c*) Traders member (iron bearing).
(Unconformity.)	
Lower Huronian (Lower Menominee series)	Negaunee formation (in small patches). Randville dolomite. Sturgeon quartzite.
(Unconformity.)	
Archean	Granites and gneisses. Quinnesec schist.

The dolomites and quartzite of the Menominee district are given the same names as are similar formations in the Crystal Falls district because the formations have been traced almost continuously from one district to the other.

STRUCTURE.

The Menominee district, like the Marquette district, is a complex, cross-folded synclinorium. (See Pl. LV.) The longitudinal folding is exceedingly close, the dips being ordinarily from 60° to 90°, and in places overturned. The cross folding is also very sharp. The Huronian rocks lie between the Archean granite on the north and the Archean Quinnesec schists of the Menominee River on the south. The full succession of formations is found in passing south from the north side of the trough, the Archean, Sturgeon quartzite, Randville dolomite, Vulcan formation, and Hanbury slates appearing in proper order. However, farther to the south the Randville dolomite, the Vulcan formation, and the Hanbury slates are twice reduplicated. This is due to folds of sufficient magnitude to bring the dolomite to the surface at the anticlines, but not the lower formations. (See Pl. LV.) The three belts of dolomite are known as the northern, central, and southern. At the south side of the district the Hanbury slates are the rocks which are exposed closest to the Archean Quinnesec schists. Whether lower formations occur between the two is unknown. If the Hanbury slates rest upon the schists, the relation is explained by nondeposition of the lower formations or by removal by erosion of the Lower Menominee series in inter-Menominee time, or partly by both.

On account of the closeness of the folding the dips are steep. In consequence, the Vulcan formation has a narrow outcrop. The formation where productive rests upon the Randville dolomite and plunges below the Hanbury slates.

VULCAN FORMATION.

Extent, position, thickness, and character.—The only productive iron-bearing formation of the Menominee district is the Vulcan. One belt of this formation extends continuously from one end of the district to the other. There are several other belts of the formation, none of which is known to extend the entire length of the district. The Vulcan formation is the basal formation of the Upper Menominee series, and therefore rests upon the upper formation of the Lower Menominee series—the Randville dolomite. The Vulcan formation is composite. It consists of three members in ascending order, as follows: The Traders iron-bearing member, the Brier slate, and the Curry iron-bearing member.

The Traders member, resting upon the Randville dolomite, consists in very large part of ferruginous detrital material which is believed to have been derived from a Lower Huronian iron-bearing formation, the equivalent of the Negaunee formation of the Marquette district. This detrital horizon is comparable with the detrital iron-bearing horizon at the base of the Goodrich quartzite in the Marquette district. However, in the Menominee district the detritus is usually fine, while in the Marquette district it is usually coarse. This detrital material grades upward into the Brier slate, which is a somewhat ferruginous member, but not ore bearing. Overlying the Brier slate is the Curry member, which is believed to be largely of nondetrital character, but which contains some detrital iron oxide. This member is believed to be the equivalent of the Upper Huronian iron-bearing formations of the Penokee-Gogebic and Mesabi districts. All the members of the Vulcan formation are not known to occur at all localities.

The Randville dolomite of the Lower Menominee is a resistant formation, and apparently had a rough topography at the time it was encroached upon by the Upper Memoninee sea. It is therefore natural that this sea should not have overridden the dolomite everywhere at the same time. Consequently, during the time when the lower horizons of the iron-bearing formation were being deposited in certain parts of the district other parts were still land areas and were not overlapped until late in Vulcan time. In such areas only the Brier slate and the Curry member, or the latter alone, will be found. Not only is this true, but parts of the Randville dolomite were not overridden at all during Vulcan time, and in these areas the Hanbury slate rests directly upon the dolomite.

The lithological varieties of rock found in the district are the same as those found in the Marquette district; that is, they comprise cherty iron carbonates, ferruginous slates, ferruginous cherts, jaspilites, ore and jasper conglomerates, and ore bodies. The iron-bearing carbonate is, however, subordinate, and the detrital materials are relatively more important than in the Marquette district. The ores are mainly soft reddish, somewhat hydrated hematite. Considerable amounts of material are black and granular. Some specular ores are found, and some ores are slaty and conglomeratic.

It is estimated that the average thickness of the Vulcan formation is approximately 650 feet, divided as follows: Traders member, 150 feet; Brier slate, 330 feet; Curry member, 170 feet; i. e., the two ore-bearing members combined about equal in thickness the intervening slates. However, the Traders member departs considerably from this average, and the total thickness of the formation varies accordingly.

Structural relations of the ores.—The iron ores of the Menominee district occur in two members, from the base upward, as follows: (1) The Traders member of the Vulcan formation and (2) the Curry member of the Vulcan formation. The iron ores may occur at any horizon within these members. However, other things being equal, they are more likely to occur at lower and higher horizons than at middle horizons in each of the members, but a number of the large ore bodies extend entirely across the members in which they occur.

In the Menominee district, conforming to the general rule, the iron-ore deposits of large size occur on relatively impervious formations, which are in such positions as to constitute steeply pitching troughs. Several troughs have pitches as steep as 60° or 70°, and the pitches of some are nearly 80°. The pitching troughs are nearly parallel to the strike of the iron-bearing formations. A pitching trough may be made (*a*) by the dolomite formation underlying the Traders member of the Vulcan formation, (*b*) by a slate constituting the lower part of the Traders member, and (*c*) by the Brier slate between the Traders and Curry members of the Vulcan formation. The dolomite formation is especially likely to furnish an impervious basement where its upper horizon has been transformed into a talc-schist, as a consequence of folding and shearing between the formations.

The iron ores now being exploited are confined to three geographic belts: (1) The more numerous and important deposits are found in the belt of iron-bearing formation extending from Iron Mountain to Waucedah, south of the southern belt of dolomite. (2) Iron ores are being or have been worked north, south, and west of the central belt of dolomite. (3) Iron ores are being mined east of the locality where the northern and southern belts of dolomite unite.

(1) It has already been explained that the southern belt of dolomite is an anticlinorium. Superimposed upon this major fold are folds of higher orders. The occurrences of the ore deposits in the Vulcan

formation south of this belt of dolomite are closely related to the subordinate folds in the dolomite. The folds of the second order superimposed upon the major folds are very close. For the western part of the district, they plunge steeply to the west. The result of these plications is to produce a number of westward-pitching synclinal troughs. The troughs are underlain by the talc-schists, the upper horizon of the dolomite, or by a slate at or near the base of the Traders member. As the result of this folding, the surface outcrop of the southern boundary of the dolomite has a notched-liked distribution, producing bays in the dolomite (see Pl. LV). The iron-bearing formation occupies the bays which open to the west into the main belt of the Vulcan formation, each bay being surrounded on the north, south, and east by the dolomite.

Beginning at the west, the first and most important set of folds of the second order are those adjacent to Iron Mountain. Here are two important folds, superimposed upon which are folds of the third order. The western produces the troughs in which the Chapin, Millie, and Walpole mines are located. The eastern fold produces the trough in which the Pewabic mine is located. The western trough is especially complicated, it being really composed of two minor troughs or rolls of the third order, with an intervening anticline, and even these folds have folds of a higher order superimposed upon them.

The next important point to the east of the Pewabic mine, where ore is produced, is at Quinnesec. The Quinnesec ore body is probably in a somewhat narrow, closely appressed fold.

Another very important producing ore center is at Norway, where are found the Norway and Aragon mines. Here are two important folds in the dolomite, both opening out to the west as at Iron Mountain. The first gives the Norway mine and the second the Aragon mine.

The Aragon mine gives, perhaps, the clearest illustration of the principle of the formation of ore in pitching troughs on impervious basements furnished by the district. (See figs. 1 and 2, Pl. LVI.) Just east of the Aragon mine is a sharp embayment in the dolomite, which may be beautifully seen above ground. There is here an amphitheater of limestone entirely surrounding the low land occupied by the iron-bearing formation. A short distance to the west of this embayment the Aragon body was discovered. Where first found it was at the top of the Traders member of the Vulcan formation, just below the bottom of the Brier slate. At this time no one could have predicted that this ore body is really related to the impervious talc-schists of the dolomite below. However, as mining continued the ore deposit gradually and irregularly widened, and at the fifth level assumed definite relations to the dolomite. From the fifth level downward this relation has continued, the main mass of the ore body being found at the apex of the trough, and long arms of ore extending up along both limbs of the

PLATE LVI.

PLATE LVI.

ORE DEPOSITS OF THE MENOMINEE DISTRICT.

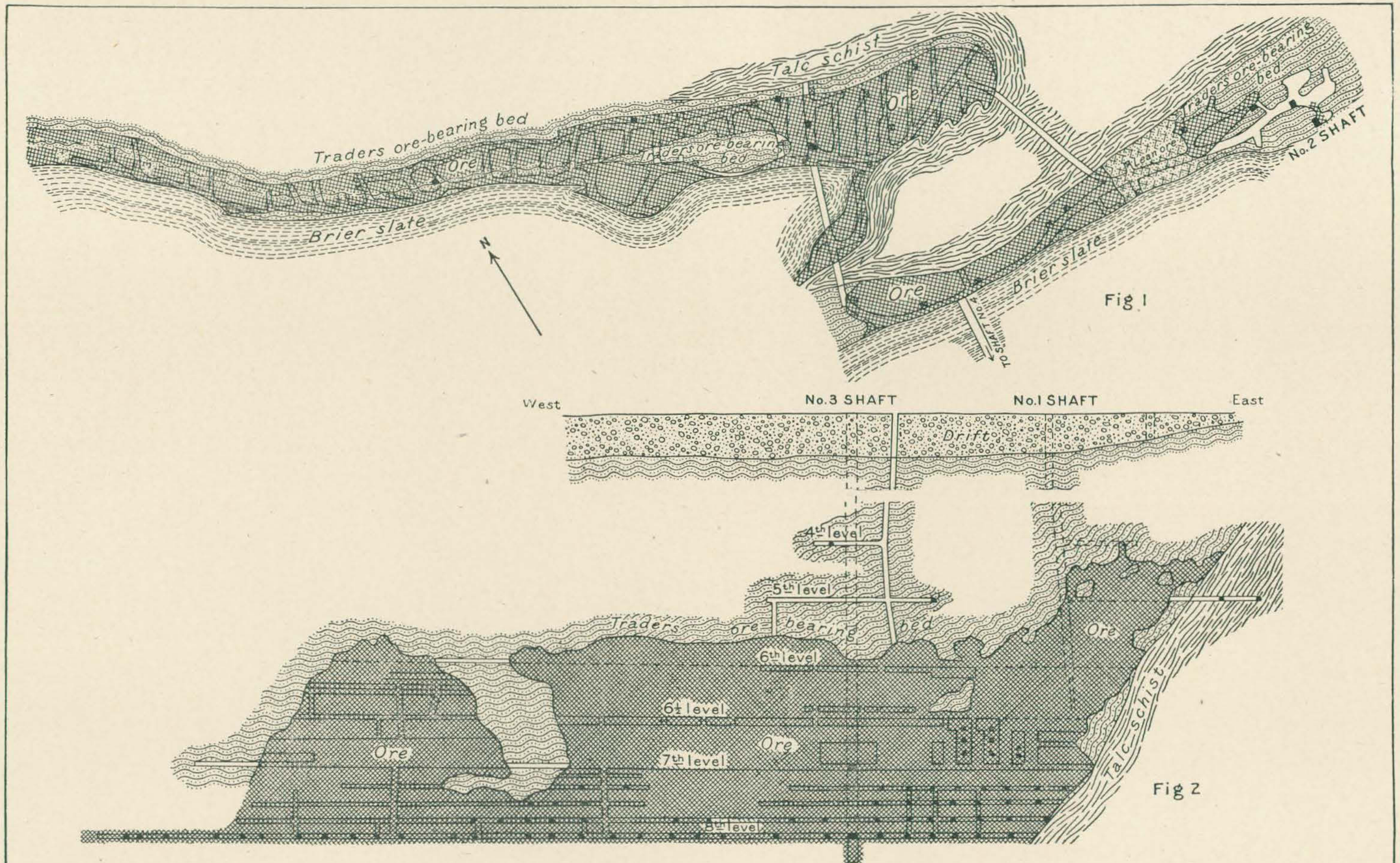
(Both ore exploited and ore now in mine are represented as ore, since the purpose of this plate is to show the manner of the development of the ore rather than the present stage of exploitation.)

FIG. 1. Horizontal section of the Aragon mine at the eighth level, showing the relations of the ore to the talc-schist horizon of the dolomite, to the ore-bearing formation, and to the Brier slate. There is here a double fold, the main ore deposit being at the bottom and along the limbs of the north syncline.

Scale: 1 inch equals 250 feet. Fig. 1, Menominee Special Folio, No. 62, 1900.

FIG. 2. Vertical east-west longitudinal section of the Aragon mine, north fold, showing even more clearly than fig. 1 the relations of the ore to the talc-schist and Traders ore-bearing formation. The very steep pitch of the ore deposit is notable, it being represented by the contact between the talc-schist and the ore-bearing formation and ore.

Scale: 1 inch equals 250 feet. Fig. 8, Menominee Special Folio.



ORE DEPOSITS OF THE MENOMINEE DISTRICT.

fold, but especially along the main dolomite wall to the north. (See Pl. LVI, fig. 1.) This occurrence is especially interesting since the ore deposit was found steadily to increase in size as it assumed definite relations to the underlying pitching trough. At the high levels, where it did not have a definite impervious basement furnished by the dolomite formation, it was comparatively small. As soon as it had assumed at lower levels definite relations to that trough it became a large ore body, and has continued to increase in size to the present depth, now reached at the eighth level, where the relations of the ore to the pitching trough are perfectly illustrated. (Figs. 1 and 2 of Pl. LVI.)

The next important groups of mines along the southern belt are those adjacent to Vulcan, including the Vulcan, East Vulcan, West Vulcan, and Curry. Here important plication of the dolomite is noted, and the occurrence of the ore is somewhat different from the deposits in the vicinity of Norway and Iron Mountain. Ore has been mined in both the Traders and the Curry members of the Vulcan formation. (See figs. 1 and 2 of Pl. LVII.) Indeed, it is from the Curry mine that the term Curry member is taken. The ore of the lower horizon now being exploited occurs immediately below the Brier slate, at the top of the Traders member. The ore of the higher horizon occurs in the Curry member, between the Brier slate and the Hanbury slate, extending from one to the other.

East of the East Vulcan mine no ore bodies have as yet been discovered except at Waucedah, where a comparatively small deposit of ore has been found.

(2) Passing now to the second belt of the Vulcan formation, that adjacent to the central belt of dolomite, the only mines which are producers at present are the Traders and Cuff. The Traders mine is near the west end of the ore-bearing formation, which in this vicinity constitutes a westward-plunging anticlinorium. However, there is a subordinate synclinorium in the anticline, as a result of which the Hanbury slate makes a plicated eastward reentrant angle. It is in this westward-pitching synclinorium that the concentration of the Traders ore has taken place.

(3) The only remaining important ore-producing locality is that adjacent to Loretto, where are found the Loretto mine (see Pl. LVII, figs. 3 and 4) and Appleton shaft. The structure adjacent to the Loretto is that of an eastward-plunging syncline, the dolomite and overlying Traders slate being to the north, to the south, and to the west. In every essential respect the structure is therefore the same as that where the large ore bodies occur in the southern iron belt, except that the fold at the Loretto is not close. No better illustration of an ore body in a trough on an impervious basement could be desired than that furnished by the Loretto mine.

Topographic relations of the ores.—The majority of the ore deposits of the Menominee district where they reach the surface are on the slopes of the elevations, the crests being usually occupied by the Randville dolomite or the Cambrian sandstone. This is true for all of the important mines of the district with the exception of the Chapin, the Aragon, and the Loretto. However, each of these deposits is so connected with troughs which rise toward the higher grounds as to make it almost certain that they had elevated feeding areas. Moreover, while the Chapin deposit was discovered in low-lying ground, a little way to the west is the broad valley of the Menominee River, which is still lower. Probably therefore there were lower areas where the water issued.

The crests of the elevations above the Ludington, Millie, Walpole, and Pewabic rise from 1,500 to 1,600 feet. The broad valley of the Menominee to the west has an elevation of less than 1,100 feet, and this valley is probably filled to the depth of 100 feet or more. Between Ludington Hill and Iron Mountain is a subordinate cross valley. In this valley is the Chapin, the surface of which has an elevation of only about 1,150 feet.

East of Iron Mountain it is notable that adjacent to each of the localities where important mines are found there are valleys across the south limestone range and the Vulcan formation, although these valleys are now partly filled with thick deposits of drift. East of the Quinnesec mine is the low-lying area occupied by a cross stream. Northeast of Norway is another transverse depression. The Norway mine is located upon the hill to the northwest. The West Vulcan mine is located upon Brier Hill, to the northeast. The Aragon mine is in the depression. East of the East Vulcan mine is the valley of the Sturgeon River. The Breen mine is on a slope with a cross valley immediately to the west. The Loretto mine pitches directly below the valley of the Sturgeon. Adjacent to the central range of dolomite the most important deposit is the Traders. This mine is on the westward slope of a hill which rises to an elevation of 1,500 feet. The ore deposit pitches toward the valley of the Menominee only a short distance to the west.

From the foregoing it appears probable that the relations of the ore deposits to the topography in the Menominee district are as definite as in the Penokee-Gogebic district; that is, all the important ore deposits were formed below slopes or crests.

Development of the ores.—Comparatively little need be said concerning the development of the ore deposits, since the Menominee district is merely a combination of the special features which occur in the Penokee-Gogebic and Marquette districts. A considerable portion of the iron-bearing members of the Vulcan formation are basal clastic deposits, probably derived from the Lower Menominee Negaunee for-

PLATE LVII.

PLATE LVII.

ORE DEPOSITS OF THE MENOMINEE DISTRICT.

(Both ore exploited and ore now in mine are represented as ore, since the purpose of this plate is to show the manner of the development of the ore rather than the present stage of exploitation.)

Fig. 1. Horizontal section of the West Vulcan mine at the eighth level, showing ore at and near the top of the Traders ore-bearing member in contact with the Brier slate, and ore between the Brier slate and the Hanbury slate.

Scale: 1 inch equals 250 feet. Fig. 9, Menominee Special Folio, No. 62, 1900.

Fig. 2. Vertical north-south cross section of the West Vulcan mine, showing the same relations as fig. 1. Here the complexity of the ore body below the Brier slate is shown. The two detached ore bodies as shown in the horizontal section are proved to be really connected. This body of ore is, therefore, essentially at the top horizon of the Traders ore-bearing member just below the contact with the Brier slate.

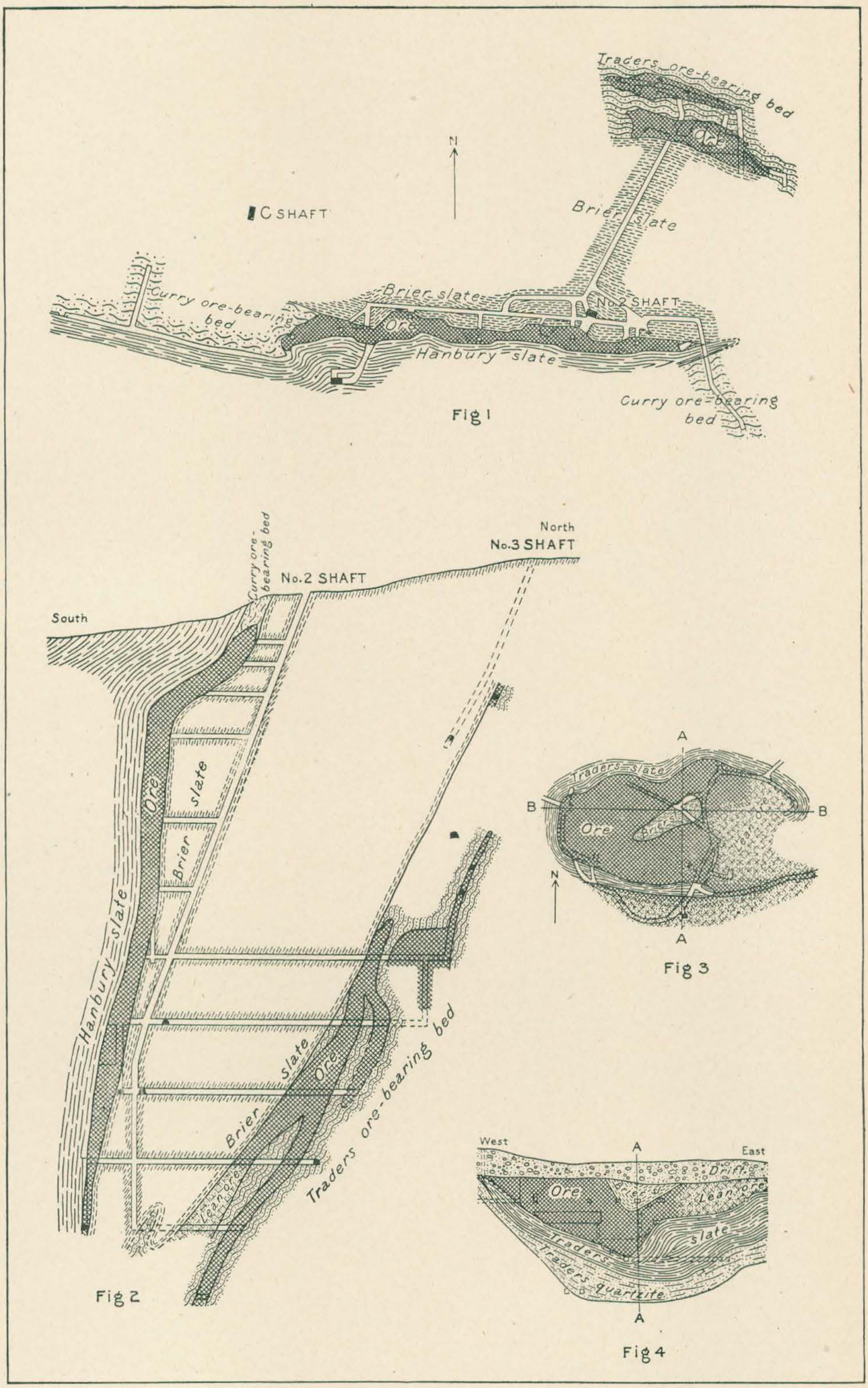
Scale: 1 inch equals 250 feet. Fig. 10, Menominee Special Folio.

Fig. 3. Horizontal section of the Loretto mine at the first level. The ore here rests upon the Traders slate, which constitutes a wide trough pitching to the east. As a result of this pitch the high-grade ore, which reaches the rock surface, to the east grades into lean ore and passes below lean iron-bearing formation.

Scale: 1 inch equals 250 feet. Fig. 11, Menominee Special Folio.

Fig. 4. Vertical east-west longitudinal section of the Loretto mine, showing same relations as fig. 3, and also that there is here a cross fold, thus forming a basin between the Traders slate and the Brier slate, which is largely filled with ore.

Scale: 1 inch equals 250 feet. Fig. 13, Menominee Special Folio.



ORE DEPOSITS OF THE MENOMINEE DISTRICT.

mation. With this material there was, of course, much quartz mingled. However, there is every reason to believe that much iron-bearing carbonate was mingled with this fragmental material. While the amount of residual iron-bearing carbonate in the Vulcan formation is now almost insignificant, oölitic cherts and jaspilites, which constitute a considerable portion of the formation, have doubtless been derived from iron-bearing carbonate, precisely as in the other districts of the Lake Superior region. Indeed, the processes of change are shown to some extent in the few specimens where iron carbonate is found. The amount of detrital ore material in the Traders member is important or dominant. The amount of carbonate in the Curry member was important, and possibly dominant.

While the iron-bearing carbonate within the Vulcan formation was somewhat abundant, we are not restricted to the Vulcan formation for a source of iron for ores. Iron-bearing carbonate and other rocks produced by its alteration exist in the overlying Hanbury formation. Moreover, these materials are more abundant at low horizons than at high horizons; that is, are more plentiful adjacent to the Vulcan formation. It is therefore probable that the water, to some extent at least, percolated through the Hanbury formation and made its way below into the Vulcan formation and carried with it iron carbonate. Therefore it can hardly be doubted that the source of the iron for the enrichment of the ore deposits of the Menominee district, as in other districts, was mainly a cherty iron carbonate. This material would be converged into the trunk troughs for the enrichment of the ore bodies. The ores therefore came from three sources: (1) original detrital iron oxide derived from the Negaunee formation, (2) iron carbonate oxidized in situ, and (3) iron carbonate contributed from higher levels of the Vulcan formation or from the overlying Hanbury formation.

The processes of concentration and circulation are very similar to those in the Penokee-Gogebic and Marquette districts. As has been seen, the pitch of the ore deposits is very steep, running as high as 60° or 70°; the pitch is parallel to the range; the outcrops of the formation are steep or vertical; the breadth of the iron-bearing formation exposed is not great. These facts show that the movement of the water was mainly parallel to the range, and that the water must have descended and ascended mainly through the broken iron formation. Moreover, since the ore deposits are below elevations the waters descended at these places and ascended in the cross valleys. However, the drift is so heavy in the Menominee district that the exact positions of the cross valleys are not always certain, but the great cross valley of the Menominee was doubtless the place at which the westward-moving waters concentrating the Traders, Pewabic, Walpole, Millie, Ludington, and probably the Chapin ascended and escaped. However, there is a possibility that in the subordinate cross valley occupied by the Chapin descending oxidizing waters met ascending carbonate-bearing waters, and thus precipitated a part of this great deposit. The cross valley at Norway is the place where the waters descending from the Norway mine to the west and the Vulcan and Curry mines to the east escaped. It is true that in the valley itself is the Aragon mine. This, however, has an amphitheater of higher ground immediately to the east, and there can be little doubt that before the filling of the cross valley there was a lower point for escape. Similar statements could be made in reference to the other mines of the district.

If the above explanation be correct, the apparent position of the great Aragon and Chapin deposits on low ground is explained by valley filling in Glacial times, the adjacent pre-Glacial valleys having probably been lower than the present level of the mines. If this explanation be correct, these great deposits are on the lower parts of the slopes; that is, at the places where descending waters have been converged from a wide variety of sources.

Time and depth of concentration.—The beginning of the final concentration of the Menominee ores must have been after the folding which produced the troughs and after the removal of the Hanbury formation covering the Vulcan formation; that is, in the interval between the Upper Huronian and the Cambrian. In the Menominee district it is certain that the process of concentration was carried far toward completion before the end of Cambrian time; for considerable areas of the Huronian rocks and certain of the ore bodies themselves, as, for instance, parts of the Pewabic and Cyclops deposits, are capped by the Upper Cambrian sandstone, at the base of which are detrital ores derived from the ore deposits below during the Cambrian transgression over the area. Certain it is that the entire Huronian formations were once capped by the Cambrian and Silurian rocks, and while in parts of the district erosion has since extended downward into the iron-bearing formation, the maximum amount is probably not so great as 200 or 300 feet. It is therefore highly probable that the main concentration of the iron of the deposits of the Menominee district took place before the end of the Cambrian period, although since that time there probably has been additional enrichment, mainly by the solution of silica and phosphorus, although some iron oxide has doubtless been added.

In June, 1900, the managers and superintendents gave the depths of the lower levels of some of the more important and deeper mines of the district as follows: Chapin, 840 feet; Pewabic, 720 feet; Aragon, 850 feet; Clifford, 160 feet; Currie, 1,175 feet; Norway, 900 feet; Millie, 600 feet; Loretto, 400 feet; Hamilton, 1,325 feet; Ludington, 1,225 feet.

THE VERMILION IRON-BEARING DISTRICT.

By C. R. Van Hise and J. Morgan Clements.

This section upon the Vermilion district is an advance statement of the economic results of an elaborate detailed survey of the district. The final report upon this district will be a monograph by the junior author, with a chapter upon the general geology by the senior author. The map herewith, Pl. LVIII, is based on work by J. Morgan Clements, W. S. Bayley, C. K. Leith, and myself. In the field work and in the preparation of the map Mr. Clements has taken the leading part. The map as here published is provisional and generalized; the maps accompanying the monograph will be of a much more detailed and accurate character.

PRODUCTION.

The production of the Vermilion district from 1891 to 1900, inclusive, was as follows:

Production of Vermilion district from 1891 to 1900.

	Long tons.		Long tons.
1891	945, 105	1896	1, 200, 907
1892	1, 226, 220	1897	1, 381, 278
1893	815, 735	1898	1, 125, 538
1894	1, 055, 229	1899	1, 643, 984
1895	1, 027, 103	1900	1, 655, 820

The total production of the district from 1884, the first year of shipment, to 1900, inclusive, has been 15,191,180 long tons.

CHARACTER OF THE ORES.

The iron ores of the Vermilion range are entirely hard blue and red hematites. The ore is partly massive and partly brecciated. The iron content, computed from cargo analyses during 1899, varies from 60.47 to 67.37 per cent, and averages about 63.7 per cent. The phosphorus content varies from 0.040 to 0.131 per cent, and averages about 0.057 per cent. The silica content varies from 2.55 to 7.67 per cent, and averages about 4.78 per cent. The water content varies from 1.04 to 7.956 per cent, and averages about 5.50 per cent.

LOCATION.

The Vermilion iron-bearing district of Minnesota occupies a broad belt running about N. 70° E. from about longitude 92° 30′ to longitude 91°. The belt lies between latitude 47° 45′ and 48° 15′. The area which has been studied in detail extends from Vermilion Lake on the west to the international boundary on the east in the vicinity of Gunflint Lake and Lake Saganaga. The belt is about 80 miles long and varies in width from 4 to 10 miles. The district lies wholly in Minnesota. The important towns are Tower, Soudan, and Ely.

SUCCESSION OF FORMATIONS.

The succession of formations in descending order is as follows:

Succession of formations in Vermilion district.

Keweenawan	Great gabbro.
(Unconformity.)	
Upper Huronian (Animikie series). Confined to east end of district	Upper slate formation. Gunflint formation[1] (iron-bearing formation).
(Unconformity.)	
Lower Huronian	Intrusives. Knife slates. Lower Huronian iron-bearing formation. Ogishke conglomerate.
(Unconformity.)	
Archean (Vermilion series)	Intrusive granites, porphyries, and greenstones. Soudan formation (the iron-bearing formation). Ely greenstone, an ellipsoidally parted basic igneous and largely volcanic rock.[2]

STRUCTURE.

The Vermilion district is one of extraordinarily complex folding. The folds are so closely appressed that a regional cleavage is prevalent except in the very hard formations. Superimposed upon the longitudinal folds are cross folds with very steep pitches, showing that the transverse folding was also severe. As a result of the close folding

[1] The Gunflint formation of the Animikie is so named from typical occurrences at Gunflint Lake on the international boundary. The Knife slates are named from Knife Lake, where this formation is especially well developed. The Ogishke conglomerate has been known for years by this name, since magnificent exposures of the formation occur at Ogishke Muncie Lake. The Soudan formation is named from Soudan Hill, where the formation first yielded large bodies of iron ore and where the relations of this formation to the Ely greenstone are especially well exhibited. The Ely greenstone is given this name from the fact that under and adjacent to the town of Ely very large and typical exposures of the formation occur.

[2] The succession of formations above given differs from that which I supposed would be found before the Vermilion district was studied in detail. I had supposed that the Animikie series was equivalent to the series here placed in the Lower Huronian. When the relations were first studied in the field by the members of the United States Geological Survey, Mr. Clements and Mr. Leith thought that the relations of the two series were those of unconformity. When I reached the field later and saw the same facts I was inclined to believe that the phenomena were more likely to be explained by overlap. However, in the season of 1900, when Mr. Leith began studies upon the Mesabi district, he showed that the Mesabi series, which is undoubtedly the equivalent of the Animikie series, with gentle inclination rests unconformably upon vertical slates and conglomerates equivalent to the Knife Lake slates and Ogishke conglomerates. I have therefore no doubt that the correct interpretation of the phenomena in the Vermilion district is that of unconformity between the Animikie series and the Lower Huronian series.

Before closely studying the Vermilion district in the field, supposing the two series to be the same, I also thought it probable that the iron-bearing formation of the Vermilion would turn out to be equivalent to the Lower Huronian iron-bearing formation of the south shore of Lake Superior in the Marquette district. But very careful work by Messrs. Clements, Merriam, Leith, and myself has failed to discover any great structural break between the Soudan formation and the great Ely greenstone formation, which is undoubtedly Archean. Therefore we now recognize an iron-bearing formation in the Archean. Here as elsewhere in the Lake Superior region, there is great unconformity between the basal Archean complex consisting mainly of granites, gneisses, greenstone-schists, and greenstones, but containing subordinate amounts of sediments and the sedimentary series of the Lower Huronian.—C. R. Van Hise.


GEOLOGICAL SECTIONS ALONG LINES A-A, B-B AND C-C
Horizontal scale
2 MILES
Vertical scale
1 MILE
Sea level
PROVISIONAL GEOLOGICAL MAP
OF A PART OF THE VERMILION DISTRICT
BY
J. Morgan Clements, W. S. Bayley, C. K. Leith, and C. R. Van Hise
Scale
2 MILES
Contour Interval 20 feet
Datum is sea level
ALGONKIAN
LOWER HURONIAN
Alk
Knife slates
Alo
Ogishke conglomerate
ARCHEAN
VERMILION SERIES
Ægr
Granite and porphyry
Æs
Soudan formation (Including areas of Ely greenstone)
Æe
Ely greenstone (Including areas of Soudan formation)
fnd
Formation not determinable
VERMILION LAKE
BURNTSIDE LAKE
LONG LAKE
FALL LAKE
WHITE IRON LAKE
BASS LAKE
MUD LAKE
MUD CREEK BAY
ARMSTRONG BAY
CLEAR LAKE
ROBINSON LAKE
ARMSTRONG LAKE
EAGLES NEST LAKES
STUNTZ BAY
PIKE RIVER BAY
ELY
SOUDAN
TOWER
Tower Junction
DULUTH AND IRON RANGE RAILROAD
R. 15 W.
R. 14 W.
R. 13 W.
R. 12 W.
T. 63 N.
T. 62 N.
JULIUS BIEN & CO. LITH. N.Y.

there is an amazing irregularity in the distribution of the formations. Masses of a newer formation from a few feet across to large areas are distributed here and there among the rocks of an older formation. Furthermore, the structure of the district is much complicated by intrusives of various ages. In connection with folding and intrusives very profound metamorphism has occurred. On account of the exceeding complexity of the folding, the presence of intrusives, and the development of secondary structures, the working out of the structure of the district has been a matter of great difficulty.

Looked at broadly, the Vermilion district may be regarded, however, as a great complex synclinorium mainly bounded on the north by granitic formations of Archean age and on the south by plutonic igneous rocks, including granite of Huronian and gabbro of Keweenawan ages.

The table of formations shows that in the Vermilion district there are iron-bearing formations in the Archean, Lower Huronian, and Upper Huronian, the same as in the Marquette district. But the Soudan is the only one of these formations which has produced ore. However, the Lower Huronian and Upper Huronian iron-bearing formations are briefly considered because they may possibly produce ores in the future and because these formations are analogous in character to the formations in like positions in the Marquette district.

SOUDAN FORMATION.

Extent, position, thickness, and character.—The greater masses of the Soudan formation are confined to three areas. These may be called the Tower, Ely, and Hunters Island areas. In each area there are several or many belts of the Soudan formation. The Tower area covers the Soudan formation of Tower and vicinity, including Lake Vermilion and the extension of these belts eastward to within a few miles of Ely. The Ely belts begin at Ely and extend in a course north of east for about 8 or 10 miles to the Kawishiwi River. The other area is on Hunters Island in Canada. Here the formation is extensive. Between these areas the Soudan formation is subordinate.

In each of these areas a close mapping has shown that the Soudan formation is a definite sedimentary formation which can be mapped the same as any other formation of similar origin. Associated with the great continuous iron-formation belts are numerous subordinate belts. These detached belts vary from those which are large and extend some distance along the strike to patches which are only a few feet across and a few paces in extent. It is probable that some of the larger areas represent parts of a once continuous formation now separated from one another in consequence of folding and subsequent erosion. However, some of the smaller areas may be at a somewhat lower horizon than the large ones. The relations of the Soudan formation to the Ely greenstone show that the former is above the latter. In many places the Soudan formation is in synclines, bounded upon both sides by the older Ely greenstone. In other places it is in belts between the Ely greenstone on the one side and the Ogishke conglomerate of the Upper Vermilion on the other, showing in such cases that it is certainly a later formation than the Ely greenstone.

No estimate can be made of the thickness of the Soudan formation. In places where there are broader belts it must be some hundreds of feet and possibly 1,000 feet or more thick, and from this thickness it varies to 0. This variability is partly explained by the fact that varying proportions of the upper parts of the formation have been removed by erosion.

The rocks of the Soudan formation include cherty iron carbonates, pyritic quartz rocks, ferruginous cherts, jaspilites, and ore bodies. The most abundant variety of material is the jaspilite. In places the jaspilites are magnetitic or actinolitic, but these varieties of rock are subordinate. The ores include hard specular hematite and reddish, somewhat hydrated hematite.

There is every reason for believing that the various forms of rocks of the Soudan formation are derived from a siliceous iron-bearing carbonate, precisely as similar rocks are derived from this material in other districts in the Lake Superior region. The analogy of the Soudan formation to the Negaunee formation of the Marquette district is especially close. Substantially every variety of rock which is found in one district may be found in the other, but in very different proportions. The transformations of the iron carbonate into the ferruginous slates, ferruginous cherts, and jaspilites is in every respect similar to the transformation of a similar rock into like products in the Marquette district, even to the two steps in the development of the jaspilite. (See p. 373.)

Structural relations of the ores.—The ore of the Soudan formation thus far found probably all occurs at a single horizon, viz, at and near the bottom of the formation, where it is associated with the Ely greenstone. All of the known iron-ore deposits of the Vermilion district rest upon impervious basements, folded so as to constitute pitching troughs. Where the iron-bearing formation is also much broken, this is further favorable to large ore deposits, precisely as in the Marquette and Menominee districts. The impervious basements are usually made by the Ely greenstone. This is best illustrated by the ore deposits near Ely. The great ore bodies of the Chandler (Pl. LIX) constitute a great eastward-plunging trough.

As shown by fig. 2 of Pl. LIX, the ore reaches the surface at the end of the trough, and it was here first discovered. However, as a consequence of the steep pitch, the ore soon passes under jaspilite. Near the surface, on both sides of the trough, as shown by fig. 1 of Pl.

PLATE LIX.

PLATE LIX.

ORE DEPOSITS OF THE VERMILION DISTRICT.

(Both ore exploited and ore now in mine are represented as ore, since the purpose of this plate is to show the manner of the development of the ore rather than the present stage of exploitation.)

FIG. 1. Vertical north-south cross section of Chandler mine, showing relations of the ore deposit to the soap-rock, Ely greenstone, and ore-bearing formation. The iron ore is in a broad U-shaped trough, bottomed by soapstone or paint-rock which grades down into greenstone. It is capped by the ore-formation material. At the place where the cross section is made the ore does not extend to the surface along either limb. Therefore, at the particular place where this cross section exists, although there is a very large ore deposit below the surface, at the surface the only rocks which are found are the greenstone, soapstone, and iron-bearing formation.

Scale: 1 inch equals 250 feet.

FIG. 2. Vertical longitudinal east-west section of Chandler mine, showing the same relations as fig. 1. The figure very well illustrates how the ore body increases in size from the surface. Where the ore reaches the drift its area is small; and this great ore deposit, which extends eastward where it constitutes the Pioneer mine, is below a heavy capping of the ore-bearing formation.

Scale: 1 inch equals 250 feet.

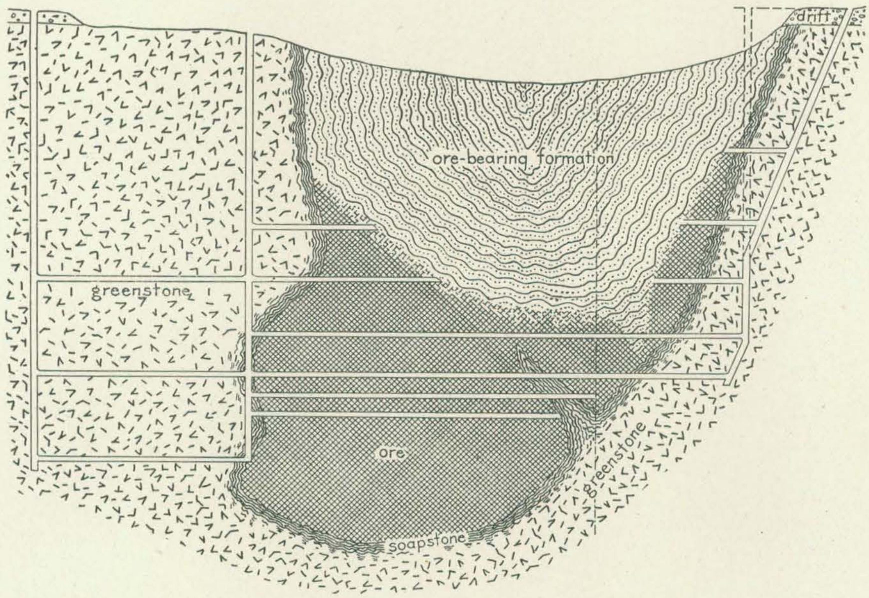


Fig I

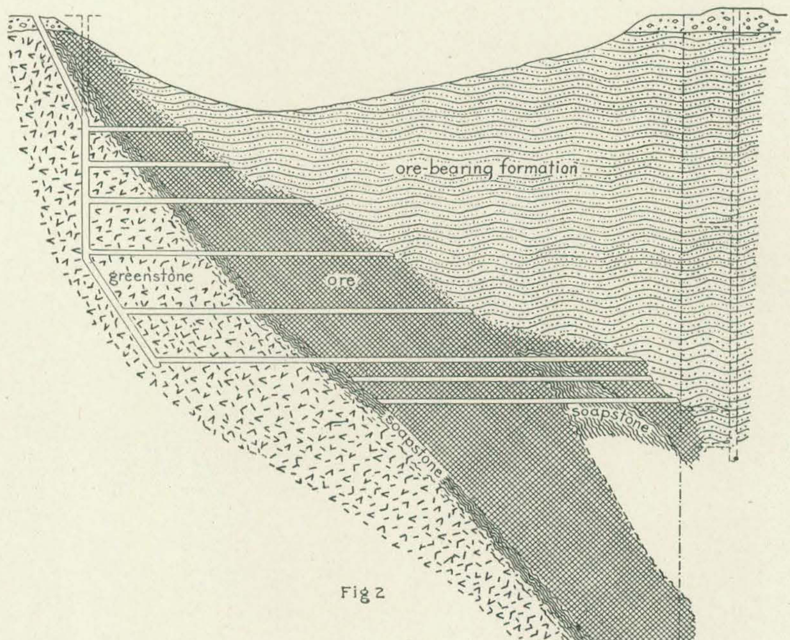


Fig 2

ORE DEPOSITS OF THE VERMILION DISTRICT.

LIX, the jasper abuts against the greenstone, so that at the Chandler the main body of the deposit is below a jasper capping. The Chandler ore mass continues eastward and constitutes the Pioneer mine. East of the Pioneer, along this same belt of ore-bearing formation, are the Zenith and Savoy mines; but at the present time we do not know whether or not development has gone far enough to determine the pitch of these deposits and their relations to the deposits of the Pioneer and Chandler.

The ore of Soudan Hill, in the case of both the north and the south bodies, is apparently in pitching synclines. The impervious basements are mainly the Ely greenstone. Associated with this greenstone are various intrusive rocks, among which are porphyry, and these may help to form the basements. In some respects the Vermilion district thus furnishes as good illustrations as are found in the Lake Superior region of ore deposits upon impervious basements in pitching troughs.

Topographic relations of the ores.—The large ore deposits of the Vermilion district are located below crests or slopes, as in the districts previously described. This is conspicuously the case with the great deposits of Soudan Hill. The crest of this hill has an elevation of 1,660 feet. This is about 150 feet above a cross valley to the east between Soudan Hill and Jasper Peak. The Chandler and Pioneer ore deposits are below comparatively low-lying ground, the upper part of the deposits being at about the 1,400-foot contour. This is surrounded on the north, west, and south by an amphitheater of high ground composed of the Ely greenstone, the higher points of which rise to an elevation of 1,500 feet. Farther to the east is a cross valley which is somewhat less than 1,400 feet high. To what extent the cross valley is filled is unknown, but the drift covering is tolerably thick. The pitch of the ore deposits is parallel to the range, the same as in the Menominee, Marquette, and Penokee-Gogebic districts.

The analogy between the ore deposits of the Vermilion district and the great ore deposits at the base of the Negaunee formation of the Marquette district, which are bottomed by the Siamo slate, is very close indeed. The chief difference is that the Ely greenstone was an extrusive volcanic upon which the iron-bearing rocks were laid down, while in the Marquette district the basal rocks are sedimentary. This, however, is of no consequence so far as the development of the ores is concerned.

Development of the ores.—From the foregoing description it is perfectly clear, if the argument concerning the genesis of the ores of the Marquette district be correct, that the same conclusions are applicable to the Vermilion district. Without again going over the details, it may be concluded that the ore deposits of the Vermilion district were produced from original cherty iron carbonate. The iron-bearing carbonate was partly oxidized in situ, thus producing some of the iron oxide. Another and probably larger portion of the iron carbonate was contributed by descending waters, and iron oxide was precipitated in the troughs by oxygen-bearing solutions. Furthermore, the silica was abstracted precisely as in the Marquette district.

Time and depth of concentration.—The final and chief concentration of the Vermilion deposits must have occurred subsequent to the profound folding and the removal of the Lower Huronian deposits which exposed the iron-bearing formation, although some concentration may have taken place between Archean and Huronian time. No criteria are available to place a limit to the close of the process. As to the depth to which the concentration has extended, precisely the same principles apply as in the Marquette district. In June, 1900, the lowest level at Soudan Hill was at a depth of 850 feet; at the Chandler mine, at a depth of 700 feet; at the Pioneer mine, at a depth of 856 feet; at the Zenith mine, at a depth of 770 feet; and at the Savoy mine, at a depth of 536 feet.

LOWER HURONIAN IRON-BEARING FORMATION.

The Lower Huronian iron-bearing formation occurs mainly in the eastern part of the district on Hunters Island in Canada. In this area the formation is definite, continuous, and persistent; but it thins to the southwest and disappears altogether before the central part of the district is reached.

As ascertained by the junior author, the formation is in two belts on opposite sides of a syncline, overlain by Knife slates, and underlain by the slates and conglomerates of the Ogishke formation.

The main belts of the formation are along the shores of a row of linear lakes known as That Mans Lake, This Mans Lake, No Mans Lake, and The Other Mans Lake. The iron formation is not very thick, varying from less than 100 feet to possibly a maximum of 200 to 300 feet.[1]

The more important rocks of the formation are iron-bearing carbonate, ferruginous slate, ferruginous chert, and jaspilite. No ore bodies have as yet been found in this formation. The southwestern part of the belt is underlain by a ferruginous and dolomitic rock which extends farther to the southwest than the iron-bearing formation.

GUNFLINT FORMATION.

The Gunflint formation (iron-bearing) is confined to the northeastern part of the district. It lies between the Vermilion series and Lower Huronian on the north and the Keweenawan series on the south. It extends from Gunflint Lake south of west continuously to Fay Lake. Still farther to the southwest patches of the formation are found at

[1] These belts were traced out by the junior author during the season of 1899.

Gobbemichigama and Disappointment lakes. At the eastern end of the Vermilion district adjacent to Gunflint Lake this belt is composed of carbonated slates, ferruginous slates, and jaspilites; but when it is traced to the southwest it gradually changes to a coarse amphibolitic and magnetitic quartz rock, and even to a banded rock containing pyroxene and chrysolite.

Where this rock occurs it is immediately adjacent to the great Keweenawan basal gabbro. The various rocks of Gunflint Lake grade into the peculiar coarse rock just mentioned, and the change takes place just in proportion as the formation nears the gabbro, and is complete where the gabbro is in contact with the iron-bearing formation. This gradation and the metamorphism resulting from the intrusion of the gabbro have been described by Grant.[1]

The amphibolitic and magnetitic varieties of the formation have been prospected, especially at Akeley Lake and vicinity, but no rich ore bodies have as yet been found. Indeed, in all places in the Lake Superior region where the iron-bearing formation has suffered this peculiar, deep-seated metamorphism, in connection with the great gabbro intrusion, concentration has not taken place so as to produce high-grade ore bodies, or at least no such ore bodies have as yet been discovered.

CANADA.

In this paper it is not my purpose to consider the iron-bearing districts of the Lake Superior region which are not producing and have not produced iron ore. Consequently I have not mentioned various areas on the United States side of the boundary, some of which are known to contain iron-bearing formations, and yet have not produced iron ore; for instance, the Huronian of the Baraboo and the Black River Falls districts, both in Wisconsin. If the plan were strictly followed, and the districts only were mentioned which have produced iron ore, except for the Michipicoten district, no mention would be made of Canada, since up to the present time ores have been exploited at only a single mine in the Lake Superior region north of the international boundary. However, this would be hardly fair, since in the Lake Superior region of Canada the iron-bearing rocks are known to have great development. (See Pl. XLVIII.) In these rocks at various places are extensive belts of iron-bearing formations. In some of them, also, iron ores actually outcrop, as for instance in the Atikokan range.

The Upper Huronian and Archean iron-bearing series exist, and possibly the Lower Huronian iron-bearing formation. Moreover, some of these series are a direct extension of the series which have been

[1] Geology of Minnesota, Vol. IV, 1899, pp. 459, 476-477. Bull. Geol. Soc. Am., Vol. XI, 1900, pp. 506-508.

productive on the United States side of the boundary. Undoubtedly equivalent with the Upper Huronian Mesabi iron-bearing series (Pl. XLVIII) is the Animikie series of Thunder Bay (Pl. XLVIII), which extends from Gunflint Lake on the international boundary east beyond Port Arthur on Lake Superior.

The Vermilion iron-bearing series has been traced by us to Hunters Island. Thence these rocks have been mapped by the Canadian survey as extending first in a northeasterly and then in an easterly direction to the Kaministiquia River, and thence eastward to the Keweenawan rocks west of Lake Nipigon. Another great belt of iron-bearing rocks with various ramifications has been traced by the Canadian survey from Rainy Lake eastward to the Canadian Pacific Railway and to Lac des Mille Lacs. (Pl. XLVIII.) In this belt occurs the so-called Atikokan range, in which large deposits of iron ore are said to outcrop.

East and north of the east half of Lake Superior various areas of iron-bearing rocks are also found. One or more belts are said to extend east from Lake Nipigon. A belt is found adjacent to the Black and Pic rivers. Several belts of iron-bearing formation have been found in the Michipicoten district.

At the present time the only one of these districts which is an ore producer is the Michipicoten. While this district has not been connected areally and structurally with any other area in the Lake Superior region, the likeness in the character of its rocks and its succession to the Vermilion district leaves little doubt in my mind that the two districts are in most essential points parallel. In the Michipicoten district the basement rock is a greenstone, showing the ellipsoidal structure on the great scale so characteristic of the Ely greenstone of the Vermilion district. Also with this greenstone are various other mashed igneous rocks, including porphyries. The iron-bearing formation in many essential respects resembles that of the Vermilion district. It contains substantially all the varieties of material in the iron formation of the Vermilion district, and in addition great quantities of pyritic quartz rock. On the bluff back of the Helen mine and at many other places iron carbonate is abundant. Near the Helen mine Mr. Merriam reports this carbonate as containing 19 to 37 per cent of metallic iron. These abundant cherty carbonates leave little doubt that the ferruginous cherts, ferruginous slates, jaspers, and iron ores have mainly developed from a carbonate as the original rock, precisely as in the various districts south of Lake Superior. However, it is clear that the pyrite of the carbonates and the pyritic quartz rocks have also made contributions. At the present time the iron formation has been developed only at the Helen mine. Here a good body of high-grade hematite has been shown by stripping to extend in considerable areas to the rock surface.[1] In 1900, the first year of shipment, 62,000 tons were shipped.

Whether or not the Michipicoten district will be a great producer in the future can not be told, of course, in advance of development.

A further analogy between the Vermilion and Michipicoten districts is furnished by an upper series in the latter district consisting of mashed conglomerates and slates, the former bearing very numerous fragments of the lower series, including the iron-bearing formation, precisely as in the Vermilion district. This clastic formation has a slaty structure and is in vertical attitude, and is almost identical with the Ogishke conglomerate and Knife formations of the Vermilion district.

As yet the various districts which may bear merchantable iron ore in quantity have been outlined only in the most general way by the Canadian survey, but the reconnaissance reports descriptive of them show that both Archean and Lower Huronian rocks occur, and that at least the Archean iron-bearing formation exists.

The Canadian survey has not attempted to separate the iron-bearing formations from the associated rocks. Such work is necessarily slow and expensive, and the vastness of the region of Canada where preliminary work was necessary has been a sufficient cause for not taking up this work. Doubtless in the future the iron-bearing formations will be separately mapped. When this is done it will undoubtedly be very helpful to the development of the iron-ore resources of this region.

With one possible qualification, so far as one can see there is no known geological cause why iron ores should not extensively exist on the Canadian side of Lake Superior. This qualification is due to glacial erosion. In this paper it has plainly appeared that the iron-ore deposits are products of the surficial belt and that they were formed mainly in pre-Glacial time. It has also been seen (pp. 334–336) that glacial erosion, which removed a considerable portion of the belt of weathering, certainly carried away large quantities of the iron ore, which have not been appreciably replaced by the processes of concentration since Glacial time. The United States side of the boundary is a region of moderately vigorous glacial erosion and very marked glacial deposition. The region on the Canadian side of the boundary north of Lake Superior is one of very vigorous glacial erosion and comparatively small glacial deposition. As a consequence the rocks are much better exposed on the Canadian side than on the United States side of Lake Superior. It is a moot question as to whether or not the Continental glaciers deeply eroded the nondisintegrated rocks. It is agreed on all hands that the larger part of the disin-

[1] Michipicoten iron range, by A. P. Coleman and A. B. Willmott: Rept. of the Bureau of Mines, Ontario, Vol. VIII, 2d part, 1899, pp. 254-258.

tegrated material was swept away. But this is as true south as it is north of Lake Superior. However, it can not be doubted that the glacial erosion was more vigorous north of Lake Superior than to the south. In so far as the glacial erosion was more vigorous, just to that extent more iron ore was lost north than south of the lake, and the conditions are to that extent less favorable for the existence of numerous large ore deposits. The weight which must be given to this qualification can only be ascertained after extended exploration and exploitation. Certainly it appears that the rocks in the Animikie area (Pl. XLVIII), between Gunflint Lake and Port Arthur, contain more of the original iron-bearing carbonate and show less of the residual material of the belt of weathering, viz, ferruginous slate, ferruginous chert, and ore bodies, than the Mesabi range (Pl. XLVIII), its continuation to the southwest. If the Animikie rocks were once as deeply altered and contained large ore bodies, these appear to have been largely swept away, thus exposing the little altered rocks. If in the Mesabi district glacial erosion had cut 150 feet deeper than it did, the larger portion of the ore deposits would have been lost. Moreover, the Gunflint formation of the Animikie district is not nearly so thick as the Biwabik formation of the Mesabi district. It may, therefore, be doubted whether the Animikie district will ever be so productive in iron ore as the Mesabi district. Whether a similar comparison should be made between other equivalent districts on opposite sides of the international boundary is uncertain. This matter is one, however, which should be considered by those who take up the development of the districts north of Lake Superior.

While, therefore, it may be possible that on account of glacial erosion the product of high-grade ore in Canada may be less than in the districts of similar size and geological position on the United States side of the boundary, it can not be doubted that in the future important quantities of iron ore will be exploited in the Canadian Lake Superior region. Doubtless also this exploitation would have begun many years ago were it not for the duty which ores mined in Canada must pay when entering the United States.

CHAPTER III.

COMPARISON AND SUMMARY.

Now that the six iron-bearing districts of the Lake Superior region south of the international boundary have been separately considered, it is possible to compare them and see in what respects they are alike and unlike.

THE IRON-BEARING FORMATIONS.

There are in the Lake Superior region three iron-bearing series which contain productive formations: (1) The Archean, (2) the Lower Huronian, and (3) the Upper Huronian. In the latter series iron ores occur at two horizons—the basal horizon of the series where in contact with the Lower Huronian iron-bearing formation, and an iron-bearing formation within the series.

It is interesting to compare the iron-bearing formations of the different districts in reference to their geographical relations. In this comparison I shall begin at the most northeasterly district and pass to the south to the Crystal Falls and Menominee districts, thence west to the Penokee-Gogebic district, thence northwest to the Mesabi district, thence north to the Vermilion district. (See Pl. XLVIII.)

The Marquette district may well be considered the key district of the region, since it is the only district in the Lake Superior region in which all of the iron-bearing horizons are found. While the Archean iron-bearing formation is known, it is not productive. The chief ore bodies are within the Lower Huronian Negaunee formation. Important ore bodies do occur at the basal horizon of the Upper Huronian and subordinate quantities of ore are found at the iron-bearing formation within the Upper Huronian.

Passing now to the Crystal Falls district to the south, all of the Huronian iron-bearing formations are found. However, the two lower of these iron formations are confined to the northern half of the district, and as yet ore bodies have not been discovered in them. In the southern half of the Crystal Falls district the iron ores all occur at the topmost ore-bearing horizon; that is, that within the Upper Huronian slate.

In the Menominee district, only remnants of the Lower Huronian Negaunee formation remain, and they bear no ore bodies. There is, however, in this district, the basal ore-bearing horizon of the Upper Huronian; and this horizon in this district is the most important ore producer. Also the horizon within the Upper Huronian, important in the Crystal Falls district, is found within the Menominee and is important.

Looked at in a broad way the three districts—the Marquette, the Crystal Falls, and the Menominee—might be considered parts of one larger district, since the Huronian rocks of all of them are areally connected. (See Pl. XLVIII.) However, in passing from the north to the south of this triple district, if we may use this expression, the important ore-producing horizon has passed from the Lower Huronian to the basal horizon of the Upper Huronian. And when we pass to the western part of the Crystal Falls district the important ore-producing horizon has become the topmost horizon within the Upper Huronian.

Summarizing, we see that in the northeastern part of the area, in the Marquette district, the Lower Huronian horizon is the great producer; in the southeastern part of the area, in the Menominee district, the basal horizon of the Upper Huronian is the great producer; and in the western part of the area, i. e., Commonwealth, Florence, Crystal Falls, and Iron River, the horizon within the Upper Huronian is the sole producer.

Passing now to the westward, to the Penokee-Gogebic and Mesabi districts, the conditions are similar to those in the western part of the Crystal Falls district. In these two districts the ore is confined to a single iron-bearing formation—that within the Upper Huronian—but this has now become a very important formation. The enormous quantities of ore derived from these two districts are at the horizon of the mines adjacent to Crystal Falls and Iron River, at the Curry member of the Menominee, and at the insignificant horizon of the mines of the Michigamme slate in the Marquette district. It therefore appears that the iron-bearing member of the Penokee-Gogebic and Mesabi districts in the western part of the Lake Superior region is a great continuous thick formation, but when traced to the east it thins out gradually, finally becomes discontinuous, and in the Marquette area is of little consequence.

Passing now to the Vermilion district north of the Mesabi district, if we include here the eastern equivalents of the Mesabi series, where the two ranges join, all the series which occur in the Marquette district are found, and each contains an iron-bearing formation; but as yet only one of them is an ore producer. All of the ore thus far exploited comes from the Archean iron formation, which is equivalent to the lowest nonproductive formation of the Marquette district. The Lower Huronian iron formation is thin and local and ores have nowhere been mined from it. The basal detrital iron-bearing member of the Upper Huronian does not exist. The topmost iron-bearing horizon, that within the Upper Huronian, is confined to the eastern part of the district, and within it no ore bodies have as yet been found.

The only productive district north of the international boundary is the Michipicoten; and here the only iron formation known is the Archean.

POSITION OF IRON ORES IN THE IRON-BEARING FORMATIONS.

Next to be considered are the positions which the ore bodies occupy within the iron-bearing horizons. The Archean iron-bearing formation is productive in only two districts, the Vermilion and the Michipicoten. In the Vermilion district all the ore deposits yet found are at the bottom of the iron-bearing formation (the Soudan), the pitching troughs being made by the underlying Ely greenstones, or else by these greenstones combined with later intrusive rocks. The Lower Huronian iron-bearing formation (the Negaunee) is productive in only a single district, the Marquette. In this district ore deposits may be found at the bottom of the iron-bearing formation, the underlying slate furnishing the pitching troughs; they may be found within the iron-bearing formation, intrusive diorite sheets or dikes or both together constituting the pitching troughs; or they may be found at the upper part of the iron-bearing formation, the contact horizon between the Upper Huronian and Lower Huronian combined with interbedded or intrusive rocks giving the pitching troughs.

The workable ore deposits belonging to the basal horizon of the Upper Huronian are confined to the Marquette and Menominee districts. In the Marquette district they occur in connection with those at the top of the Lower Huronian Negaunee formation, and are controlled by the same condition. In the Menominee district they are at basal or nearly basal positions in the formation, the impervious pitching troughs being furnished by talc-schist belonging at the top of the Randville dolomite, or else by a slaty member of the iron-bearing formation.

The highest iron-producing horizon, that within the Upper Huronian, is an ore producer in all of the districts south of the international boundary except the Vermilion. In all of these districts the ore deposits show a marked preference for the lower parts of the iron-bearing formations, although these are not the bottom formations of the Upper Huronian. In the Marquette, Crystal Falls, and Menominee districts, the ores rest upon impervious pitching troughs composed of slate. This slate in the Menominee district has been given the name Brier. In the Penokee-Gogebic district, in all but two cases, the ores rest upon pitching troughs made by a combination of quartzite underlain by slate and by dike rocks. In the Mesabi district the ores are in pitching troughs, often composed of argillaceous or cherty portions of the iron-bearing formation itself, rather than the underlying slate and quartzite. In all districts alike the ores show a marked preference for subordinate depressions on the crests or slopes.

Still further generalized, we may say that within the iron-bearing formations the large ore bodies are very generally found with the following relations: (1) They rest upon an impervious basement; (2) this impervious basement is commonly in a pitching trough; (3) the ore formation is usually much plicated and broken; (4) the majority of the ore bodies occur below crests or slopes, not below valleys.

CLOSENESS OF FOLDING.

The different districts vary greatly in the closeness of the folding. Moreover, both the longitudinal folding and the cross folding vary in closeness. The closeness of the folding in both directions is an important factor bearing upon the shape of the ore deposits and the amount of them which is exposed at the surface. The statement first made will exclude the intrusive igneous rocks. Usually the longitudinal folds correspond with the greater dimensions of the ore bodies and the cross folds determine the steepness of the pitch, but there are important exceptions to this. Where the rule applies, the most gentle folds give wide U-shaped troughs, the closer folds narrower U-shaped troughs, and the most intense folds give V-shaped troughs. Where the folding is gentle the breadth of the ore bodies is often considerable and the pitch is slight. Consequently a broad area of an ore body is likely to be exposed at the surface. As the complex folding becomes closer the area exposed at the surface becomes smaller and smaller. Where the cross folding is intense and in consequence the pitch very steep the area of ore exposed at the surface may be very small indeed, the body plunging steeply and quickly below the rocks. Where intrusive igneous rocks occur these statements may need modification to some extent, but in many instances the igneous rocks were present in the formations before the folding, and in such cases the principles are applicable.

The districts will be considered in the order of the closeness of folding, the district being first taken up in which the folding is most gentle and that last in which it is most intense.

In the Mesabi district the folding is the most gentle of any in the Lake Superior region. This series is a gently southward-dipping monocline, the average dip being perhaps 10°. This monocline is bent by gentle cross folds which produced subordinate plunging anticlines and synclines of different orders, thus affording cross troughs and arches. The cross troughs, which pitch to the south, have been followed by the ore bodies. Therefore in the Mesabi district the greater dimensions of the ore bodies correspond with the cross folding and the shorter lateral dimensions with the major folding of the district. But the major folding is also very gentle and, therefore, the pitch slight. As a consequence the ore deposits of the Mesabi district give the largest exposures of ore at the surface of the solid rocks in the Lake Superior region.

The Penokee-Gogebic series is another monocline, but the dip is here from 35° to 80° N., being for the major part of the producing district 55° to 70° N. There are also here subordinate cross flexures. Cross faulting and faulting parallel to the bedding also occur. In this district the pitch of the ore bodies is controlled, not by the cross folds, but by a set of intersecting dikes which, as explained on pages 340–343, unite with a quartzite to produce pitching troughs parallel to the strike of the iron-bearing formation instead of transverse to it as in the Mesabi district. The pitch in most cases is from 10° to 30°. This pitch commonly carries the ore deposits below the surface within comparatively short distances. However, the areas of the ore deposits which reached the drift were rather large, and the majority of them were discovered by test pitting.

In the Crystal Falls district there are two cases. The first comprises those deposits which are peripheral to the Hemlock volcanics. These have steep dips. Upon the major folds are subordinate cross folds which give pitching troughs. The second case comprises those ore deposits in the slates away from the Hemlock volcanics. These slates are somewhat sharply plicated, giving U- or V-shaped troughs.

In the Marquette district the folds are rather close, but not so close but that the majority of the basins are U-shaped rather than V-shaped. This statement is applicable to the central part of the district, where deposits occur at the bottom, within, and at the top of the Negaunee formation. (See pp. 373–379.) The pitch of these ore bodies is ordinarily from 20° to 30°. Therefore the ore deposits ordinarily present a fairly good breadth of exposure at the solid rock surface, but plunge somewhat quickly below the rock, as in the Gogebic district. In the western part of the district the Michigamme and Spurr mines present a case of southward-dipping monoclines similar to those of the Crystal Falls district.[1] The end of the Republic syncline is somewhat sharply plicated, the compression having here been much more intense than in the main area. As would be expected from the intensity of folding, the Republic trough has a steep pitch, being on an average between 40° and 45°.

In the Menominee district the plications are exceedingly sharp. Superimposed upon the sides of the major anticlinal folds of the dolomite are sharp V-shaped folds, which have pitches of from 50° to 60°, or even more. In this district the areas of deposits which reach the drift are therefore comparatively small. The ore deposits pass quickly below the rock surface, and some of them are of much greater size

[1] The Republic trough, by H. L. Smyth: Mon. U. S. Geol. Survey Vol. XXVIII, 1897, pp. 525–580.

below the surface than at the surface. A notable case is the Aragon mine.

In the Vermilion district we find the maximum of folding, both longitudinal and cross. Upon the folds of the first order are those of the second order, upon these folds are the folds of the third order, and so on down to minute plications. In most cases these plications are so sharp as to make the limbs of the folds nearly or even quite parallel. However, in many cases, notwithstanding this, the turns are rounded rather than sharply V-shaped. Moreover, the cross folding is so intense as to give steep or vertical pitches. Indeed, the pitches are often so steep that the folds may be almost equally well seen on ground plan and upon vertical cross section. As a result of the extraordinary complexity of the folding, both longitudinal and cross, the iron-bearing formation and underlying greenstone have a most remarkably irregular distribution. Indeed, this distribution is so very complex that many have believed it to be explained by intrusion of the greenstone rather than by folding. On account of the sharpness of the folds the pitch of the ore bodies is usually steep, and comparatively small areas reach the rock surface.

SUMMARY OF GENESIS OF THE ORES.

As to the genesis of the ores, cherty iron-bearing carbonate is the main original rock. This is found in every district in the entire Lake Superior region, with the exception of the Mesabi district, where iron silicate also is very important. The rocks are metamorphosed along two main lines. The first of these lines produces amphibolitic and magnetitic quartz rocks or schists, and occasionally also pyroxenitic and chrysolitic rocks. These rocks develop under deep-seated conditions in connection with igneous intrusives, and especially the basal gabbro intrusives of the Keweenawan. Where the iron-bearing formations have thus been altered no workable ore bodies have as yet been found. The second line produces ferruginous slates, ferruginous cherts, jaspilites, and ore bodies. These rocks develop mainly in the belt of weathering, although in many cases the production of the jaspers required two stages—first the formation of the ferruginous slates and ferruginous cherts in the belt of weathering, and later dehydration when the formations were deeply buried.

In a number of the districts in which the Lower Huronian iron-bearing formation occurs the upper part of the formation was exposed to weathering before Upper Huronian time. When the Upper Huronian sea transgressed over these iron-bearing formations detrital ferruginous sandstone and conglomerate were produced, which, so far as they contain iron oxide, are on their way toward ore bodies. To some extent, also, the ore bodies are due to the oxidation of the iron carbonate in place. But all of the facts irresistibly lead to the conclusion that the final and most important step in the production of the ore bodies was secondary enrichment by downward-percolating waters below crests or slopes where such waters were converged by the pitching troughs. The waters which followed the more circuitous routes transported iron carbonate; waters more directly from the surface, which did not pass through iron carbonate, bore oxygen; the two kinds of solutions mingled and precipitated iron oxide. The waters ascended and escaped below the valleys. Finally, the great quantity of water which was converged in these troughs and moved downward abstracted the silica and carried it elsewhere.

THE QUANTITY OF IRON ORE AVAILABLE.

If the foregoing reasoning be correct, it is perfectly clear that the ore bodies can not be expected to extend beyond the depth to which the descending waters may bear oxygen and precipitate iron oxide. Up to the present time all but an insignificant fraction of the ore has been taken from above the 1,000-foot level. Many ore deposits before reaching the depth of 1,000 feet have become smaller and poorer, and a number have been worked out. Two or three ore deposits have been sufficiently persistent, so that they have been worked to the depth of 1,500 feet, but the great majority of deposits, even in the oldest districts in which there has been time for deep development, has not been worked to such depths as this. I have no doubt that vastly more high-grade iron ore will be taken out in the Lake Superior region above the 1,000-foot level than below it. If this be true, iron ores of the Lake Superior region bearing more than 60 per cent of metallic iron are not inexhaustible. Indeed, a very appreciable percentage of such ores yet discovered has already been exploited. But high-grade ores are not the only source of supply.

Thirteen years ago practically all of the material shipped from the Lake Superior region contained more than 60 per cent metallic iron.[1] For the last five years large quantities of ore have been shipped from the ranges south of Lake Superior containing less than 60 per cent, and considerable quantities of ore have been shipped running from 40 to 50 per cent metallic iron.[2] If all material be called iron ore in which the percentage of iron is 50 per cent or more, with an average amount of phosphorus, a large quantity of material left behind, wasted, or not developed at all would be ore. If material be called iron ore which runs more than 40 per cent metallic iron, and this material would be ore in Europe, this would add greatly to the quantity of available ore.

[1] Mineral Resources U. S., 1887, pp. 37-42.

[2] Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. V, 1896, pp. 28-32; Twentieth Ann. Rept. U. S. Geol. Survey Pt. VI, 1899, pp. 33-36.

Already some low-phosphorus, high-silica ores which bear no more than 40 per cent metallic iron have been marketed for mixture with the Mesabi ores. I have no doubt that within another generation a considerable proportion of the material shipped from the Lake Superior region will run between 40 and 50 per cent metallic iron, and that low-phosphorus, high-silica ores containing considerably less than 40 per cent metallic iron will be marketed.

The exhaustibility of high-grade iron ores in the Lake Superior region can not be too strongly insisted upon, for belief to the contrary almost invariably results in lack of foresight and waste on the part of the operators. The policy of mining only the richest ores which can be marketed to-day, and frequently in handling this material in such a manner as to make it difficult to recover the somewhat lower-grade material at a later time, is very shortsighted policy, even from the point of view of the mining men and ignoring the future of the nation. The sagacious policy is to treat the low-grade ores which can not be marketed at the present moment as a resource which will certainly have a value in the future. Moreover, taking into account the enormous increase in the amount of ore mined, I have no doubt that the demand for the low-grade ores which are at present completely ignored or wasted will come much sooner than mining men believe. The total product of the Lake Superior region since mining began in 1850 to 1900, inclusive, is 171,418,984 long tons. The amount mined in the decade between 1891 and 1900, inclusive, is 114,017,546 long tons, or 66.5 per cent, or nearly seven-tenths, of the total amount mined. The product for the year 1900 surpasses that of any previous year and is one-ninth of the aggregate of this and all preceding years. It is certain that the product of the current decade will far surpass that of the last decade.

The mining men should seriously consider how many decades' supply such as that of 1891 to 1900 of high-grade material is in sight, or even discoverable, on the United States side of the boundary. If this amount be placed at 1,000,000,000 long tons, mining at the rate of 20,000,000 tons per year would exhaust the supply in the first half of the twentieth century, or in about the same length of time that mining has been carried on in the Lake Superior region. The exhaustion within a few decades of the high-grade ores of the Lake Superior region *now discovered* is little short of a certainty. It is therefore plain that the material in which the percentage of iron is below the present market demand and which must be handled in connection with present operations should be stock piled, and that the mines be developed and exploited with the expectation in a comparatively short time of mining material running between 50 and 60 per cent metallic iron, and within a comparatively few decades of material running between 40 and 50 per cent metallic iron.

EXPLORATION.

GENERAL.

If the foregoing paper presents an approximately correct statement of fact as to the occurrence of the iron ores of the Lake Superior region, and an adequate theory as to their development, certain rules follow as to methods of exploration. Various explorers have applied a part of these rules, perhaps without definitely formulating them. Indeed, in many cases the explorations have been directed with exceptional intelligence, considering the state of knowledge of the districts when the exploratory work was done. However, a very frequent procedure in exploration has been that of chance, the explorer putting down test pits or drill holes, in some cases in great numbers within a small area where his fancy dictated, or under some theory which had no basis in fact. One in many test pits or drill holes has, under the law of chance, found ore, and the lucky hit has been taken as evidence of unusual sagacity upon the part of the explorer. This method, or lack of method, of chance exploration is nowhere better illustrated than by much of the exploratory work in the Vermilion district. This district is one which above all others demands an understanding of the structure, a careful mapping of the ore-bearing and other formations, and a comprehension of the principles of the occurrence of the ores within the iron-bearing formation; for it is a district of almost unparalleled intricacy of structure. The natural consequence of these difficulties is that the chance plan of exploration has been here best exemplified, and the expenditures in exploration in the district have been immense and largely wasted. In other districts, in which the distribution of the iron-bearing formations is more regular, exploration to a greater degree has been well directed. However, in the simplest districts a very large amount of chance or random work has been done and great sums of money have been lost.

In many cases a sufficient amount of money has been thrown away upon a single tract of 40 acres, where there was no reasonable prospect of success, to have mapped areally and studied scientifically an entire district. The unscientific and unpractical method of exploration by chance has undoubtedly led to the discovery of many large ore deposits; but the waste of money in this work has been simply enormous, amounting to many millions of dollars.

In the hope that such waste may be lessened in the future, I here attempt to formulate rules to guide exploration. A number of these rules are general and apply to the entire Lake Superior region; others of them are special, applying only to individual districts. The general rules are as follows:

(1) Exploration should first be directed to outlining accurately the

iron-bearing and adjacent formations. For certain districts upon which reports have already been published by the United States Geological Survey this has already been done in large part; but even these maps should be supplemented by much more detailed mapping of the more favorable areas, since it is not possible for the Government geologists to make economic maps for the various mining companies. It is, therefore, the first duty of the explorer of an area, small or large, to make or have made an accurate large-scale geological map with structure sections. Such a map should show as exactly as possible the limitations of the iron-bearing and adjacent formations on the property to be explored. Wherever it is possible to subdivide the iron-bearing formation into various members the map should show these subdivisions. Not only should the map give all these generalized results, but it should give in detail the information upon which they are based. Thus, the map should show all natural outcrops in due proportion with their strikes and dips. It should show the observations of a careful magnetic survey made by the methods explained in Chapter II of Part II of Monograph XXXVI of the United States Geological Survey (pp. 336–373), or by some other equally good method. Such a magnetic survey may reveal an iron-bearing formation where outcrops fail to do so. Where there are various outcrops of an iron-bearing formation, a magnetic survey may enable one more accurately to plat its boundaries. Not only this, but the bending of the lines of maximum variation and the change in dip may help to elucidate the structure, showing where the folds are. Frequently, also, a magnetic survey may help to subdivide an iron-bearing formation into two or three members, some of which are strongly magnetic and others less strongly magnetic. In some instances the slightly magnetic belts are those which are most likely to bear ores. In others, strongly magnetic belts are those most likely to bear ores. No general rule can be given on this point. The rule established by a magnetic survey of the individual district, and especially of the properties where ore is known, must guide in further search for ore.

An excellent example of an iron-bearing belt geologically mapped in advance of exploration is the Wisconsin end of the Penokee-Gogebic range from Penokee Gap to Montreal River. This area was accurately mapped by the late Prof. Roland D. Irving on a scale of 3.6 inches to the mile.[1] This map shows not only the distribution of the various formations, but the observations upon which the distribution is based, both the actual outcrops and the magnetic data being given. From Potato River to the Montreal River in the eastern part of the district, a distance of over 12 miles, only two outcrops were found upon the iron-bearing formation; but so correctly were these outcrops, the outcrops

[1] Pls. XXIV and XXVI inclusive, of Atlas of Geology of Wisconsin.

of the adjacent formations, and the magnetic observations interpreted that Professor Irving located a belt of iron-bearing formation about 1,000 feet wide, years before any exploratory work was done on this part of the belt. Within this belt is confined every mine which has been discovered in Wisconsin in the Penokee-Gogebic district.

Careful mapping by a competent geologist, both of ledges and of magnetism, leading to the elucidation of the structure, costs very little as compared with underground work. The results obtained by a careful surface survey will in all cases make the expenditure of money underground much safer and much more likely to lead to success. Notwithstanding these undoubted truths, it has been, until within a few years, very exceptional for the practical mining men to avail themselves of careful surface geological and magnetic surveys. At the present time the easily discoverable deposits have been found; therefore, what is here said in reference to close geological and magnetic mapping previous to underground work has far greater force than it had ten or twenty years ago.

(2) Exploration should be confined to the iron-bearing formations. The correctness of this principle is so evident for most areas that it needs no emphasis. Nevertheless, at various places vast sums of money have been expended in direct violation of it. For instance, in the early days of exploration on the Gogebic range, great sums of money were spent in exploring the granite below—to the south of—the iron-bearing formation and the slate above—to the north of—the iron-bearing formation. In the Vermilion district within the last few years vast sums of money have been spent in drilling in the middle of large areas of the great basal Ely greenstone. However, even the principle that work is to be confined to the iron-bearing formation needs qualification. The irregular ore deposits in the Upper Huronian slate, exemplified by those of Florence, Commonwealth, and Iron River, are so bunchy and occur so irregular through the slate that the slate itself may be considered the economic formation, and in this case the exploratory work should not be confined strictly to the belts of ferruginous chert and jasper and other well-known rocks of the iron-bearing formation.

(3) Exploration should be confined to those parts of the iron-bearing formations in which the weathering processes have transformed the original iron-bearing rocks to ferruginous slate, ferruginous chert, and jaspilite, with bands and sheets of iron oxide; for every iron-ore deposit which is at present exploited in the Lake Superior region is confined to the portions of the iron-bearing formation showing these alterations. In proportion as soft iron ore or hematite is in places abundantly interbanded in the slate, chert, or jasper, or is in shots or small masses within these rocks, this is favorable to the existence of ore deposits. Uneven distribution of the iron oxide is a favorable sign,

even distribution is an unfavorable sign. The negative side of the above rule is that exploration should avoid those parts of the iron-bearing formation which are little altered and those in which deep-seated alterations have changed it to an amphibolitic or magnetitic slate or schist. Nowhere in the Lake Superior region, where the entire iron-bearing formations have been transformed to amphibolitic and magnetitic schists are ore bodies being exploited, nor have ore deposits running above 50 per cent metallic iron been found. This statement applies to the west end of the Penokee-Gogebic district, at least so far as the Bad River, probably as far as Tylers Fork, and possibly to the Potato River[1] and to that part of the iron formation east of the East Branch of Black River. The same statement applies to the east end of the Mesabi range, to the south belt of the Gunflint iron-bearing formation of the Vermilion district from a short distance west of Gunflint Lake to the western point at which the iron formation occurs at Disappointment Lake, to smaller areas in the other iron-bearing districts of the Lake Superior region, and to the whole of the iron-bearing formation of Black River Falls in Wisconsin. At various localities, as, for instance, at Penokee Gap on the Penokee range, at Akeley Lake and vicinity on the Gunflint formation, and at Black River Falls in Wisconsin, large sums of money have been spent in exploration in the lean, strongly magnetitic varieties of the iron-bearing formations, but as yet not one valuable ore deposit has been found in the refractory varieties of rock. Possibly, in the future, when lower-grade ores come into the market, these leaner portions of the iron-bearing formations will be drawn upon, but for the present they are not marketable.

The exclusion, for the present at least, of the amphibolitic and magnetitic portions of the iron-bearing formations from consideration in exploration is very interesting, the explanation of the exclusion being ascertainable only by an understanding of the difference between the nature of the deep-seated metamorphism of the iron-bearing carbonate and the superficial or weathering metamorphism of the same variety of rock. (See pp. 320–322.)

(4) The iron-bearing formations are likely to carry ore deposits of workable size in proportion as they are thick and pure, and where they are not pure throughout, in proportion as they contain thick belts which are pure. No merchantable ore deposits have been found within the iron-bearing formations where but a few feet in thickness, and but rarely where so thin as 100 feet. All the great ore deposits of the Lake Superior region of the United States are confined to those parts of the iron-bearing formation which are in considerable volume; in but few cases as small as 150 feet in thickness, and commonly several hundred feet in thickness. Even if an iron-bearing formation is in great volume and yet is subdivided by many layers of impervious

[1] Mon. U. S. Geol. Survey Vol. XIX, pp. 215–224.

material, such as slate or interbedded igneous rock, it will not be likely to carry merchantable ore deposits. However, if a considerable belt of iron-bearing formation is free from impurities within a large formation containing impurities, ore bodies of workable magnitude may have formed within the pure belt.

(5) Within the iron-bearing formations of the proper character and in sufficient volume search should be first made for contacts with other formations, either sedimentary or igneous. These contacts may be at the outer boundaries of an iron-bearing formation, or may be within an iron-bearing formation. Within the iron-bearing formations the contacts may be caused by an interstratified slate, or may be due to an intrusive igneous rock. When a contact is found, the search should be first confined to the iron-bearing formation comparatively near the contiguous rock, and later slowly extended from it.

(6) The iron-bearing formations adjacent to contacts are especially likely to be fruitful in ore where considerable thicknesses of the iron-bearing formations are above the contacts rather than below them. The most favorable contacts are those at the bottoms of the iron-bearing formations, for in such cases the entire iron-bearing formations are above the contacts.

(7) Those contacts are especially favorable to the existence of ore bodies in which the formation in contact with the iron formation is relatively impervious. This impervious formation may be a sedimentary shale, slate, or schist; may be a layer of quartzite underlain by a slate; may be a schist produced from mashing of a limestone; may be a surface volcanic or schist produced from the same; may be an intrusive igneous rock or a schist produced from the same; or, finally, may be any combination of these. These impervious strata are often soft, being heavily stained with iron oxide and are frequently known by the mining men as paint-rock or soapstone.

(8) The contacts are most likely to bear ores where the basement formation constitutes a pitching trough. The pitching troughs may vary from sharply V-shaped to broadly U-shaped. Where pitching folds occur, even if troughs are not at first located, it is a favorable indication, for where subordinate anticlines are found synclines are necessarily adjacent. Every iron-ore deposit of the first magnitude in the Lake Superior region of the United States rests upon an impervious pitching trough.[1] However, in some cases this fact has not appeared until development had gone far. This is very well illustrated by the Aragon mine in the Menominee district, which was found just below

[1] See The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Mon. U. S. Geol. Survey Vol. XIX, 1892, Pl. XXX, p. 508, and Pl. XXI, p. 510.

The Marquette iron-bearing district of Michigan, by C. R. Van Hise and W. S. Bayley, including a chapter on the Republic trough by H. L. Smyth: Mon. U. S. Geol. Survey Vol. XXVIII, 1897, Pl. XVI, p. 338; Pl. XXVIII, p. 394; Pl. XXIX, p. 398, and Pl. XXIV, p. 545.

The Menominee special folio, Michigan: Geologic Atlas of the U. S., folio 62; U. S. Geol. Survey, 1900, fig. 4, p. 7; fig. 5, p. 8; figs. 8, 10, 12, 13, p. 9.

a little anticline of the Brier slate. When this deposit was followed it was found to rest upon a syncline and there became of great size. (See Pl. LVII.)

(9) The more shattered and broken the iron-bearing formation, the more favorable is this to the production of ores. Few or no large ore bodies have been found where the iron-bearing formation has a uniform strike.

(10) In reference to topography, the favorable places for exploration are usually the minor depressions on the slopes or elevations. Such places are especially favorable if impervious basement formations are so resistant as to constitute higher lands about the minor depressions, and thus form drainage basins. The ore is likely to reach the rock surface at subordinate depressions, because in most cases the ore deposits are softer than the surrounding rocks, and consequently erosion has cut somewhat deeper into the ores. These depressions invariably contain a mantle of drift. Therefore, wherever other conditions are such as to be favorable for the development of ores, and minor depressions filled with drift are found, such places should be examined. Frequently explorers avoid these favorable places, since there underground water must usually be handled.

While the topographic criterion probably would apply throughout if the topography were now that of pre-Glacial times, the great modifications by glacial erosion and deposition make it necessary to apply this criterion with caution. Ores may be and have been found below areas which are low lying.

(11) Exploration should at first be shallow. All or nearly all of the ore deposits in the Lake Superior region yet discovered somewhere approach or reach the solid rock surface. Therefore, the first step in exploration should be to penetrate the drift by numerous test pits, trenches, or drill holes, in order to find, if possible, a deposit just below the drift. A deposit once found should then be followed wherever it goes. Of course, in those areas where the drift is very deep, and in which it is advisable to put a test shaft through the drift, it may be best to do rock work under the drift with diamond drills or cross cuts, and thus make the best use of the expensive test shaft, rather than to sink other equally expensive test pits. But if the drift be shallow, the first step in actual exploratory work is thoroughly to test the area by work to the rock surface. Had this method been generally followed in exploration, many of the ore deposits which were discovered only by expensive rock work would have been found at the rock surface at a much less expense; for in many cases later developments have shown that ore deposits found by deep work through rocks reach the surface within short distances. Where the conditions are favorable for test pitting or drill work through the drift, only after thorough work has failed to find ores should rock work be begun. Of course,

in a case in which geological work renders it probable that an ore deposit may exist below a marsh, swamp, or lake, in many cases the cheapest way to explore such a place is to use some projecting point or island of rock as a base upon which to do rock work, rather than to handle great quantities of water in advance of the known existence of an ore deposit.

INDIVIDUAL DISTRICTS.

While all of the above are believed to be general rules which should guide in the exploration for iron ore in the different districts in the Lake Superior region, they combine in different ways so as to give local peculiarities upon the basis of which still more definite rules may be given concerning each district. Each district will therefore be separately considered.

Penokee-Gogebic district.—On account of the moderate pitches of the ore deposits, they expose a rather large area at the base of the drift; therefore the early work should be to the rock surface. The first essential in wise prospecting in the Penokee-Gogebic district is to find the junction of the iron-bearing formation and the underlying fragmental quartzite. (See Pl. XLIX.) Having determined the position of the foot-wall quartzite at several places, the next step should be to run a line of test pits east and west across the property to be explored, just north of the line between the ore formation and quartzite, with the hope of finding an ore deposit, and if not this, a dike rock. Other conditions being equally favorable, the west end of the property should be first examined, for the majority of the ore bodies pitch to the east, and a deposit found upon this part of the property would be likely to remain longer on the land explored. If the above preparatory work does not develop an ore body, but a dike rock is struck, the thickness of this dike, its inclination both to the south and to the east or west should be carefully determined. If several dikes are found, the area adjacent to the stronger should be first prospected. If its pitch can not be made out, assume that it is to the east, giving a trough between it and the quartzite which opens out to the east from the apex. If the dike be actually found to have, or is taken to have, an eastward pitch, very careful exploration should be made in the triangular area between the foot-wall quartzite and this dike to a distance extending to 200, 300, or even 400 feet east of the junction of the dike and quartzite and an increasing distance north in passing to the east. Usually the work should not extend more than 400 feet north of the quartzite. If an ore body exists upon the property in question at or within a reasonable distance from the surface, this triangular area is the place, as shown by the actual position of previously known deposits, at which it is most likely to be found. If a dike be found to have a western pitch, the triangular area west of the apex between this dike and the quartzite should be explored.

The known existence of a dike adjacent to and pitching toward a property would be a good reason for a thorough exploration upon the property near the discovered ore deposit. Under such circumstances a well-defined dike carrying an ore body upon adjacent land would warrant exploration through a considerable thickness of ferruginous chert in order to strike an ore body which might be below the rock surface of the land to be explored. But in general a property ought first to be well explored by test pits or drill holes which do not go below the surface of the rock, unless there is a great thickness of drift above it. If heavy drift overlies the rock surface, as already explained, this may be a sufficient reason for making the most of a test pit in exploring the area adjacent to it, either by cuts in the rock or by means of the diamond drill. As a matter of course, such exploration is much more expensive than where the country rock is near the surface. Under no circumstances should money be expended in exploration south of the fragmental quartzite, or farther north than 400 or 500 feet, or, at the outside, 600 feet; and work such distances north of the quartzite should be undertaken only in case of failure to find an ore deposit resting upon the fragmental quartzite.

The above statements give the limits of wise exploration, so far as the area of the iron-bearing formation is concerned. A further limitation is topographic. Other things being equal, crests and slopes should be explored rather than the valleys. While the minor cross valleys should not be neglected, the major cross valleys have as yet failed to yield valuable ore deposits.

Mesabi district.—While there are no hard and fast rules to be laid down to govern exploration in the Mesabi district, the work thus far done shows certain general features which may be of value in locating and carrying on further exploratory work.

The ore deposits of the Mesabi district have a great horizontal extent; they may occur almost anywhere within the limits of the iron-bearing formation; they are heavily drift covered. All the important ore deposits of the Mesabi district somewhere extend to the rock surface; that is, they extend as rich ore bodies directly to the drift. Moreover, the area of an ore deposit which reaches the drift is large; indeed, for the great ore deposits is far larger than in any other district. In the greater proportion of the deposits thus far discovered, exploratory work to the lower limit of the drift only has been necessary. This has been so frequently the case that formerly it was assumed that if rock was struck after penetrating the drift there was little use in going farther. However, it is now known that parts of ore deposits frequently lie under a moderate thickness of ferruginous slate or ferruginous chert, and it is the practice to penetrate some little distance into such rocks which may be reached in exploratory work. Of course an ore deposit which is found on one tract of land—for instance, a certain 40 acres—may pitch below the rock upon another tract, and those who explore this land may be obliged to do rock work. Not a few cases are known where earlier exploratory work, done mainly by test pitting to the rock surface, had failed to locate ore deposits, and later work by drilling through the rock has brought them to light. Due to this fact, there has been a tendency of late to go to the other extreme, and spend large sums in penetrating a great thickness of barren Biwabik formation material in the hope of finding ore. It should be remembered that much the greater area of the ore deposits thus far found come to the rock surface, and that when ore lies under rock, the rock usually has but very moderate thickness.

An examination of the map will show that the majority of the ore deposits now worked have their greatest bulk in middle or lower-middle horizons of the iron-bearing formations. Other known deposits not yet mined and not appearing on the map have the same position. If in any area the northern boundary of the Biwabik formation be known, the first work should be done at about the same distance south of this boundary as the average of the deposits already shown up.

If the boundary between the iron-bearing formation and the Pokegema formation to the north can be shown to have a backward swing, this is usually evidence of the existence of a syncline or trough in the Biwabik formation; and it has been found that such synclines are favorable to the deposition of ore bodies. As a matter of fact, in the present stage of exploratory work, the northern boundary of the Biwabik formation is so imperfectly known that for considerable areas the use of this criterion is not practicable. The exact location of the northern boundary of the Biwabik formation usually comes after and as a result of exploratory work. However, the formations north of the iron-bearing formation are harder and better exposed than the Biwabik formation, and it is frequently possible actually to observe major synclines in these rocks and thus infer their presence in the iron-bearing formation to the south. An examination of the map will show a number of synclines in the Biwabik formation to be indicated by northern swings in the harder formations to the north, as, for instance, in the Virginia area.

The positions of the troughs or synclines in the Biwabik formation may be indicated in another way. While the drift has greatly obscured their positions, it may be stated as a general proposition that the minor cross streams approximately follow the rock synclines. This is particularly likely to be the case where ore deposits are in the synclines, for two reasons: First, the ore deposits are softer than the associated rocks and their more rapid erosion has resulted in depressions which carry the small streams; second, the concentration of the deposits by underground water has resulted in solution and slump.

Finally, the associated rocks have frequently been found to be of value as an indicator of the proximity of ore deposits. Most mining men who have done much exploratory work in the district have in mind certain peculiar phases of the iron-bearing formation which they think are likely to be associated with iron ore. These phases vary greatly from place to place, and are given different importance by different men. Our work has not sufficiently progressed to allow of a classification of these rocks. It may be stated, however, that they represent altered phases of the iron-bearing formation, viz, ferruginous slates and ferruginous cherts, rather than the unaltered greenish and slaty phases to be seen in the higher horizons.

As a matter of present practice, because of the great length and breadth of the deposits, a comparatively few test pits or drill holes over a 40-acre tract are likely to locate a deposit if one of considerable magnitude exists, even when such holes are put down without reference to the surface topography or to the boundaries of the Biwabik formation. Indeed, it has been the custom in the past for explorers to take options on parcels of land, usually in units of 40 acres, or one-sixteenth of a section, anywhere within or close to the limits of the iron-bearing formation, and distribute their drill and test-pit work symmetrically in these areas. If ore be found, of course a considerable number of holes are put in to explore it. A principal factor which has governed the choice of these areas for exploratory purposes has been the proximity of known deposits, but in a number of instances the cross drainage lines have also been a guiding factor.

In summary, the favorable places for exploration in the Mesabi district are—

First. Middle or lower horizons in the iron-bearing formation.

Second. Backward (northern) swings in the iron-bearing or lower formations, showing the probable existence of a trough.

Third. Cross drainage lines which are likely to be superimposed upon troughs, especially if ore deposits have been developed in them.

Marquette district.—In the Marquette district, since the pitches of the ore deposits are not great, good-sized areas of the ores commonly reach the drift, and the early work should be exploration through the drift. It is to be remembered that there are three important classes of ores in this district; those at the bottom of the Negaunee iron-bearing formation, those within the Neguanee formation, and those at the top of the Negaunee formation, which run up also into the horizon of the Goodrich quartzite. The ores within the Michigamme formation will not be considered.

In prospecting for the first class of ores—those that rest upon the Siamo slate—a trough in the slate should be sought. A plunging syncline may be marked by a swing of the boundary line between this formation and the Negaunee formation, or a trough may be formed by a combination of the slate with a cutting dike or mass of greenstone, or a trough in the slate may be supplemented by an intersecting greenstone. Such troughs are illustrated by the mines east of Negaunee.

In the second class of deposits—those within the Negaunee formation—the pitching troughs are wholly formed by the intrusives. Here valleys of the iron-bearing formation, when nearly surrounded by an amphitheater of greenstone, furnish particularly favorable areas. The Lake Angeline and Cleveland Lake deposits finely illustrate this. Where the Negaunee formation in a valley is ferruginous slate and ferruginous chert, rather than grünerite-magnetite-schist, this is favorable. Pitching troughs bottomed by soapstone may exist underground which can not be discovered at the surface, since, where an intersecting intrusive is of small size and has been transformed to soapstone, it is eroded as rapidly as the Negaunee formation, and thus its existence is not discovered by outcrop or any topographic feature.

The third class of deposits, the hard ores, must always be prospected for near the contact of the Negaunee formation and the Goodrich quartzite. As in the previous cases, the ore bodies are particularly likely to exist if the two are folded so that the contact forms a pitching trough; and if this be bottomed by soapstone the conditions are still more favorable for the discovery of large deposits.

In the Marquette district, while, with other things equal, slopes should be first explored, it is to be remembered that this is a district of thick valley filling; that a number of the ore deposits occur below comparatively low-lying areas, and therefore that the structural factors above given should be controlling considerations rather than the topographic, although the latter should not be ignored.

Crystal Falls district.—In the eastern part of the southern half of the Crystal Falls iron-bearing district the explorer should use the Hemlock formation as the key rock. This is the basal formation upon which the Upper Huronian slates are laid down. The iron-bearing formation should be sought near this volcanic formation, and once located, exploration should follow along its strike. The majority of the ore deposits which have been found thus far average about one-fourth of a mile distant from the Hemlock formation. However, some of the ores are found much closer to this formation, as in the cases of the Hemlock and Mansfield mines. Furthermore, some of the deposits have been found as much as a mile, or even more, from the Hemlock formation, as in the case of the mines adjacent to Crystal Falls. The places adjacent to the Hemlock formation which are most favorable are those where the formation has a serrated outline, swinging in and out, showing that it is a folded area, and hence giving a series of troughs in which concentration of ore may occur. Other things being equal, this slate above embayments in the Hemlock volcanics should first be explored.

In the western part of the southern half of the district where are located the mines near Commonwealth, Florence, Iron River, etc., no specific rules can be given at present. The general principle that the ores occur in pitching troughs upon impervious slate holds, but the difficulty is in reference to key rocks. The rocks which approach most closely to key rocks are the carbonaceous and graphitic slates. These, however, are ordinarily soft, therefore largely covered with drift, and hence very difficult to map. I am therefore unable to give definite rules applicable to this part of the area further than that the search should be either for iron-bearing formation material itself or for the carbonaceous slates and schists, and that the prospecting work should follow these horizons.

I am not sufficiently familiar with the relations of the ore deposits to the topography in the Crystal Falls district to give definite rules in this matter. However, it is certain that here as elsewhere many of the larger mines occur upon crests or slopes. Illustrations of this are the Commonwealth and Florence. However, certain mines occur in comparatively low-lying areas, as, for instance, the Mansfield.

Menominee district.—In the Menominee district, since the pitches of many of the ore deposits are steep, the areas which reach the drift may be small, and hence some of them are difficult to discover by surface work alone. In this district there are four contact horizons along which search ought to be made, as follows: (*a*) The top of the Randville dolomite; (*b*) the contact of the Traders member with the Brier slate; (*c*) the contact of the Curry member with the Brier slate; and (*d*) the contact of the Curry member with the Hanbury slate. Where the contacts are plicated, giving embayments, these are especially good places to look for ore, for here pitching troughs may be expected. This is finely illustrated by the Walpole and Pewabic mines. The reentrant embayments of the Randville dolomite have already been sufficiently emphasized; and, above all, these areas upon which they open out are the most favorable places for prospecting; but it should be noted that an ore body, the main part of which rests upon the dolomite, may be first discovered along the contact between the Traders member and the Brier slate, as in the case of the Aragon mine. The Vulcan formation adjacent to plications of the formations above or below and adjacent to plications of the intermediate belt of slate should be very closely examined, whether the plications seem to mark anticlines or synclines, for where subordinate anticlines are found synclines are likely to be adjacent. This, again, is well illustrated by the Aragon, which was found just below a little anticline of the Brier slate.

To illustrate, we may consider the southern iron-bearing belt between Vulcan and Waucedah. Here the southern outline of the Randville dolomite should be represented on a large-scale map with the utmost care. If natural exposures are not adequate for this, the first step in exploration is to determine this outline by pits through the drift, which need not extend into the rock. When the dolomite is outlined, if embayments are found, these locate places for elaborate exploration. The embayments may open to the east or to the west. The areas for exploration are along the strikes of the rocks in the directions in which the embayments open. The distance from the head of the embayments to which explorations ought to extend should be determined by studying the relations of the ore deposits of the Chapin, Walpole, Pewabic, Norway, and Aragon mines to the associated limestone embayments.

Explorations along the contact of other belts of the iron-bearing members with the adjacent formations should follow a similar course.

In the Menominee district, other things being equal, the upper parts of slopes are the most favorable places for exploration. The majority of the larger deposits are found on such elevations. None of the great cross valleys are known to carry ore deposits. But it is to be remembered that the subordinate cross valleys contain two great deposits—the Chapin and Aragon—so that low-lying areas should not be neglected where other indications are favorable.

Vermilion district.—In the Vermilion district the rock in which the ore occurs is red hematitic jasper rather than the black magnetic iron-formation material. The known iron-ore deposits are all at the bottom of the Soudan formation. The pitching troughs are especially likely to occur at the ends of the iron-formation belts where they are surrounded upon three sides by the Ely greenstone. Places where the ends of these pitching troughs are on slopes, and amphitheaters of greenstone rise above them, are especially favorable for exploration. In proportion as the iron-bearing belts are broad and are heavily ferruginous jasper, this is favorable to successful exploration. But very frequently the broad jasper belts end not by a single fold but in a number of fingers, the ends of each of which, if of sufficient magnitude, are favorable places.

In the Vermilion district the pitches are ordinarily very steep. Therefore the area of a given ore deposit which reaches the rock surface is comparatively small. Moreover, the ore deposits which rest upon greenstone may fail to reach the surface. However, the exploration should begin at the contacts of the Soudan formation with the Ely greenstone, and especially at the ends of the folds or fingers, and should pass away from these contacts. This work at first should be to the rock surface, as elsewhere. The largest of the discovered ore deposits, those of Soudan Hill and Ely, were first discovered at the surface, and were traced below the surface. However, on account of the steepness of the pitch, the Chandler ore body quickly passed under rock, and could be reached only at the Pioneer by rock work. In this district, as in other districts where an ore deposit on an adjacent property pitches toward a property to be explored, this of course warrants rock work. Also where a well-defined pitching trough of good size is found in which the rock is heavily ferruginous jasper at its base, but showing no ore deposit at the rock surface, diamond-drill work would be warranted to test the bottom of the trough, with the hope of finding ore deposits which are very small where they reach the surface.

POSTSCRIPT TO MESABI SECTION.

[To face p. 434 of Part III, Twenty-first Annual Report, U. S. Geol. Survey.]

Since the Mesabi section of this paper was written a large amount of exploratory work has been done in that district. This work has in the main furnished confirmatory evidence for the conclusions above given, but facts have appeared which require slight modification of certain statements.

Many of the shallow pitching troughs containing ore (as in the Hibbing group) do not have their longer directions transverse to the trend of the range, but parallel to it. In such cases minor troughs carry the ore to the south in tongues, giving the southern boundaries fluted forms, and the deposits as wholes very irregular shapes. While the lobes of ore transverse to the range may be marked at the surface by slight topographic depressions, large portions of such deposits, particularly the northern portions, are not confined to depressions.

One of the principles which the senior author has strongly emphasized has been completely confirmed for the Mesabi district by recent work. The outlets for the water circulation in the rock troughs containing ore deposits there, as elsewhere, are higher, and in many cases much higher, than the bottoms of the ore deposits. This is in full accord with the theory of ore concentration in pitching troughs; for, as fully explained, difference in elevation between the inlet and outlet of a rock trough will cause the underground water to search the ground to a considerable depth below the level of the outlet, and yet escape at this outlet. Indeed, such a circulation was characteristic during the formation of the deposits of all the other iron-bearing districts of the Lake Superior region. But the Mesabi deposits are so shallow that some of the mining men have supposed that the circulation was wholly downward; whereas, following the rule, it has a downward component in the early part of the course and an upward component in the later part of the course.

The occurrence of the bulk of the iron-ore deposits between the elevations 1,450 feet and 1,600 feet has often been referred to by mining men as a guide for exploration. This does, indeed, furnish a valuable guide, but it is essentially the same as one of the guides for exploration mentioned in this paper, i. e., that the ore deposits are to be looked for in middle or lower horizons of the iron-bearing formation, which for the most part lie between these levels. If the ore deposits are concentrates formed by underground waters working down the south slope of the range, it is clear, as fully explained in the body of the paper, that the maximum activity of this water will be along the middle slopes. Along the productive part of the range, the lowest ground to the south has an elevation in the neighborhood of 1,350 to 1,400 feet, while the highest ground to the north varies in height from 1,600 to 1,800 feet, and the northern and southern boundaries of the iron-bearing formation lie within even closer limits.

The middle slopes of the range and also of the iron formation are thus somewhere between the 1,450-foot and 1,600-foot levels; and here are found the bulk of the iron-ore deposits. In other words, the laws of concentration by underground water given in the paper show why the bulk of the deposits are necessarily at middle slopes, and therefore somewhere between elevations of 1,450 and 1,600 feet. Yet an examination of the map shows differences in elevation of the surfaces of deposits in certain cases as great as 200 feet; and such variations in the productive part of the district, where the maximum difference in elevation of the borders of the iron-bearing formation does not exceed 400 feet, show that the so-called "rule" is a most elastic one. It is clear that the fortunate combination of the many factors mentioned in this paper are necessary for the concentration of the deposits.

During the present activity in exploration the western Mesabi lands are receiving considerable attention, and several deposits of low-grade ore, some of them before known, have been exploited. Much of this ore is at present not marketable because of a considerable content of silica in a loose form, resembling sand, but most of it is likely ultimately to find sale.

THE ARKANSAS BAUXITE DEPOSITS

BY

CHARLES WILLARD HAYES

CONTENTS.

ILLUSTRATIONS.

THE ARKANSAS BAUXITE DEPOSITS.

By Charles Willard Hayes.

DISTRIBUTION OF BAUXITE DEPOSITS IN THE UNITED STATES.

Although aluminum is one of the commonest of the elements which enter into the composition of the earth's crust, it usually occurs in combination with silica as silicate, and the oxide is comparatively rare. Like iron, the metal forms a number of oxides varying widely in their physical properties, which depend chiefly on the amount of water contained in combination. Thus corundum, the anhydrous oxide Al_2O_3, is found in small quantities associated usually with crystalline rocks. Diaspore, Al_2O_3 H_2O, and gibbsite, Al_2O_3 $3H_2O$, the first containing less and the second more water than bauxite, are found somewhat more widely disseminated than corundum, but always in small quantities. The only oxide which is found in sufficient quantity to form an important ore of the metal is bauxite. When pure this mineral has the formula Al_2O_3 $2H_2O$, although the proportion of water shows considerable variation and the aluminum may be partly replaced by iron. Ordinary bauxite, like the analogous hydrated sesquioxide of iron, limonite, probably contains several hydroxides in varying proportions. It also generally contains a variable amount of silica, which accompanies it as an impurity.

Bauxite has been discovered in commercial quantities at only three localities in the United States. These are the Georgia-Alabama district, a small district in southwestern New Mexico, and the Arkansas district. The Georgia-Alabama district has been described by McCalley,[1] Spencer,[2] and the present writer.[3] The only account of the New Mexico district is that published by Blake,[4] while the Arkansas deposits have been described by Branner[5] and Williams.[6]

[1] Alabama bauxite, by Henry McCalley: Proc. Ala. Indus. and Sci. Soc., 1892.

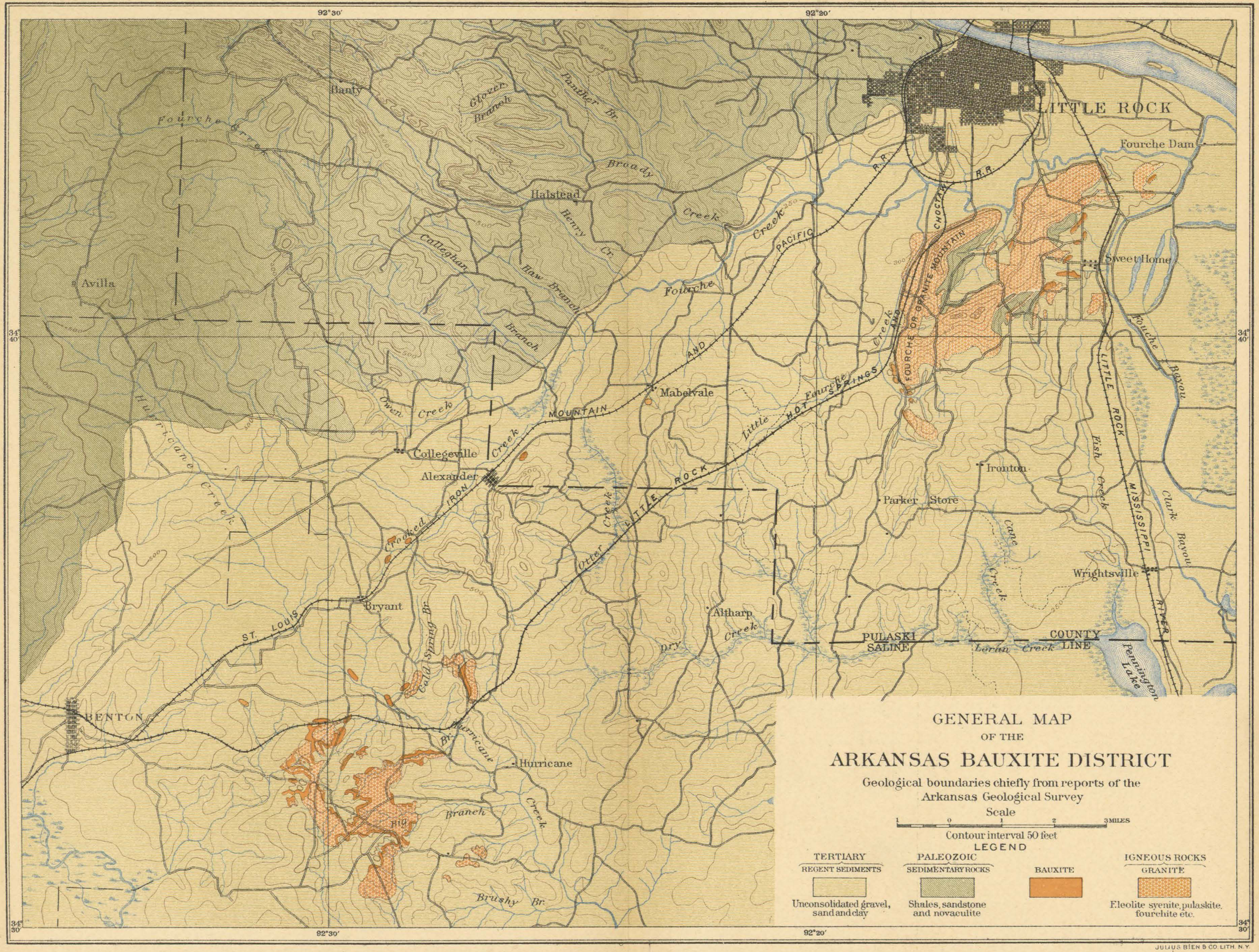
[2] The Paleozoic group, the geology of ten counties of northwestern Georgia, by J. W. Spencer: Geol. Survey Georgia, Atlanta, 1893.

[3] Bauxite, by C. W. Hayes: Sixteenth Ann. Rept. U. S. Geol. Survey, 1894–95, Part III.

[4] Alunogen and bauxite of New Mexico, by William P. Blake: Trans. Am. Inst. Min. Eng., Vol. XXIV, 1894.

[5] Bauxite in Arkansas, by J. C. Branner: Am. Geol., March. 1891. The bauxite deposits of Arkansas, by J. C. Branner: Jour. Geol., Vol. V, 1897.

[6] Igneous rocks of Arkansas, by J. F. Williams: Ann. Rept. Geol. Survey Arkansas, 1890, Vol. II.



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In the report on the Georgia-Alabama district by the present writer, it was pointed out that the ore there occurred in small isolated deposits, which would probably be exhausted within ten years from the time the report was made, in 1894. Since then the demand for the ore has increased, and the deposits may possibly be exhausted before the expiration of the time estimated. Three companies have been actively engaged in mining bauxite in this district; one of these has exhausted all of the deposits which it controlled, another is working upon its last deposit, and the third has left less than half a dozen which contain any considerable amount of ore. The constantly increasing demand for the ore and the prospective exhaustion of these deposits in the near future have compelled the operators to seek another field. Anticipating this necessity, two of the companies operating in the Georgia-Alabama district have invested heavily in the Arkansas district, and two additional companies have recently been organized in the latter field.

The Arkansas deposits have been known since 1891, when they were briefly described by the State geologist, but owing to the abundant supply of ore in the more accessible district they received little attention until it became evident that the deposits of the latter would shortly be exhausted. Only a small quantity of ore has yet been shipped from Arkansas, but preparations are being made for a large output in the near future. Additional railroad facilities have recently been secured, so that the difficulties of transportation have been largely overcome.

The field work on which the following report is based occupied about four weeks in the spring of 1900. The writer wishes to express his obligation for courtesies and assistance extended to him in the prosecution of the work, particularly by Messrs. Perry and McKenzie, general manager and superintendent of the Southern Bauxite Company; and to Mr. George Nethercutt, superintendent of the Illinois Chemical Company's mines.

LOCATION OF THE ARKANSAS BAUXITE REGION.

The bauxite deposits in Arkansas are, so far as known, confined to a small area lying south and southwest of the city of Little Rock. The region is about 20 miles in length and 5 or 6 miles in breadth, its longer axis extending northeast and southwest. It lies in the southern part of Pulaski County and in the northern part of Saline County. The location of the region and its general geographic relations are shown on the accompanying map (Pl. LX). By far the larger number and more important deposits are found in two small districts, occupying the extremities of this region. The northeastern is the Fourche Mountain district, which extends about 5 miles southward from the city limits of Little Rock, and embraces Fourche Mountain and the associated areas of igneous rocks. The second district, which is the more important of the two, occupies the southwestern extremity of the region, embracing about 12 square miles in Bryant Township. Between these two subdistricts are several isolated deposits of the ore, generally without any associated igneous rocks, but so distributed as to connect the main deposits at the extremities of the region.

GENERAL GEOLOGIC AND PHYSIOGRAPHIC RELATIONS.

The geology of the region southwest of Little Rock has been studied by the Arkansas geological survey, and the following outline of its geologic history is derived largely from the State survey reports:

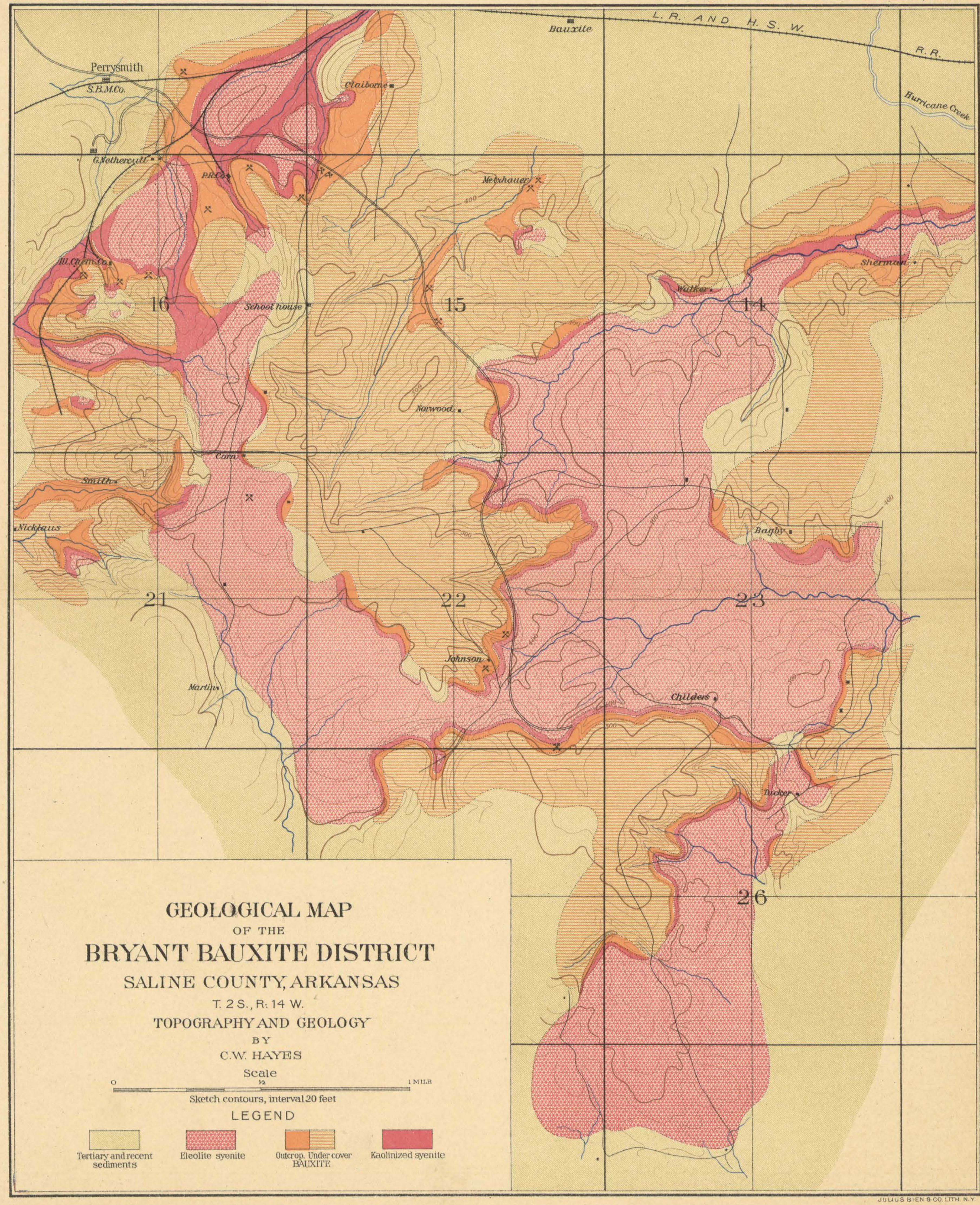
The region is occupied by three distinct groups of rocks. These are the Paleozoic sediments on the northwest, the Tertiary and recent sediments on the southeast, and the areas of intrusive igneous rocks which occur in the two bauxite districts above outlined. The boundary between the Paleozoic and Tertiary formations extends southwestward from the western edge of Little Rock approximately parallel with and a short distance to the west of Fourche Creek. This line, as shown on the accompanying map, is taken from Griswold's report[1] on the novaculite region. To the west of this line the rocks are chiefly shales, with beds of novaculite, and belong to the Lower Carboniferous and Lower Silurian. These beds have been intensely compressed and thrown into a series of folds whose axes in this particular region extend about N. 60° W. The structure of these rocks is very similar to that found in the southern Appalachian region of Tennessee, Georgia, and Alabama, and, like the latter, the folding to which it is due probably culminated at the close of the Carboniferous. It is impossible to determine definitely whether or not these folds in Arkansas are continuous with those of northern Alabama, since the intervening region is occupied by later sediments which effectually conceal the older rocks. The two regions, however, present so many similarities that it appears more than probable that the folds, if not absolutely continuous, are at least very closely related, alike in their age, the character of the rocks in which they occur, the date of their origin, and the nature of the forces by which they were produced. The folding of the rocks was followed by a long period of erosion, which probably several times reduced the region to a nearly featureless plain. It remained an area of dry land until late in Cretaceous time, when it was invaded by the sea and the older rocks were covered by Cretaceous sediments for some distance north of the present Tertiary boundary. The region was again elevated and the marginal Cretaceous sediments were removed, while at the same time the surface underlain by the older rocks was deeply etched, the softer rocks being removed and the harder ones left as ridges standing above the general

[1] Whetstones and novaculites of Arkansas, by L. S. Griswold: Ann. Rept. Geol. Survey Arkansas, 1890, Vol. III.

level. The material thus removed was carried toward the southeast and deposited. In later Tertiary time the region was again slightly depressed and the sea advanced somewhat beyond the present limits of the Tertiary sediments. The materials laid down in this Tertiary sea were chiefly clays containing considerable vegetable matter, a few marly limestones, and, finally, a great mass of sand and coarse gravel. A plain sloping gently to the southeast was built up along the margin of the older rocks. Its surface near the inland margin was composed of coarse material derived in part directly from the older rocks to the northwest and in part from the underlying Cretaceous and Tertiary beds, which had been many times worked over by the waves. The coarse reworked material was, therefore, most abundant within a narrow zone along the former sea margin where wave action was most effective, the fine material having been carried by littoral currents to a greater or less distance seaward. These gravels, which originally formed a continuous sheet over a belt bordering the old Paleozoic land, have been correlated by Hill and McGee with the Lafayette formation of the Gulf and Atlantic States. They were doubtless deposited for the most part approximately at sea level, but may also be due in some measure to the deposition of streams upon their flood plains.

At some period after the folding of the Paleozoic rocks, and probably also after the greater part of the erosion which these beds have suffered was accomplished, they were invaded by intrusive igneous rocks. The time of this intrusion has not been accurately determined, but, according to J. Francis Williams, it probably occurred some time during the Cretaceous. If most of the erosion of the older rocks had been accomplished as he is inclined to believe, it must have occurred late in Cretaceous time. Great masses of molten material were forced up from below, probably doming the strata over them and filling cracks in the overlying rocks, thus producing dikes. Some of the latter may have reached the surface, but there is no evidence that this region was at any time the locus of extensive volcanic activity. The continued erosion of the surface, following the intrusion of these igneous rocks, almost completely removed the sedimentary cover before the deposition of the Tertiary sands and clays. Immediately following this removal of the sedimentary rocks, and before the igneous rocks were again covered by the Tertiary sediments, the conditions were favorable for the formation of bauxite. This was deposited as a more or less continuous sheet, covering the surface of the igneous rocks and extending beyond their margins, where it was interstratified with the Tertiary sediments laid down before and after its formation.

Toward the end of Tertiary time the region was elevated. The sea margin retired toward the southeast, and the streams flowing from the Paleozoic highland on the northwest extended their lower courses across the littoral belt to the margin of the retreating sea. Erosion in



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the newly emerged, unconsolidated deposits was rapid, and the constructional plain bordering the Paleozoic land was deeply dissected. The region has probably suffered several oscillations since Tertiary time, but these have been only of minor importance, and their duration was not sufficient for the formation of well-marked coast lines.

The present topography of the region bears witness to these various episodes through which it has passed. To the northwest of the boundary separating the Paleozoic and Tertiary formations the surface is characterized by a number of parallel ridges extending about N. 60° W. These are formed by the outcropping edges of hard Paleozoic strata, the intervening valleys being upon softer rocks. The topographic features in this part of the area are, therefore, due largely to differential erosion, and the relief bears a very close relation to the structure. Southeast of the Paleozoic boundary the topography belongs to an entirely distinct type, that of a deeply dissected plateau. This plateau was formed of horizontally bedded materials almost entirely unconsolidated, and hence the present topography has not been determined by differences in the character of the rocks or by structure. The streams flow in broad, level valleys which extend nearly to their headwaters. The cols between opposing streams are low and broad, and only the smallest tributaries are cutting their channels. In some places the Tertiary sands have been consolidated by iron oxide, forming a ferruginous sandstone, and this has to some extent helped in the preservation of certain portions of the original plateau surface. The same effect has been produced where the gravel forming the upper surface was exceptionally coarse and heavy. The effect of these two factors, however, has been only slight, and the preservation of those portions of the plateau which remain depends more largely upon their location with reference to the main drainage lines. The largest areas of the plateau surface which remain in the district under consideration are just south of Alexander and between the waters of Hurricane and Holly creeks south of Bryant. The surface of these remnants of the plateau is slightly rolling, generally covered with coarse quartz and quartzite pebbles, and limited by abrupt slopes to the ravines which deeply indent its margins. It is probable that the surface of the igneous rocks from which the original cover of Paleozoic rocks had been removed was entirely covered by the Tertiary sediments. When erosion was renewed on the plateau surface by the elevation of the region the downward-cutting streams soon encountered the granite and were turned aside to the less resistant sands and clays. The surface of the syenite has, therefore, suffered little change since it was uncovered. The Fourche Mountain region is near the Arkansas River, where erosion has been most active, so that the greater part of the Tertiary cover has been removed, and the ridges of igneous rocks stand up boldly above the surrounding level or undulating plain. It is probable that if the region were elevated 100 feet or less, and the streams thereby again stimulated, the whole of the Tertiary cover between Fourche Mountain and the Paleozoic rocks to the northwest would quickly be removed. There is little doubt that this intervening region is occupied chiefly by Paleozoic rocks under a thin cover of Tertiary.

In the Bryant district conditions of erosion have been less favorable and the syenite surface is less completely uncovered. The highest land here, instead of being formed by syenite ridges, as in the Fourche Mountain district, consists of remnants of the Tertiary plain. The syenitic areas occupy intermediate elevations between the old plateau and the valleys of the larger streams. Their outlines in this region are extremely irregular, owing to the irregular manner in which the cover has been removed by erosion. As will be shown later, the syenite in the Bryant district is different from the prevailing type in the Fourche Mountain district, and the forms which the two varieties assume on weathering are quite distinct. This accounts in part for the differences in form of the syenitic areas in the two districts, the different stages of erosion, however, being the chief factor in producing the differences in form.

DETAILED DESCRIPTION OF THE BAUXITE DEPOSITS.

The two districts outlined above will be taken up separately and described in some detail, since each possesses certain peculiarities. The isolated deposits will then be described.

BRYANT DISTRICT.

This district is represented on the accompanying map (Pl. LXI). It lies in T. 2 S., R. 14 W., and covers between 8 and 9 square miles.

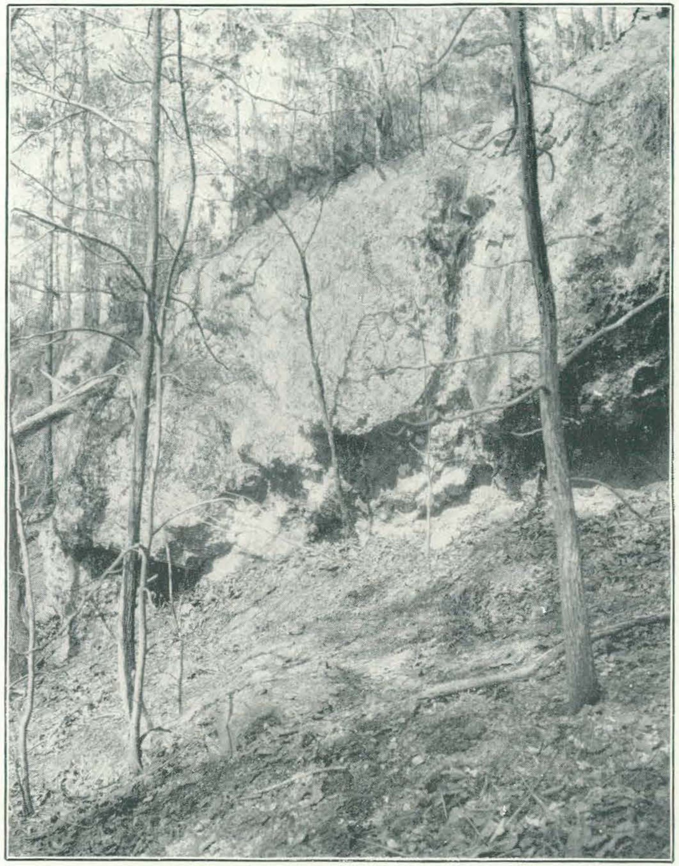
The formations to be considered are (1) igneous rocks, (2) kaolin, or chimney rock, and (3) Tertiary and later sediments, including bauxite.

IGNEOUS ROCKS.

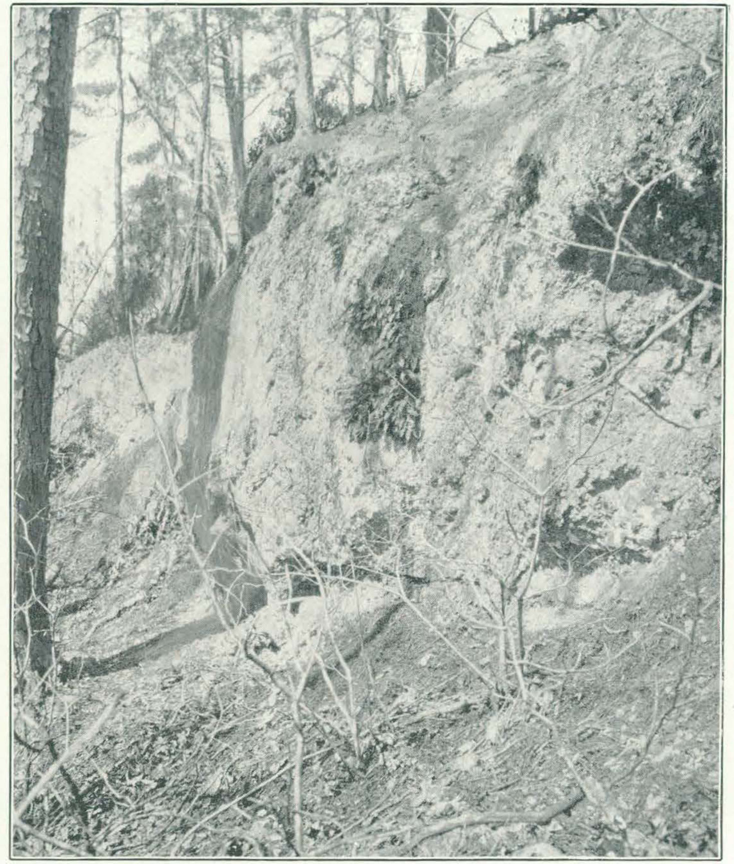
The igneous rocks have been studied and described by the late J. Francis Williams, of the Arkansas geological survey. The prevailing variety in this region is eleolite-syenite, which is described as follows:[1]

> It is a light-gray rock, with occasionally a pinkish or buff tinge given it by the flesh-colored or yellowish eleolite crystals. In general it is coarse-grained, but it varies extremely in this regard. It presents macroscopically a trachytic structure, which occasionally inclines toward a porphyritic structure on account of a diminution in the size of all the constituents except the feldspar.
>
> A pegmatitic appearance is very common and is due to the peculiar arrangement

[1] The igneous rocks of Arkansas, by J. Francis Williams: Ann. Rept. Geol. Survey Arkansas, 1890, Vol. II, pp. 130, 131; also p. 127.



A.



B.

OUTCROPS OF BAUXITE BED IN McGRUES HOLLOW, BRYANT DISTRICT.

of the large tabular feldspars. Feldspar and eleolite are easily recognized macroscopically, but the basic silicates present are usually too small to be identified by the naked eye.

For the most part it appears in large, flat, horizontal, or slightly sloping areas of smooth rock. Where enough soil has collected on these areas to allow of it, they are usually covered with a dense growth of cedars. It is, however, quite common to find open spaces of bare rock an acre or more in extent completely surrounded by a belt of trees; such openings are known as "cedar glades." In these glades the surface of the rock is generally smooth, and it is not an uncommon thing to find spaces containing several thousand square feet completely free from cracks or joints of any kind.

This rock, in the strict petrographic sense, is a syenite and not a granite, and although the latter term is universally employed by the inhabitants of the region, and also commercially, it appears preferable to use the less familiar but more accurate term syenite.

The outlines of the syenite represented on the map accompanying the report above cited were found to be incorrect in many particulars. These boundaries were, therefore, traversed and accurately mapped in connection with the study of the associated bauxite. In some cases the cover of sand is thin and contains numerous bowlders of the underlying igneous rocks, so that the exact extent of the outcrops of the latter is difficult to determine. Generally, however, the boundaries are perfectly sharp. In addition to the typical eleolite-syenite, which consists essentially of orthoclase and eleolite, another variety also occurs in which the orthoclase is more or less completely replaced by plagioclase. The latter differs, however, only slightly from the typical rock and a microscopic examination is necessary to discriminate the two varieties. There are also porphyritic phases and some dikes, but these are unimportant in the present connection.

KAOLINIZED SYENITE, OR CHIMNEY ROCK.

Wherever the surface of the syenite is protected from active erosion and yet is within reach of atmospheric agencies, it is covered by a formation probably varying in thickness from 30 to 60 feet, and evidently derived from the underlying rock by the ordinary process of rock decay. This consists essentially of kaolin, the hydrated silicate of aluminum. It is generally white except where stained by the percolation of iron-bearing solutions. It can be easily cut, and quickly disintegrates when exposed to the weather in such a position as to absorb moisture. Where it is slightly protected, however, it becomes quite hard after a short exposure to the air. This material is locally used for building chimneys, being sawed out in blocks of the required size with an ordinary crosscut saw. Although it appears to be entirely homogeneous and without structure when cut, the fractured surfaces, after exposure to the weather for a short time, generally show, more or less distinctly, the structure of the syenite from which it was derived. The downward percolation of surface waters sometimes gives it the appearance of stratification, but no true stratification has been observed in this rock. The thoroughly kaolinized phase is separated from the fresh syenite by an intermediate zone in which the alteration is only partial. This retains the structure of the original rock, but is changed in color and crumbles readily to sand. The feldspar crystals retain their form, although they have undergone considerable alteration. This intermediate layer is probably not more than 3 to 6 feet in thickness, although it was difficult to obtain anything approaching exact measurements. The layer of kaolinized syenite is readily eroded, so that natural outcrops are extremely rare. Its outcrops are generally represented by a zone, surrounding the syenite areas, covered with feldspathic sandy soil and occasional bowlders of the syenite itself. Where the surrounding Tertiary sands are higher than the syenite surface the soil covering the kaolin zone is composed of sand derived from the former rather than the latter. It is impossible to say how far this altered phase of the syenite extends under the cover of Tertiary sediments. If the conclusion is correct that the alteration is due to the action of percolating surface waters, it can not extend beyond the influence of the latter. It is probable, therefore, that under a thickness of 100 or 200 feet of Tertiary sediments the surface of the syenite would be found nearly or quite fresh.

TERTIARY AND LATER FORMATIONS.

These may be divided into two classes, the first composed of detrital deposits, chiefly gravel, sands, and clays, and the second of chemical deposits, bauxite and associated halloysite, gibbsite, and kaolinite. The first class comprises (1) stratified marine sediments and (2) unstratified fluviatile and beach deposits. This region has been studied and described by Harris,[1] Hill,[2] and McGee.[3]

According to Harris, the marine sediments belong to two formations, the Midway and the Lignitic. The Midway is relatively unimportant, consisting of some inches of impure limestone, observed at a few points in the vicinity of Little Rock. The Lignitic, on the other hand, consists of sands, sandy clays, and beds of lignite, and has a thickness of several hundred feet. Its materials show rapid alternations in character, both horizontally and vertically, changing from black carbonaceous clay to coarse white or yellow sand and gravel. Occasionally the sand beds have become cemented by iron, forming layers of brown or red sandstone. In some places, as at the northern

[1] The Tertiary geology of southern Arkansas, by Gilbert D. Harris: Ann. Rept. Geol. Survey Arkansas, 1892, Vol. II.

[2] The Neozoic geology of southwestern Arkansas, by Robert T. Hill: Ann. Rept. Geol. Survey Arkansas, 1888, Vol. II.

[3] The Lafayette formation, by W J McGee: Twelfth Ann. Rept. U. S. Geol. Survey, 1890–91, Pt. I.

edge of Saline County, these beds are sufficiently thick and uniform to be quarried for building stone.

The greater part of the surface underlain by these Tertiary sediments is composed of a later unstratified deposit. This consists of sand and gravel, in part the coarser constituents of the underlying formations and in part foreign material derived from the older formations to the northwest. This is called the Lafayette formation by McGee, and is correlated with similar material which occupies a corresponding position east of the Mississippi embayment. Harris does not give it a distinctive name, but refers to it as "reworked," "rehandled," or "rearranged" material, in distinction from the stratified and laminated material on which it rests. His view as to the origin of the material is indicated by the terms which he applies to it. Hill names this material the Plateau gravels, and subdivides it into a stratified division, now occupying only the high, flat stream divides, and an unstratified division, consisting of the débris from the former redistributed over terraces and lowlands. He correlates it with the Uvalde formation of southwestern Texas and with the Lafayette formation of the Gulf and Atlantic States.

This broad belt of coarse material evidently marks the position of a fluctuating coast line, and is in part a beach formation and in part the product of rapid meandering streams. It doubtless originally formed a rather uniform layer covering a smooth plain, the coarsest material being on the landward or northwest side of the belt, and growing gradually finer seaward—that is, toward the southeast. As the land rose and was trenched by streams, the fine sands and clays of the underlying beds were more easily removed than the coarse gravel, and the latter was largely rearranged upon the new slopes and stream terraces.

BAUXITE.

As stated above, the chemical deposits grouped under the general term bauxite may be regarded, in this district at least, as the basal members of the Tertiary. They differ radically in appearance, composition, and origin from all the other overlying Tertiary formations. While largely a chemical precipitate, the bauxite has some features which characterize ordinary detrital sediments. The most striking of these is its occurrence in the form of a bed having great lateral extent compared with its thickness. There is also some degree of stratification, the upper and lower portions of the bed differing somewhat uniformly in composition over the whole district.

The bauxite bed rests directly upon the kaolinized syenite or chimney rock, described on a previous page. As shown on the map of the district (Pl. LXI), its outcrops are in contact on one side with the overlying sands and gravels and on the other with the underlying kaolin. They are separated from the syenite by a narrow belt occupied by the outcrop of the kaolin. Since the latter is much softer than either the syenite or the bauxite, it is more readily eroded, and its outcrop generally occupies a shallow depression between the harder syenite and bauxite on either side. The unconsolidated Tertiary sands and clays are also more readily eroded than the bauxite, so that where erosion is well advanced the bauxite outcrop is apt to form a low ridge. The surface of the syenite is undulating, and the bauxite bed, which conforms to that surface, presents corresponding undulations. The altitude at which its present outcrop is found varies between 320 and 540 feet above tide, and it is probable that if those portions of the bed which have been removed by erosion were compared with the portions still concealed a considerably wider variation in altitude would be found.

In thickness the bauxite bed varies from nothing up to a possible maximum of 40 feet. The prevailing thickness over the greater part of this district is probably between 10 and 15 feet. In the present state of development, however, there is no basis for an accurate estimate of the thickness except at a few points. Its greatest thickness occurs in the northwestern portion of the district, in section 16, where it is at least 30 feet. From this section it thins somewhat regularly eastward and southward, although there appear to be numerous abrupt local variations in thickness in all parts of the district.

If the conclusion is correct that the bauxite was deposited as a bed mantling the undulating surface of the syenite and subsequently covered by the Tertiary sands and clays, its present outcrop probably represents but a small part of its actual extent and a much smaller part of its original extent. Systematic prospecting by drilling will be required to determine, even approximately, the distance from the present outcrops to which the bauxite bed extends beneath the Tertiary sands. An attempt is made on the accompanying map to indicate in a general way the probable extent of the bed under cover. The outlines there shown are based on the evidence of a few wells and inferences from observed direction and rate of thinning in the bed itself. It is quite probable that with increasing distance from the syenite areas the bauxite bed will not only grow thinner, but will contain increasing amounts of foreign detrital material. It will also probably be found interbedded with other Tertiary formations, or perhaps resting upon the Paleozoic rocks which there cover the syenite. The shaded portion of the map is intended, however, to represent only the probable extent under cover of a bed sufficiently thick and pure to be workable.

The bauxite in the Bryant district occurs in two distinct forms, (1) granitic and (2) pisolitic. At nearly every point where the bed has been opened up sufficiently to show the underlying kaolinized syenite its lower portion is composed of the granitic ore. This has a yellowish-gray color and a spongy structure, and is entirely free from any trace of pisolites. Generally more or less distinct traces of the granitic structure can be detected in this spongy material, the individual feldspars being replaced by a porous skeleton of alumina. Occasionally the original feldspar cleavage surfaces can be detected, though this is not generally the case, and often no trace of the original granitic structure remains. This granitic ore also occurs in the form of well-rounded bowlders from 2 or 3 inches to 2 feet in diameter. These bowlders are most abundant immediately over the stratum of the same material, but they are sometimes present when the latter is wanting, and are found more or less abundantly scattered through the whole upper portion of the bauxite bed. They are surrounded by a dense structureless shell from one-half to three-fourths of an inch in thickness. Within this shell is the same porous, spongy material that forms the basal stratum of the bauxite bed. Both porous interior and compact outer shell consist essentially of the hydrated aluminum oxide. It appears probable that this variety of bauxite is in every case derived directly from the syenite by the decomposition of the feldspar and eleolite and the removal in solution of the silica, lime, and alkalies, the alumina alone remaining of the original constituents. The material forming the basal stratum of the bauxite bed was doubtless derived directly from ledges of the syenite in place, while the bowlders of the same material were probably waterworn fragments of syenite which were freely moved about by waves or currents and received deposits of aluminum hydroxide on the outer surfaces. The conditions under which this process may have taken place will be more fully discussed later.

In the second form of ore of the Bryant district the pisolitic structure is always present, although varying widely in its degree of development. The pisolites are small round bodies, from the size of a pea to an inch in diameter, which consist of a nucleus surrounded by concentric layers of differently colored and textured material. The nucleus is generally softer than the outer layers, and darker colored. It is also generally intersected by radial cracks, apparently produced by the shrinkage of the material, and is sometimes represented by a fine powder or clay-like substance. The pisolites may be simple, containing a single nucleus, or compound, in which case the nucleus is itself a rounded fragment of some one of the several varieties of bauxite. These pisolites are embedded in a matrix which also varies considerably in amount and character. In some cases the matrix constitutes the larger part of the mass, while the pisolites are inconspicuous. It is then a compact structureless material somewhat resembling clay, but much harder. Ore of this character is apt to be very siliceous. At the other extreme is a mass of pisolites with barely enough matrix to fill the interstices between them and not enough to form a strong cement. The pisolites themselves are here more uniform in size and appearance than is the case in the Georgia-Alabama district. The majority vary between one-half and three-quarters of an inch in diameter. The fine oolitic structure is almost or quite absent and the largest pisolites of the coarse gravel ore are only rarely compound. Another difference is that the pisolites contain, generally, a larger nucleus and fewer concentric layers.

As might be inferred from the above, the pisolitic ore presents great diversity in appearance, but the several varieties pass into each other by such gradations that they are not easily classified. In some portions of the district the ore has somewhat the appearance of a partially compacted bed of gravel, the pisolites separating readily from the matrix, which consists of a structureless clay-like substance. This variety, constituting the gravel ore, can be readily dug with a pick and shovel and is prepared for market by washing and drying. The greater part of the bed in NE. ¼ sec. 16 has this form.

In the western part of the same section the ore is much more compact and forms a ledge which resists erosion and makes a prominent outcrop on the hillside, as shown in the accompanying illustrations (Pl. LXII). The matrix as well as the pisolites is here compact, and the latter are not readily separated from it. They are generally darker than the matrix, varying from red to dark purple or black. This ore requires blasting in mining, and is prepared for market by crushing and drying, without washing.

Another type of ore is seen in the NE. ¼ sec. 15. This also has a compact matrix and forms a solid rock body, but the pisolites are smaller and generally contain much empty space. The nuclei appear to have shrunk away from the inclosing concentric shells, probably through loss of water. In this ore the matrix is slightly reddish, and the pisolites are only a little more deeply colored.

These three varieties represent the greater part of the pisolitic ore in this district, although they are not sharply distinguished and there are numberless variations from the types described.

The pisolitic ore above described forms the upper portion of the bauxite bed. In some cases it constitutes the whole of the bed, resting directly upon the kaolin, but it is generally separated from the latter by a lower stratum of the granitic ore. It generally contains more or less abundant bowlders of the granitic ore, and the line separating the two varieties is rarely a sharp and definite one. Also, when several varieties of pisolitic ore occur in the same locality they are not arranged in distinct strata, although the general order of arrangement of the several varieties is somewhat uniform over considerable areas.

The composition of the bauxite varies within rather wide limits.

The purest variety is the granitic type, selected samples of which contain less than 3 per cent of silica and less than 1 per cent of ferric oxide. This variety contains more water than the bihydrate, bauxite, and corresponds in composition very nearly with the trihydrate, gibbsite[1]—Al_2O_3 $3H_2O$. The silica varies from 3 per cent or less in this gibbsite or granitic ore up to 20 or 30 per cent in some of the white bauxitic kaolins. The physical appearance of the ore undergoes a gradual change corresponding to the change in content of silica, and with long practice the miners become very skillful in estimating the composition of the ore by its appearance.

The iron varies from less than 1 per cent of oxide in some of the granitic and very white siliceous ores to over 50 per cent. The highly ferruginous ore is nearly free from silica and contains about the same amount of phosphorus as the common brown iron ores of the South.

In the Bryant district there is rather well-marked gradation in the character of the ore from one part of the district to another. The southern portion of the district is characterized by a preponderance of the granitic type and the central portion by the pisolitic, grading northward into the gravel ore. The iron increases rapidly toward the north, and in the northern portions of secs. 9 and 10 the ore at the surface is highly ferruginous, although recent prospecting has revealed a large amount of nonferruginous ore of which no indication was afforded by the natural exposures. North of the mapped area, in the channel of Hurricane Creek and beyond, there are large exposures of the ore carrying 50 per cent and more of ferric oxide.

At only a single point was there noted any considerable admixture of foreign material with the bauxite. The railroad cutting in the NW. ¼ sec. 10 exposes the bauxite bed, which consists of a deep-red, sandy matrix, containing a few pisolites and numerous fragments of sandstone and shale up to 3 inches in diameter. There are also rather obscure traces of stratification, with low dip to the southeast.

Some portions of the bauxite bed contain considerable iron, which is apparently secondary to the deposition of the bauxite itself. It often occurs in irregular convoluted plates intersecting the bed. On the sides of a cut these often appear as a narrow ribbon of limonite from half an inch to 1½ inches in thickness. A similar band of limonite frequently forms a shell about bowlders of granitic bauxite, in which case it is evidently due to secondary deposition of iron in the porous material of the bowlder. It is quite likely that this secondary iron is confined largely to the outer portion of the bauxite bed.

A short distance north of the area shown on the accompanying map of the Bryant district are some deposits of bauxite which properly belong with the latter, although they are separated from them by the

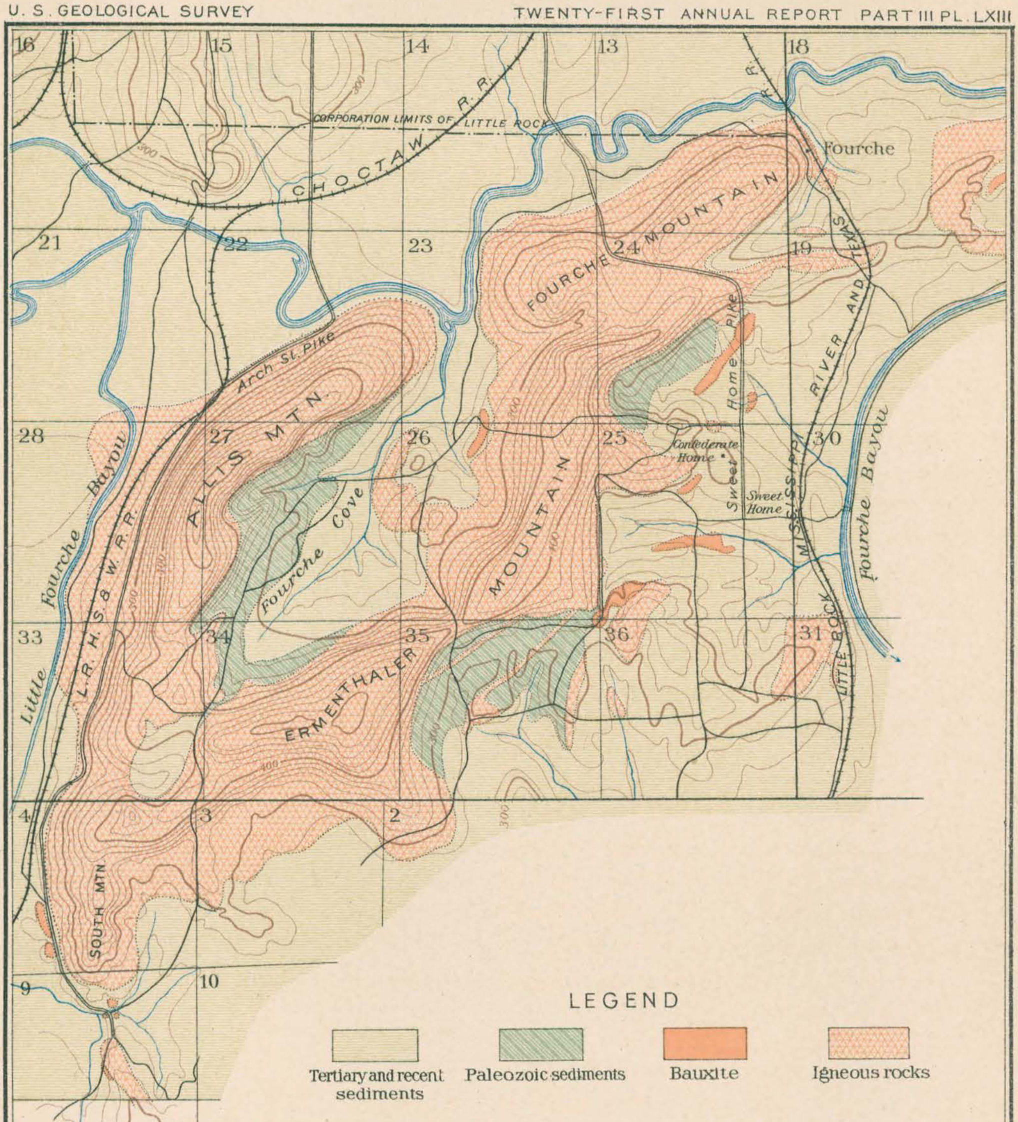
[1]The credit for having discovered and identified this gibbsite by means of numerous chemical analyses properly belongs to Mr. R. S. Perry, general manager of the Southern Bauxite Company.

valley of Hurricane Creek. Two groups of deposits occur in this region. The first includes the deposits exposed in the channel of Hurricane Creek, on Cold Spring Branch where it crosses the county road, and a little farther east on the Davis place. The ore is very ferruginous and at several points has been opened for iron ore, which it closely resembles on its outcrop. The three deposits are probably nearly or quite continuous under cover and contain the largest body of highly ferruginous ore yet discovered. The utilization of this ore is doubtless only a question of time. It closely resembles some of the Irish bauxites which are largely employed as iron ores.

The second deposit lies 2½ miles southeast of Bryant, on the headwaters of Cold Spring Branch. It appears to occupy a shallow depression between two large areas of syenite, although its relations are considerably obscured by the overlying sand. The ore is covered by 18 inches of sandy soil containing fragments of bauxite. Below this is a layer of bauxite from 1 to 2 feet thick, having a slightly shaly structure and consisting of gravel ore embedded in an abundant gray or white mottled matrix. The shaly structure may be due to weathering or to an indistinct stratification. Below this is a layer, 3 or 4 feet in thickness, consisting of large and small bowlders of pisolitic ore embedded in a matrix of loose gravel ore. The bowlders are from 2 inches up to 2 feet in diameter. Below this bowlder bed, and separated from it by an irregular surface, is 4 feet of soft bauxite containing some pisolites, which decrease in number downward. This has a yellowish, cream color and looks like a bauxitic clay. It differs materially from the kaolin which underlies the bauxite in the Bryant district, although the latter may also be present here but not exposed.

FOURCHE MOUNTAIN DISTRICT.

This district is represented on the large-scale map forming Pl. LXIII. As already stated, it occupies the northeast extremity of the bauxite belt, and, lying near the Arkansas River, erosion has here gone much further than in the Bryant district. No portion of the constructional Tertiary plain remains, but the high land is composed entirely of igneous rocks, which reach an altitude a little above 500 feet. As a result of this more extensive erosion the igneous rocks occupy a relatively large proportion of the surface; also, considerable areas of the Paleozoic cover are exposed about the flanks of the syenite ridges. The boundaries of the formations represented on this map are in the main taken from the geologic map of the Fourche Mountain region accompanying Volume II of the Annual Report of the Geological Survey of Arkansas for 1890. The boundaries have been changed in a few cases, and a more careful examination of the region would doubtless necessitate other changes. These changes would be chiefly in extending the boundaries of the igneous rocks so as to include areas



GEOLOGICAL MAP
OF THE
FOURCHE MOUNTAIN BAUXITE DISTRICT
PULASKI COUNTY, ARKANSAS

Topography and geologic boundaries, from
Arkansas Geological Survey

Scale
1 0 1 MILE

Contour interval 20 feet.

JULIUS BIEN & CO. LITH. N.Y.

covered by bowlders and soil evidently derived from the syenite itself. Such areas would appear to belong properly with the syenite rather than with the overlying Tertiary sediments. These changes in formation boundaries, however, are mere matters of detail, and do not materially affect the value of Dr. Williams's map. On the map published herewith no attempt has been made to represent the several rock types differentiated by Dr. Williams. The igneous rocks are represented by a single pattern, and the more or less altered Paleozoic rocks by another; also, the discrimination between Tertiary and Pleistocene is omitted. A very detailed study of the district might enable one to make this discrimination, but it would probably differ materially from that represented on Williams's map, the basis for which does not readily appear to one on the ground.

IGNEOUS ROCKS.

The igneous rocks of this district present considerably more variety than do those of the Bryant district, although the larger part of the area is occupied by the pulaskite, or "blue granite." This is described by Dr. Williams as follows:[1]

> When macroscopically examined the first thing which strikes the eye is the peculiar semiporphyritic appearance of the rock. The feldspar crystals stand out conspicuously on account of their highly perfect cleavage planes and the light reflected from them. The crystals are not usually sharply defined, but show a rough surface, due to the early formation of crystals of a second generation. Occasionally a flake of dark mica or portion of a crystal of hornblende or augite is visible, but in general the basic silicates are not conspicuous. In the spaces not occupied by the large feldspars a mass of finer-grained material appears, which shows minute reflecting surfaces, indicating that it is made up of small feldspars of a second generation.
>
> The color varies between wide limits, in some cases being a dark bluish-gray, while in other localities the rock is light gray (not the "gray granite"), but still retains something of the bluish tinge. The color depends upon that of the feldspar, and is not due, as might be supposed, to an admixture of dark-colored minerals in varying proportions.

Gray granite, or eleolite-syenite, similar to that found in the Bryant district, also occurs in the Fourche Mountain district, but forms a relatively small portion of the area. The igneous rocks form two main ridges, which unite toward the southwest. The eastern ridge bears the names Fourche, Ermentraudt, and South mountains, and the western ridge the name Allis Mountain. Between the two is Fourche Cove, opening northward, in which the syenite is for the most part covered by Tertiary sediments. The Paleozoic rocks, which originally covered the entire area, are now found in two areas along the eastern base of Fourche and Ermentraudt mountains, and also along the eastern base of Allis Mountain, extending around the southern end of the cove. They consist chiefly of shales which have been intensely folded and to

[1] Op. cit., pp. 39-40.

some extent altered by the intrusion of the igneous rocks. The extent of the alteration, however, is surprisingly small considering the great mass of molten matter with which they have been in contact.

The kaolinized phase of the syenite, which is so persistent an accompaniment of the latter in the Bryant district, is very inconspicuous in this region. It has been observed chiefly in Fourche Cove and at the southern point of South Mountain. It doubtless occurs elsewhere, but the conditions of erosion are such that it has been removed from the greater part of the region, and most of its outcrops are effectually concealed by débris from the higher granite ridges or from the adjacent areas of sand. The blue granite, or pulaskite, has a very different habit of weathering from the gray granite, or eleolite-syenite. Instead of forming broad, smooth areas of solid rock, its surface is covered to a considerable depth by angular bowlders, which are nearly as fresh as the rock in place. It is probable, however, that where the weathering takes place under a light cover of porous sand the rock is altered to kaolin, as in the case of the eleolite-syenite.

BAUXITE.

The bauxite of the Fourche Mountain district is confined chiefly to secs. 24 and 25, T. 1 N., R. 12 W., lying east of Ermentraudt Mountain, and to secs. 4 and 9, T. 1 S., R. 12 W., at the southern end of South Mountain. It also extends into the corner of secs. 26, 35, and 36. A single deposit is found in the eastern side of Fourche Cove, in secs. 23 and 26, and there is also a small one in the SW. ¼ of sec. 17. The striking regularity in the thickness of the bed observed in the Bryant district and its close conformity to the margin of the syenite are less conspicuous in this district. It is unsafe, therefore, to make any inference regarding the extent of the deposit under cover, and no attempt in this direction has been made on the accompanying map. The deposits much more closely resemble the isolated deposits to be described later than the continuous bed of the Bryant district. Throughout the whole of the district the ore is remarkably uniform in character. Only the pisolitic variety has been found, the granitic variety, so far as known, being entirely absent either in the form of bowlders or in that of ledges. Also the pisolites present little variation in size and structure. They are medium sized, both the oolitic and the coarse gravel ore being entirely absent in the outcrops. Somewhat greater variety may be found, however, when the deposits are more extensively opened.

The northernmost deposit of the Fourche Mountain district occurs in the SW. ¼ of sec. 17. Abundant fragments of pisolitic bauxite cover the side of a low ridge forming an oval area whose axis is parallel with the margin of the granite area on the northwest. The top and southern side of the ridge are covered with sand and gravel with many partly rounded bowlders of quartzite. The bauxite evidently extends southward under this cover, but no means are at present available for estimating its extent or thickness.

The next deposit met with is found on the Sweet Home pike, about 2 miles from the city limits of Little Rock. It forms a ledge exposed on the east of the road, in which it is at least 8 feet in thickness, and probably more. It appears to dip slightly to the east and to pass under the sand in that direction. The outcrop crosses the pike and extends for about half a mile toward the southwest, as indicated by numerous fragments of ore on the surface. It is separated from the syenite and the Paleozoic rocks on the west by a belt about the width of its own outcrop, in which there is no exposure of rock in place. The ore has a strongly marked pisolitic structure, the individual pisolites varying from one-fourth inch to an inch in diameter, the majority of them being between one-fourth and one-half inch. So far as observed, it contains no large bowlders. The pisolites are mostly composed of a hollow shell, containing a small amount of a fine, powdery substance. Some are entirely filled with a soft, clay-like material.

The next outcrop is to the east of the Sweet Home pike, in the SW. ¼ of sec. 24. This appears to form a low, dome-shaped mass, dipping slightly to the east. It may, however, be a continuation of the same bed which outcrops to the northwest. It is overlain by stiff red and gray clay, evidently belonging to the Tertiary beds. The next outcrop is in sec. 25, a short distance to the southwest of the Confederate Home. It forms a low ridge parallel with the edge of the syenite, and probably dips away from the latter to the southeast. The next deposit, in the S. ½ of sec. 25, forms a large exposure in the flat land of the creek bottom and extends in a low ridge to the westward, but appears to have no close connection with the syenite. A shaft has been sunk on the summits of the ridge formed by the bauxite and near the western end of the outcrop. It was filled with water at the time the district was examined, but is said to show 4 feet of hard, somewhat ferruginous bauxite, then 8 feet of stratified bauxitic clay of various colors, some layers having a slightly pisolitic structure. Below this the shaft penetrates 13 feet of white or grayish "joint clay" with no pisolites. This latter is probably a massively bedded sediment belonging with the Tertiary and not derived from the alteration of the syenite. Several wells between this deposit and the one last mentioned have penetrated the bauxite under a few feet of sand and clay, indicating that the bed is continuous between the two outcrops. In the southwest corner of sec. 25 is a considerable exposure which occupies a depression between two areas of syenite. On the east it appears to lie directly upon the syenite, while on the west it is separated by a considerable interval covered with sand. The outcrop extends southwest into the corners of the adjoining sections. The bauxite is here immediately overlain by a coarse ferruginous sandstone. The thickness of the bed is difficult to estimate, but it is probably under 20 feet. All of these deposits are very similar in character to the first one described, having a pisolitic structure and being free from bowlders. The principal variation is in the amount of iron, which, however, is rarely excessive.

The second group of deposits, at the southern end of South Mountain, is considerably smaller in extent. At the end of the Arch street pike, in sec. 9, T. 1 S., R. 12 W., there are several small deposits which appear to have been originally continuous, occupying a depression between the granite of South Mountain and a smaller area lying farther south, but in the axis of the higher ridge. The bed, as exposed north of the pike, is probably between 10 and 15 feet in thickness. If these several deposits are portions of an originally continuous bed, this thins rapidly toward the south, and at the most southerly exposure seen becomes less than 2 feet in thickness. Its relation to the syenite is here clearly seen to be similar to that prevailing in the Bryant district. The bed dips to the southwest, away from the adjoining syenite, from which it is separated by a bed of kaolin about 10 feet in thickness. The latter passes downward directly into the syenite, which is here the variety called by Williams pulaskite or "blue granite."

About half a mile northwest of these deposits are two much larger in extent lying west of the pike. They form low ridges extending in a north-south direction, parallel with the margin of the syenite, and separated from it by a narrow belt, probably underlain by kaolin, but in which there is no exposure. They were doubtless originally continuous, but have been cut through by a small stream flowing westward. The bauxite bed is probably 10 or 15 feet in thickness and is similar in character to the other deposits of this region.

This group of deposits at the south end of South Mountain contains a large quantity of ore, which appears to be of good quality. Unless different portions of the bed vary widely in composition, so as to necessitate expensive hand picking, the ore can be mined very cheaply, owing to the entire absence of overburden.

It is probable that in the Fourche Mountain district the original slopes of the syenite on which the bauxite was deposited were much steeper than in the Bryant district, and it is doubtful if the bauxite deposits covered so large a proportion of the syenite surface. If they were as extensive here as farther south, their present limited extent is due to the more extensive erosion which this region has suffered. The bauxite has been completely removed from the higher portions of the syenite, if it ever existed there, and remains only in patches around the outer margin of the original deposits. Those deposits which are found nearest the margin of the syenite doubtless rest upon the kaolin derived directly from the latter. This is certainly the case with the group at the south end of South Mountain, but the deposits which are more distant from the margin of the igneous rocks, as those in the SE. ¼ of secs. 24 and 25, are probably interstratified between sedimentary beds of Tertiary age. The repeated reworking by wave and stream action of the unconsolidated Tertiary deposits and the concentration on the surface of the coarser materials render it in most cases difficult or impossible to determine the relation which the bauxite bed bears to the adjoining formations.

ISOLATED DEPOSITS.

In addition to the deposits of the two subdistricts above described, a number of isolated deposits occur in the intermediate region. Their location is shown on the accompanying general map (Pl. LX), and they will be briefly described.

MABELVALE.

A single deposit occurs about a quarter of a mile south of Mabelvale station, on the Iron Mountain Railroad. It occupies the point of a low spur extending from the higher land on the southeast, and its surface rises about 15 feet above the surrounding lowland. The bauxite, so far as can be observed, forms a circular, dome-shaped mass about 115 feet in diameter. Its surface is covered by 18 inches of sandy soil containing fragments of bauxite. Below this is a solid ledge of bauxite, 5 feet and probably more in thickness, as the bottom is not exposed. The ore is very uniform in character, generally white or cream colored. The pisolites are abundant, and from one-eighth of an inch to one inch in diameter. These are embedded in a compact matrix, from which they separate with moderate ease. They consist of a thin shell, containing in most cases a small amount of black, yellow, or gray powder. A few contain a hard, horny substance and a few soft, white clay. On exposed surfaces the pisolites weather out, giving the ore the typical vesicular structure. The ore of this deposit is quite siliceous, containing from 14 to 18 per cent of silica. At the margins of the deposit it passes into a bauxitic clay, the pisolites becoming less abundant and finally disappearing at a distance of 15 or 20 feet from the typical bauxite. The surrounding clay has a mottled pink color and contains many small iron concretions. This relation appears to hold on three sides of the deposit, while the relations on the fourth side are concealed by the overlying coarse gravel. No syenite is found in the vicinity of this deposit nearer than Fourche Mountain, which is about 5 miles distant. In its form and relations to the surrounding formations it closely resembles the bauxite deposits of the Georgia-Alabama district, and it is quite possible that it may have been produced under conditions similar to those which prevailed in that district, although, as will be shown later, the chemical reactions involved must have been entirely distinct in the two cases.

ALEXANDER.

About a mile northeast of Alexander, opposite the northern point of a rather high ridge, is a small deposit of bauxite whose relations are probably similar to those observed at Mabelvale. The exposures, however, are less satisfactory and the ore was observed only in the form of loose bowlders covering the surface. It appears to pass into a bauxitic clay containing occasional pisolites. The ore is highly ferruginous, and probably contains much silica also. No syenite occurs in the vicinity, and the bauxite is apparently interbedded with red and blue fissile clays and ferruginous sandstone. Numerous thin bands of lignite are said to occur in the clays which form the above-mentioned ridge.

BRYANT.

About a mile northeast of Bryant station there are several deposits of bauxite, in the northwestern portion of sec. 25, T. 1 S., R. 14 W. The only one which is well exposed is in the northwest quarter of the section. It outcrops on a gentle slope and appears to be in the form of a bed interstratified with the Tertiary sediments. It consists of a layer of hard pisolitic bauxite 2 or 3 feet in thickness, which is very uniform in appearance and contains no large pebbles or bowlders. Below this is 3 feet of soft bauxitic clay, mottled white and red, containing a few pisolites. This also contains some iron concretions. Its total thickness could not be determined, nor the character of the material on which it rests. No syenite occurs in this vicinity, and these deposits are in this respect similar to those of Alexander and Mabelvale.

BEARDEN.

A fourth deposit similar to the above occurs about 3 miles southwest of Bryant, in the SW. $\frac{1}{4}$ of sec. 5. The bauxite here occupies the bottom of a shallow depression, its surface being exposed in a ravine, and numerous fragments overlying an oval area several hundred feet in diameter. Neither the thickness of the deposit nor the character of the underlying material could be determined. The ore is uniform in appearance, having a pisolitic structure and containing considerable iron. It appears to dip toward the southeast at a low angle, and it is possible that an area of syenite may occur to the northwestward, entirely concealed by the overlying sand and gravel. No indications of the syenite, however, are present, and this deposit must be classed with those above described, which are entirely dissociated from any areas of the igneous rocks. It is quite possible that this bauxite bed may extend toward the southeast, under the cover of sand, and be continuous with the bed which extends northwest from the Bryant district.

ORIGIN OF THE DEPOSITS.

In considering the origin of the Arkansas bauxite deposits it may be well to review briefly the theory which has been accepted for the origin of the ore in the Georgia-Alabama region. The deposits are there found embedded in residual clay derived from the weathering of limestone. The limestone overlies a great mass of shales, and the formations are intersected by numerous faults, along which water has in the past found easy access to great depths. The shales are made up largely of silicate of aluminum. They also contain considerable iron sulphide in the form of pyrites. It is believed that surface waters, carrying oxygen in solution, gained access to these shales and, by oxidizing the pyrites, set free sulphuric acid. This, under the conditions present, decomposed the aluminous shales, forming alum and sulphate of aluminum. Ascending currents carried these salts in solution to the surface, and, coming in contact with the limestone during their upward passage, they were decomposed, forming sulphate of lime and aluminum hydroxide, together with basic sulphate of aluminum, which was subsequently changed to aluminum hydroxide on exposure to the air. The aluminum hydroxide thus produced formed a gelatinous precipitate which collected about vents of springs. It was kept in motion by the ascending water and thus formed concentric structures. The reactions indicated above are all known to take place in nature, and the process is one which is readily understood.

It will be seen at a glance that the conditions involved in the process above outlined are for the most part absent from the Arkansas region. Not only are there no limestones or aluminous shales in the vicinity of the bauxite deposits, but the latter are so intimately associated with the igneous rocks that genetic connection between the two is immediately suggested. An entirely different process must, therefore, be appealed to to explain the formation of these deposits.

The pisolitic structure which characterizes the upper portions of the bauxite bed indicates that they were formed as a chemical precipitate. So far the origin of the deposits in the two regions is the same. While the formation of aluminous pisolites has never been observed in nature, the process which produces the same structure in calcareous and siliceous materials has been observed and fully described. In all cases where this structure results the material is deposited either from solution or from suspension in the form of a fine precipitate. In all cases the material precipitated collects about nuclei, composed either of a foreign substance or of compacted portions of the precipitate itself, and, being kept in motion, fresh surfaces are continually exposed on which additional concentric layers of the material are deposited. In many cases organic agencies in the form of algæ are instrumental in the formation of the concentric structures, but this agency does not appear to be essential. It may be assumed, then, that the material forming the bauxite deposits was in solution or in suspension in the form of a gelatinous precipitate. This applies to all the material having a pisolitic structure. The granitic bauxite forming the lower portions of the bed, and the bowlders with rounded surfaces and porous structure, are evidently of a different origin. The rounded forms suggest water action, either of streams or of waves of sufficient intensity to move masses of considerable size. The presence of even a trace of the granitic structure characteristic of the associated syenite is conclusive evidence that the material is residual or pseudomorphic and that this variety of the ore was at one time waterworn bowlders or solid ledges of that rock.

The syenite under ordinary atmospheric conditions weathers to a final product consisting essentially of the hydrated silicate of aluminum, or kaolin. It is evident, therefore, that the conditions which prevailed during the deposition of the bauxite must have been totally different from those prevailing at the present time. The bed of kaolin which, everywhere in the Bryant district, and probably elsewhere, intervenes between the outcrops of the syenite and the bauxite is the product of such decomposition as is going on at the present time. It is impossible to say definitely whether the bauxite when formed was laid down upon a surface of fresh syenite or of kaolin. The former, however, appears to have been the case. Otherwise fragments of the kaolinized syenite would be found in the bauxite, for it is scarcely probable that when the syenite was once changed to kaolin it would undergo a further change to bauxite. In other words, there is no indication that the kaolin is an intermediate product between the fresh syenite and the bauxite. No fragments of the kaolinized syenite have been observed in the bauxite, but, on the other hand, the bowlders with granitic structure embedded in them indicate that the syenite presented a fresh surface from which they were derived.

Dr. Williams[1] has suggested two theories to account for the deposition of the bauxite.

The first is that the bauxite was formed by the decomposition of a bed of clastic material which was derived principally from the syenite. He regards it necessary that two transformations should have taken place: First, the decomposition of the syenite, with the formation of kaolin; and, second, the alteration of kaolin to bauxite by the removal of the silica.

[1] Op. cit., p. 124.

The second theory, which he regards as the more probable, is that the Tertiary sea penetrated to the still highly heated igneous rocks and that, under the influence of high pressure and high temperature, the constituents of the syenite were dissolved and brought to the surface in solution, the water emerging in the form of hot springs. As soon as the pressure was removed and the temperature was reduced, the excess of dissolved matter began to precipitate in the form of a basic hydrate of aluminum and iron, while the more soluble salts of the alkalies were still held in solution. The continual bubbling and movement of the water would result in the formation of concretions about some small nuclei.

One difficulty with this theory is that a sufficient time must have elapsed after the intrusion of the igneous rock for its complete solidification and the erosion of the overlying Paleozoic cover. Allowing the most rapid erosion conceivable, the time required to remove several hundred feet of indurated shales and sandstones must be very considerable, and it appears scarcely credible that the intrusive rock should have retained any considerable portion of its original heat until the completion of this process. It may be, however, that the region has been subjected more recently to igneous intrusions or dynamic disturbances which have given rise to thermal springs capable of producing the chemical results in question. The occurrence at the present time of hot springs only 30 miles distant from the bauxite deposits makes this view plausible.

Another difficulty in the way of the hot-spring theory is that the bauxite generally has the form of a rather uniform layer spread over the surface of the syenite. It does not occur, at any rate in this part of the district, in local accumulations such as would be expected to form about the vents of springs. It may be, however, that the even distribution of the material is due to the fact that the region was covered by the sea at the time the deposition took place. Under such conditions currents might so distribute the solution before or during the precipitation that local accumulations would not be formed. Some of the isolated deposits already described have somewhat the form which might be expected in a spring deposit, but this may be only superficial and disappear when they are more fully exposed.

A more serious objection to the theory which requires a deep-seated origin for the whole of the alumina contained in the bauxite bed is the presence in the deposits of the granitic ore. Conditions were certainly present at the surface favorable to the solution and removal of the silica, lime, and alkalies contained in the syenite and the deposition, in place of the constituents removed, of some alumina in addition to that which originally occurred in the rock.

Again, if the alumina were derived from considerable depths the passages by which it reached the surface should be in evidence.

Although large areas of the syenite are perfectly bare of any cover, no fissures or other channels of any kind have been observed by which water from great depths could reach the surface. This, of course, is negative evidence, and has weight only in proportion to the area of the syenite exposed.

While the objections to a theory of a wholly deep-seated origin for the bauxite appear serious, it is even more difficult to explain the conditions which must have prevailed at the surface if the reactions giving rise to the deposits were entirely superficial.

It seems probable that the true explanation will combine the two theories—on the one hand that which ascribes the deposits wholly to a deep-seated origin, and on the other that which ascribes them to superficial chemical reactions.

To summarize briefly, the main facts which a theory for the origin of these deposits must explain are as follows:

(1) The bauxite deposits are confined to the immediate vicinity of the two main syenite areas or the intervening region, which is also presumably underlain, in part at least, by similar intrusive rocks.

(2) The deposits contain little foreign detrital material, and, so far as observed, no fragments of the Paleozoic rocks originally covering the syenite.

(3) The ore occurs as a bed having great lateral extent compared with its thickness.

(4) The ore bed occurs as a tolerably regular mantle, following the undulations of the syenite surface, varying in altitude 220 feet or more, and only slightly thicker in depressions than on elevations.

(5) The ore bed, wherever it is in contact with the syenite, is generally composed of two distinct varieties—the granitic below, resting on the altered syenite, and the pisolitic above.

(6) Those deposits which are underlain by Tertiary sediments or which occur at a distance from the syenite contain only pisolitic ore.

(7) The pisolitic ore bears evidence of having been brought to its present position in solution and then deposited as a noncrystalline precipitate.

(8) The granitic ore bears evidence of having been formed by the action of a chemical solvent upon the fresh syenite.

(9) The bowlders of granitic ore are thoroughly waterworn.

(10) The ore bed is immediately overlain by horizontally bedded sediments, probably marine.

The theory which best conforms to these premises may be briefly outlined as follows:

The syenite of the bauxite region was intruded under a light cover of Paleozoic rocks. These were subjected to rapid erosion and the surface of the syenite was exposed. Either its subjacent portions retained a considerable portion of their original heat or a fresh supply of heat was furnished by renewed intrusions or dynamic disturbances. The region was then covered by a body of water probably cut off from the sea, and salt or highly alkaline. The alkaline waters by some means gained access to the heated portions of the syenite and dissolved its minerals. The heated waters returned to the surface heavily charged with the constituents of the syenite in solution. They were still efficient solvents, however, and acted upon the syenite at the surface, removing most of the silica along with the lime and alkalies, but leaving the alumina and depositing in place of the constituents removed about as much more alumina as the rock originally contained. Some of the alumina brought to the surface in solution was thus deposited by this metasomatic process, replacing a part of the silica removed from the syenite, but a larger part was thrown down as a gelatinous precipitate on the bottom of the water body and somewhat evenly distributed over the undulating syenite surface, at the same time acquiring the pisolitic structure and becoming mingled with the bowlders of aluminized syenite. Most of the spring exits were in the immediate vicinity of the syenite areas, so that there the water was most strongly impregnated with the various salts in solution and hence precipitation of the alumina was most rapid. Wherever the ascending solutions found their way to the surface by an isolated conduit through the Tertiary sediments already deposited a local deposit of greater or less extent was formed. The precipitation of the alumina must have taken place almost immediately after the solution emerged from the conduit, otherwise the bauxite would have been much more widely disseminated, or even entirely dissipated, in the surrounding sediments.

The formation of the bauxite bed marks a single episode in the history of the region, during which conditions were very exceptional. This episode was abruptly inaugurated and as abruptly terminated. Conditions returned to the normal, and the change from the unusual chemical deposits to the ordinary sedimentary beds is sharp and distinct. The formation of the chemical deposits may have been terminated by a cessation of circulation of the chemical solvent, by a sudden exhaustion of the heat supply, or by a change in the conditions of the water body in which the deposits were being formed. The latter cause appears the more probable one for the production of so abrupt a change. If such a water body were comparatively small, of exceptional composition, and protected from the incursion of detrital sediments, as appears probable, the establishing of free connection with the open sea would introduce changes which might completely alter the character of the deposits being formed.

The theory outlined above is the best at present available, though it is confessedly unsatisfactory and incomplete. Additional light will be thrown on the subject by a study of the various chemical reactions which are assumed to have taken place in passing from the syenite to the bauxite, and also by further study of the relations which the deposits bear to the various associated formations. Such information will come only with the further development of the field.

ECONOMIC RELATIONS.

DEVELOPMENT.

In view of the distance of these bauxite deposits from the consumer it is manifest that a great saving would be effected by refining the ore at the mines. Much of the ore is at present used in the manufacture of aluminum sulphate, or commercial "alum," which is in large demand by paper manufacturers. It is at present cheaper to transport the bauxite to the sulphuric acid than the acid to the bauxite. The reduction of zinc ores, however, can be made to yield a large amount of sulphuric acid as a by-product with very little additional expense. This does not bear long transportation, and if utilized at all it must be near the point of production. The proximity of the Missouri zinc deposits to the Arkansas bauxite deposits suggests the practicability of bringing the two ores together and utilizing the by-product of one process in performing the other. When used as an ore of aluminum the bauxite is first converted into pure anhydrous alumina, Al_2O_3. About 2 tons of bauxite are required for the production of 1 ton of alumina. The value of the bauxite at the mine is about $3 per ton, whereas the value of the alumina is $60 per ton. Hence, if the refining were done at the point of production the value of the product shipped would be increased about ten times, while the weight would be decreased one-half. Since the freight on the crude ore to the factories in Pennsylvania and elsewhere is nearly twice the value of the ore at the mines, the saving in freight alone by this reduction in weight would be very considerable, even though the rates might be somewhat higher on the refined than on the crude product. Considerable advantage would also result from having the refining plant at the mines by reason of the greater ease with which a blended ore might be obtained exactly suited to the refining process employed. The only advantage which the present plan offers is the fact that plants for the treatment of the ore are already established and the necessary skilled operatives and the required chemicals are at hand in the East, while they are entirely lacking in the Southwest. This, however, is a temporary advantage, and when it is recognized that the Arkansas field must supply the raw material for the production of aluminum and the aluminum salts for many years to come, it is evident that economic considerations demand the establishment of refining plants at the point of production. Little if any demand has hitherto existed for the necessary chemicals in the Southwest, but it is altogether probable that both sulphuric acid and caustic soda can be produced as cheaply in Arkansas as at any other point in the United States when the necessary plants are once established. It is evident from the figures given in this report that refining plants may be established with perfect assurance of the supply of ore being sufficient for many years.

The present method of drying the ore serves merely to drive off most of the moisture. It is probable, however, that a considerable saving in weight may be effected by grinding the ore and heating it to a sufficiently high temperature to drive off a part of the chemically combined water. If all the water were driven off, the ore would be rendered very much less soluble, but the solubility appears to be little if any affected so long as from 6 to 8 per cent of water remains. A reduction in weight of 20 to 25 per cent might therefore be effected, and the consequent saving in freight would doubtless more than compensate for the expense involved in the process. Another advantage would be that a more uniform product could be supplied to the consumer, and one which would require no preliminary treatment before use. The crushing and grinding machinery now required by each consumer would thus be concentrated in a few plants at the mines.

An attractive and promising field is open for experiment in the treatment of the ore after mining. A reduction of a few per cent in the content of iron and silica increases the value of the ore so much that a heavy inducement is offered for the discovery of some method of treatment which shall secure this result. Competition with foreign ores and with the Georgia-Alabama district renders it possible to ship only the very best of the Arkansas ore, and any method of removing the objectionable constituents will render a much larger proportion of the output salable, and correspondingly cheapen mining.

The commercial development of the Arkansas bauxite field is as yet in its infancy. Although the nature of the deposits was recognized in 1891, their value was not appreciated until several years later. It was assumed by those interested in the bauxite trade that the Georgia-Alabama fields would supply all demands for the ore for many years to come, and its superior shipping facilities and nearness to market gave its product a decided advantage over that of the Arkansas field. A study of the geologic conditions under which the Georgia-Alabama deposits occur, however, showed that the amount of ore contained in them was limited and that the field would be exhausted within a few years. This led to an examination of the Arkansas field and to heavy investments in the lands containing the deposits. The first investor in the field was the Southern Bauxite Company (Perry & Smith), which secured a majority of the deposits. Shortly afterwards the Pittsburg Reduction Company secured several hundred acres of land in the

Bryant district, and the Illinois Chemical Company a somewhat smaller amount. Both of these companies have a large quantity of good ore in sight and have made some shipments.

A plant has been established at Mabelvale for the manufacture of alumina and aluminum salts. It was afterwards found that the bauxite at that point was too siliceous for use by the soda method, and the proprietor, E. Metznauer, secured a small tract of land in the Bryant district from which a considerable amount of good ore has been taken.

Shippers have, until recently, been dependent on the Iron Mountain Railroad, which involved a wagon haul of from 3 to 6 miles from the different portions of the Bryant district. In April, 1900, the Little Rock, Hot Springs and Western Railroad was opened for traffic, connecting with the Choctaw system in Little Rock. This road cuts through the northwestern portion of the field, and spurs are being built directly to the mines. A spur will also probably be built to the mines from the Iron Mountain road, while Perry & Smith have a charter and survey for a road intersecting the entire district and connecting with both trunk lines. With these increased shipping facilities the chief obstacle to the development of the district is removed, and it will doubtless become a large producer in the near future.

AMOUNT OF ORE.

An attempt is made on the accompanying map of the Bryant district to indicate, in addition to the actual areas of outcrop, the areas within which the bauxite bed, having a workable thickness, probably occurs under a cover of Tertiary sediments. It should be definitely understood, however, that the areas thus represented have not been tested in such a manner as to determine whether or not they contain bauxite. The estimates as to the extent of the ore are based entirely upon inference from observed relations at its outcrop, and, as represented, it can be regarded at best as only an approximation to the actual conditions. The map has been drawn conservatively, and it is quite possible that the ore extends farther than thereon represented. This, however, is a matter to be determined only by future systematic prospecting. It will be seen that the area of the ore bed under cover, if the inference is correct, greatly exceeds that of the outcrops and at present visible. The following table gives estimates of the amounts of ore in the outcrops and under cover contained in the several sections. They must be taken with a wide margin of allowance for probable error, but the amounts may possibly exceed those given rather than fall below. The average thickness of the bed on which the estimates are based has been taken much below the maximum observed in the several sections. It may still be too high, but is probably below rather than above the actual figure. This element in the estimates is liable to be materially changed as the field is more thoroughly prospected.

Estimates of amount of ore in Arkansas bauxite region.[1]

Section.	Quarter.	Outcrops.			Under cover.		
		Area.	Average thickness.	Amount.	Area.	Average thickness.	Amount.
		Acres.	*Feet.*	*Tons.*	*Acres.*	*Feet.*	*Tons.*
9	SW.	0	....	....	3	8	73,000
9	SE.	9	8	218,700	21	8	510,400
10	SW.	23	9	628,800	42	10	1,275,900
10	SE.	0	....	....	10	12	364,600
16	NW.	12	10	364,500	14	12	510,400
16	NE.	26	10	790,500	20	13	790,000
16	SW.	11	12	401,000	75	12	2,734,200
16	SE.	6	6	109,400	46	8	1,117,900
15	NW.	14	10	425,300	120	12	4,375,000
15	NE.	10	10	303,800	120	12	4,375,000
15	SW.	2	10	60,700	153	10	4,708,900
15	SE.	8	6	145,800	52	10	1,579,800
14	NW.	1	6	18,200	35	10	1,063,300
14	NE.	17	5	258,200	60	5	911,400
14	SE.	0	....	....	73	8	1,774,200
13	NW.	4	5	60,700	35	5	531,600
13	SW.	0	....	....	3	5	45,600
21	NW.	22	8	534,700	75	10	2,278,500
21	NE.	6	15	273,400	10	15	455,700
22	NW.	6	10	182,300	130	10	3,949,400
22	NE.	16	10	486,000	43	10	1,306,300
22	SW.	7	6	127,600	28	8	680,500
22	SE.	14	8	340,200	25	8	607,600
23	NW.	3	8	72,900	13	8	315,900
23	NE.	3	8	72,900	62	8	1,506,800
23	SW.	8	10	243,000	20	10	607,600
23	SE.	6	5	91,100	33	7	701,700
27	NW.	5	6	91,100	17	8	413,200
27	NE.	1	8	24,300	55	5	835,400
27	SE.	1	5	18,200	20	5	303,800
26	NW.	5	8	121,500	95	7	2,020,300
26	NE.	5	6	91,100	47	5	713,900
26	SW.	3	5	45,600	18	5	273,400

[1] The specific gravity of bauxite is taken as 2.5, and the amount of ore in a bed 1 acre in extent and 1 foot thick as 3,038 tons of 2,240 pounds.

	Tons.
Total amount estimated in outcrops	6,601,500
Total amount estimated under cover	43,711,200

The aggregate amount of ore in these deposits as indicated in the above table is very gratifying. Even if future prospecting should necessitate the revision of the table by reducing both the area under cover and the thickness of the bed the aggregate tonnage would still retain respectable proportions. No attempt has been made to estimate the amount of ore in the several isolated deposits above described, nor in the Fourche Mountain district. In these deposits the difficulties of determining the thickness of the bed are much greater than in the Bryant district. Also the relations of the bed to adjacent formations are more obscure, so that no basis is afforded for estimating the extent of the bed under cover.

QUALITY OF THE ORES.

How much of this aggregate will prove to be merchantable ore is a question which it is quite impossible to answer at the present time. The two constituents which detract from its value are iron and silica. The former is chiefly objectionable when the acid method is employed in refining, and the latter when the alkali method is employed. The experimental mining of the last year has shown that no difficulty will be experienced in obtaining ore which will run under 3 per cent in one or the other of these objectionable ingredients. The granitic variety promises especially well, since it generally contains less than 3 per cent of silica and almost no iron, except that which is segregated and can be removed by hand picking in the mine. Commercial analyses[1] of this variety give the following results:

Analysis of granitic variety of bauxite.

	Per cent.
Alumina (Al_2O_3)	63.00
Silica (SiO_2)	2.25
Iron (Fe_2O_3)	1.95
Water	31.50 to 32.75

Sp. gr., 2.7.

This agrees much more nearly with the composition of gibbsite ($Al_2O_3\ 3H_2O$=alumina 65.4, water 34.6) than of bauxite ($Al_2O_3\ 2H_2O$= alumina 73.9, water 26.1). If the definition of the bauxite family given by Lauer[2] be accepted, this material will be excluded. According to Lauer, the silica, iron oxide, and water may replace one another in all proportions, and the sum of these three variable elements always amounts to about 27 per cent. While this generalization is hardly borne out by the analyses of American bauxite, it is nevertheless true that the high content of water and the low content of silica and iron place this granitic bauxite in a class by itself. Although it possesses

[1] Analyses furnished by Mr. R. S. Perry, general manager Southern Bauxite Co.

[2] The bauxites: a study of a new mineralogical family, by Francis Lauer: Trans. Am. Inst. Min. Eng., Vol. XXIV, 1894, pp. 234-242.

no trace of crystal form except that which it inherits from the original feldspar, it would seem to belong more properly with gibbsite than with bauxite.

Some portions of the bauxite bed contain a very large amount of iron, going as high as 55 per cent Fe_2O_3. These highly ferruginous ores, however, make up but a small proportion of the entire deposits. In the Bryant district they are confined chiefly to the outcrops which occur north of Hurricane Creek and to the northern portion of the area represented on the accompanying map in secs. 9 and 10. It is possible that a part of this ferruginous bauxite may sometime be utilized as an iron ore, but there is no immediate prospect of this.

The iron of these ferruginous ores, and that which is present in greater or less amount in most of the bauxite of this region, giving it a reddish or mottled appearance, was doubtless precipitated along with the alumina. In addition to this iron, which is an original constituent of the bauxite, many of the outcrops contain veins of limonite, which is doubtless a secondary deposit. These, as already described, have the form of irregular undulating plates intersecting the bauxite bed and appearing on the sides of a cut as bands from 1 to 2 inches in thickness. They are in most cases nearly vertical, and appear to occupy shrinkage cracks. While the iron which is present as an original constituent will doubtless remain constant in amount, or nearly so, with increasing depth of cover, it is probable that this secondary limonite will be found to be confined largely to the outcrop. Prospecting has not gone far enough to afford definite information on this point, and it can only be stated as fairly probable. It is probable also that the ore will be found to contain a smaller percentage of silica at some distance under cover than upon the outcrop. It is frequently observed that rocks which are compact and very siliceous on their outcrops are soft and porous under cover. This is due to the transfer of silica in solution from one part of the bed to another and its deposition in the exposed portions by the evaporation of the solvent. This decrease of silica with increasing depth of cover has been noted in the Georgia-Alabama deposits, and in the Arkansas deposits the conditions are even more favorable for the transfer of silica to the outcrop.

If, as appears probable, the ore is found to improve in quality by a decrease in both iron and silica with increasing depth under cover, this improvement may be sufficient to compensate for the added expense of mining under a heavy overburden.

MINING AND PREPARATION OF ORE FOR MARKET.

As already stated, the ore shipments thus far made from the Arkansas district have been largely experimental, and final mining methods have not yet been developed. For working the outcrop the methods will be extremely simple. The few inches or feet of soil covering the bauxite bed is removed, and the ore is taken out by ordinary quarrying methods. In some cases, as at the Illinois Chemical Company's mines, shown in Pl. LXIV, the ore requires blasting. On the Pittsburg Reduction Company's property, in the adjoining quarter section, the ore has the appearance of a partially compacted gravel bed, and can be mined with little or no blasting. In sec. 22, where the granitic ore is most abundant, the bed is only slightly compacted and can be easily worked with a pick.

Where the bed contains bowlders of granitic ore, hand picking is necessary to separate the different varieties. This will add somewhat to the cost of preparing the ore for the market, but the increased cost will probably be more than compensated for by the higher grade of the product. Hand picking is also rendered necessary where there is much segregated limonite. By careful attention in mining this form of iron can probably be almost entirely eliminated.

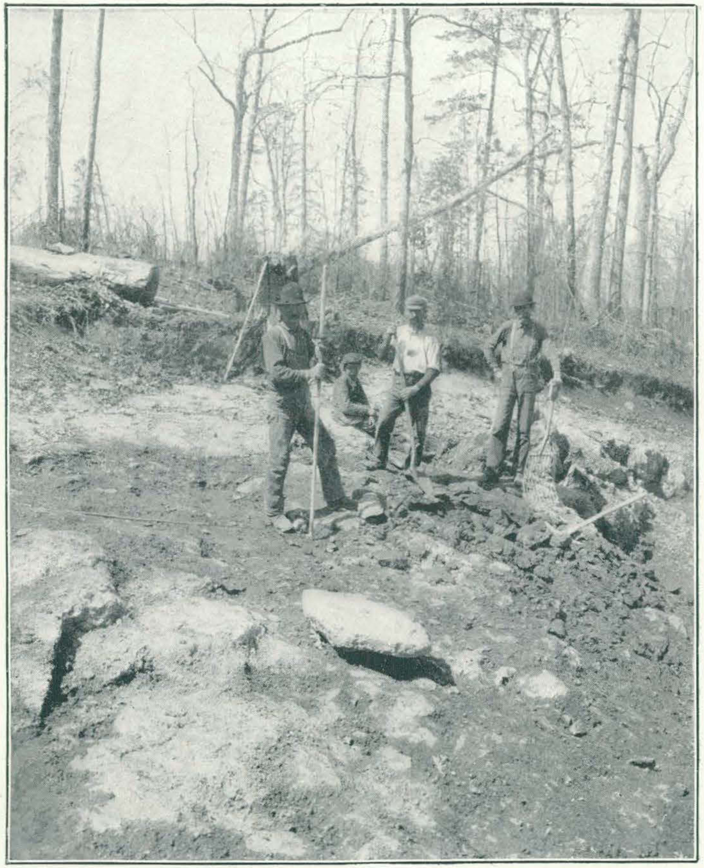
The greater part of the outcrop of the ore bed is so located that it can be mined without serious trouble from water, as natural drainage will be readily secured in most cases. The Metznauer bank was opened in a creek bottom, so that pumping was necessary, but most of the bed lies well above drainage.

Some variety in method of treating the ore after mining is necessary. The compact ore of uniform texture and composition, such as that being mined by the Illinois Chemical Company, is merely crushed to about three-quarters of an inch and then passed through a rotary drier. This company has a small plant in operation for this treatment. The gravel ore is mixed with more or less bauxitic clay and requires washing.

What will be the largest and best-equipped plant in the district is being erected by the Southern Bauxite Company. This is located at Perrysmith, just north of the Little Rock and Hot Springs Railway, in the northwest corner of the district. It will contain washers, two improved rotary driers, and probably a series of crushers and screens. The mill is connected with the ore deposits to the southeast and south by a well-graded and macadamized road. It is proposed to employ traction engines for hauling the ore from the bank to the mill.

The Pittsburg Reduction Company is also planning to erect a washer and drier in the NE. ¼ of sec. 16. This site is already connected with the Little Rock and Hot Springs Railway by a spur. The ore lies on either side of a narrow valley in which the mill is to be located, and can be delivered to the mill very readily by short tram roads. The chief disadvantage of this location will probably be the scarcity of water in summer.

A. BAUXITE BED EXPOSED IN MINING, BRYANT DISTRICT.



B. METHOD OF MINING BAUXITE, BRYANT DISTRICT.

Showing depth of cover and characteristic appearance of pisolitic bauxite.

TENNESSEE WHITE PHOSPHATE

BY

CHARLES WILLARD HAYES

CONTENTS.

ILLUSTRATION.

TENNESSEE WHITE PHOSPHATE.

By Charles Willard Hayes.

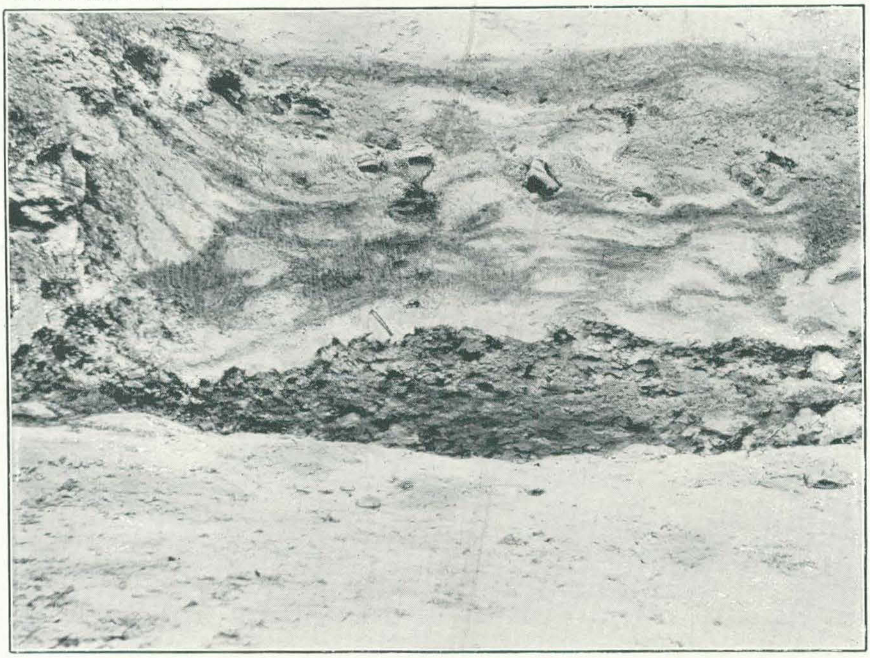
INTRODUCTION.

The deposits of white phosphate in Perry County, Tennessee, were described at some length in the Seventeenth Annual Report, Part II. At the time the field work was done on which that report was based these deposits had been very imperfectly prospected, so that their extent and geologic relations could not be satisfactorily determined. Since 1896 the district has been thoroughly prospected and some of the deposits are being actively developed. The Perry Phosphate Company has established a plant near Toms Creek post-office and has opened mines on both sides of Wilsdorfs Branch near its junction with Toms Creek. The rock is hauled by wagon 5 miles to the Tennessee River and sent to market in barges.

The district was revisited by the writer in October, 1899, and again in March, 1900. Every locality in the district where phosphate had been reported, or where leases had been taken with a view to mining, was examined. The many prospect pits, but more especially the mines opened on Wilsdorfs Branch, afforded an excellent opportunity to determine the geologic relations of the deposits. In general the conclusions reached from previous examination of natural outcrops were confirmed, but additional facts were observed which throw much light on the mode of formation of the deposits and their probable extent.

DESCRIPTION OF THE WILSDORF DEPOSITS.

The mines of the Perry Phosphate Company are at Toms Creek post-office, on either side of Wilsdorfs Branch near its junction with Toms Creek. The openings are at the points marked *H* and *K* on the map of Toms Creek accompanying the 1896 report. The principal development has been on the east side of the branch. At the time of the previous examination the breccia phosphate was found on the hillside, extending around the point and eastward some distance up the valley of Toms Creek. A few shallow pits had been dug and a small amount of the lamellar variety of phosphate was found embedded in the clay. The entire natural outcrop, however, consisted of the breccia. An area of about one-half acre has been stripped along the hillside and the phosphate removed. From the face thus exposed a drift has been run about 150 feet into the hill, with numerous cross-cuts on either side. The phosphate found under cover is composed entirely of the lamellar variety, the breccia being apparently confined to the surface outcrops. A continuous bed of phosphate is found, varying from 1½ to 7 feet in thickness. It is not horizontal, but shows considerable undulations, varying in altitude as much as 10 feet in 100. The phosphate rests in part upon an undulating floor of limestone and in part upon purple and blue clay which intervenes between the phosphate and the limestone. It does not replace any particular stratum, as is so clearly the case with the brown phosphate, but, where the surface of the limestone rises in knobs and hummocks, the phosphate bed passes over these like a blanket. In addition to the lamellar plates, but intimately associated with them, are portions of the phosphate which are almost structureless, generally greenish in color, and slightly softer than the plates. The bed shows a certain amount of stratification, though the planes are not continuous for any distance and are not strictly horizontal. It has the appearance of plates deposited from solution rather than from suspension in water. It has apparently suffered considerable motion, which has resulted in the production of numerous fractures, and in most cases these fractures have subsequently been recemented by phosphate. In some cases the different layers are separated by a thin film of greenish clay. The upper surface of the phosphate bed is much less regular than the lower surface. A part of these irregularities appear to be due to secondary motions by which the mass has been broken up, but more largely to original irregularities of deposition. Overlying the phosphate bed is a layer of clay from 3 to 8 feet in thickness, made up of irregular bands and lenses varying slightly in composition and color. This clay contains variable quantities of phosphate, consisting of small fragments of the separate plates and large irregular masses up to several tons in weight. The latter are generally much broken and often constitute breccias composed of angular fragments of lamellar phosphate held together by phosphate which has been subsequently deposited in the cracks and thus acts as a cement. These masses, as well as the smaller fragments scattered through the clay, do not appear to occupy their original position. The small fragments are most abundant in the light-yellow and blue portion of the clay and are less abundant or wanting in the deep-red clay. They are frequently quite soft and in some cases resemble deeply decayed white chert. Above the phosphatic clay is another layer of clay about 6 feet in thickness, containing many limestone bowlders. These vary in diameter from 1 to 6 feet, and are evidently residual, having characteristic irregular solu-



A.

B.

BED OF WHITE PHOSPHATE AT MINES ON WILSDORF BRANCH, PERRY COUNTY, TENNESSEE.

tion outlines. Finally, above this layer are several feet of red and yellow clay containing much angular chert. This cherty clay forms the surface soil. The appearance of the phosphate bed is shown on Pl. LXV. It also shows the overlying clay with its embedded bowlders of phosphate and limestone.

On the opposite side of Wilsdorfs Branch the phosphate has been opened by stripping, and the conditions are somewhat similar to those above noted. The phosphate bed is here also continuous, but somewhat thinner, varying from 2 to 4 feet in thickness. Above this, instead of the obscurely bedded clay, there is from 8 to 10 feet of clay, sand, and gravel, the latter containing pebbles as large as 3 inches in diameter, but mostly between one-half inch and 1½ inches. The gravel is well rounded and, so far as observed, composed entirely of chert. This material was evidently deposited by running water, but the bedding is extremely irregular and the materials are imperfectly sorted. The material gives the impression of having been deposited by a stream flowing under hydrostatic pressure; in other words, of being a cave deposit. Above the gravel is clay similar to that on the opposite side of the branch, containing large irregular masses of phosphate, and finally a thin layer of cherty clay soil forming the surface.

ORIGIN OF THE DEPOSITS.

As stated in the former report on these white phosphates, the conclusion arrived at from examination of the surface outcrops was that the lamellar variety had been formed by deposition from solution in cavities in the limestone. The observations recently made on the more extended exposures amply confirm this conclusion. They show, moreover, what could not be determined from the surface outcrops, that the cavities in which deposition took place were very extensive, forming, in fact, large caverns in the limestone. It appears that the phosphate was deposited in a somewhat uniform and continuous layer on the floors of these caverns in general, following their undulations, but more was deposited in the depressions than on the elevations. Phosphate was also deposited in less regular cavities in a limestone above the stratum in which the main cavern formed. When this limestone was dissolved these masses settled down with the residual clay in which they are now embedded. During this readjustment, brought about by the solution of the limestone, the phosphate was repeatedly fractured and recemented, giving it a brecciated structure. The phosphate was doubtless deposited in these caverns from quiet water, but they also contained at times rapid streams which carried sand and gravel and formed alluvial deposits. The latter differ distinctly from those formed by surface streams under ordinary conditions. Since the stream was more or less confined above by the roof of the cavern, as well as at the sides, the water was sometimes under hydrostatic pressure. Under such conditions the laws which govern ordinary stream transportation and deposition do not apply, and the deposits possess certain characteristics which clearly indicate the conditions under which they were formed.

EXTENT OF THE DEPOSITS.

Since the lamellar variety of the white phosphate was deposited in limestone caverns, it will be found only where the conditions were favorable for the formation of caverns. It need not be expected above the top of the Silurian, since the Carboniferous limestone in this region contains so large a proportion of chert and other impurities that it probably never gives rise to the formation of caverns. It should further be noted that certain horizons in the Silurian limestone are much more soluble, and hence better adapted to cavern formation, than others. This is the characteristic of certain beds of Upper Silurian limestone which have a granular crystalline structure and are composed largely of crinoid stems. Wherever these beds are exposed by stream cutting they are apt to be cavernous. At numerous points in this region the streams sink and flow for considerable distances in underground channels, and this is most often the case where the erosion of the valleys has reached the surface of this easily soluble limestone. The white phosphate therefore, although its connection with any particular bed is in a measure accidental and not essential, as is the case with the brown phosphate, may be expected to occur in greatest quantity at the horizon of these particular beds. Hence the latter, identified by their peculiar fossils and physical characteristics, will afford a guide of some value in further prospecting.

Since this phosphate was deposited in caverns, it can not be expected to have very great lateral extent. As stated in the previous report, it is essentially a pocket deposit, although the possibilities for extensive deposits are much greater than were recognized at the time that report was made. The examination of one deposit, no matter how thoroughly it is exposed to view, will not enable the prospector to make definite estimates as to the extent of any other deposit. Doubtless similar natural exposures may lead to inferences of some value, but they can not be depended upon to take the place of actual prospecting. Each deposit must be examined itself, and the amount of rock which it contains, as well as its character and the depth of overburden, must be determined by systematic exploitation, similar to that which has been employed by the Perry Company at Wilsdorfs Branch. The necessity for this thorough examination of each individual deposit can not be dwelt upon too strongly.

Probably the greater part of the white phosphate in this district will be obtained by open workings. The character of the overburden—unconsolidated clay in which movement takes place with great ease—is such that underground working will be attended with the greatest difficulty. Substantial and expensive timbering would be required wherever the phosphate was removed, and doubtless even then a large proportion of the rock would be wasted. The specific gravity of this rock is so much greater than that of the brown phosphate that a very much greater overburden can be removed with profit for the same thickness of bed. Where the phosphate bed has a thickness averaging 3 feet it is probable that 16 or 18 feet of overburden can be removed with profit while the rock commands present prices. The phosphate which is disseminated through the overlying clay can be saved easily with the proper plant, which should include screens and washers. Owing to the much greater density of this rock, the matter of drying is less important than with the brown phosphate. It would, however, probably pay to dry the rock before shipment, and this might be done by open-air burning, or more economically with an ordinary rotary drier.

DEPOSITS IN OTHER PARTS OF THE DISTRICT.

Considerable interest attaches to the distribution of the white phosphate and the possible extension of the productive territory. If the conclusion outlined above is correct—namely, that the phosphate deposits were accumulated in caverns in the limestone—a consideration of the geologic conditions prevailing elsewhere in the district should be of material assistance in locating other deposits.

The topography of the region between the Tennessee and Buffalo rivers has been described in a previous report, but its main features may be again briefly described in order to render statements regarding the distribution of the deposits intelligible. For a considerable distance the Buffalo and Tennessee rivers flow north nearly parallel with each other, and their tributaries head upon the intervening land and join the trunk streams very nearly at right angles, flowing east to the Buffalo and west to the Tennessee. The tributaries of the Buffalo are very short as compared with those of the Tennessee, so that the divide between the two drainage basins is much nearer the former stream than the latter. Streams of considerable size enter the Tennessee at intervals of about 5 or 6 miles, and shorter ones frequently intervene between these main tributaries.

Beginning in the vicinity of Perryville, the creeks of the first class which enter the Tennessee are Spring, Lick, Toms, Roan, and Crooked; while the streams of the second class are Parish Branch, between Spring and Lick creeks, and Deer creek, between Lick and Toms creeks. These creeks are characterized by rather narrow, level valleys and are separated by ridges rising 300 or 400 feet higher than the valley bottoms. These ridges are simply portions of a deeply dissected upland plateau, the altitude of which in this region is between 900 and 1,000 feet. They are capped by the Lower Carboniferous chert, and are entirely covered with forests. While these ridges reach a tolerably uniform elevation, the distance from their summits down to the limestone is quite variable. Thus, in the ridge between Lick and Spring creeks the chert is comparatively thin, the limestone reaching more than two-thirds of the way from the valley bottom to the top of the ridge. The rocks of the region are, in a general way, horizontal, though not strictly so, and when considered in broad area they show considerable undulations. It should be remarked that the Devonian appears to be entirely wanting in this region, the Lower Carboniferous chert or cherty limestone resting directly upon some member of the Silurian, usually the sparry crinoidal limestone above described. The beds descend toward the north, and in Roan and Crooked creeks the valleys are not cut down to the surface of the limestone. On Toms Creek there is a dip to the westward which carries the surface of the limestone below the creek valley about 4 miles from its mouth. It then rises so that the limestone is exposed between this point and the Tennessee River, but again dips westward, and the surface of the limestone is probably near the river surface at the mouth of Toms Creek. On Roan Creek the limestone is nowhere exposed except in the bed of the Tennessee River near its mouth. It will be readily understood that the conditions favorable for the deposition and preservation of deposits of white phosphate are most favorable in those regions where the surface of the limestone reaches a short distance above the level of the valley bottoms. Where the surface of the limestone is too high above the valley bottoms the deposits, if they were ever present, have been largely removed by erosion, whereas the conditions for the formation of caverns are not present where the limestone surface is below the level of permanent ground water in the valleys.

On the south side of Spring Creek about three-fourths of a mile from the Tennessee River is a small deposit of white phosphate, on the hillside, from 75 to 100 feet above the level of the creek. The slope is steep and covered with a thin layer of chert, through which the limestone ledges project at many points. The deposit has been thoroughly prospected by means of a long trench on the hillside and also a shaft. The chert is confined chiefly to a few inches of surface soil. Under this is yellow clay, with fragments of limestone and some chert, down to the surface of the solid limestone ledges. The latter is extremely irregular, and the small cavities contain numerous bowlders of white phosphate embedded in the yellow or blue clay. The amount of phosphate exposed in the cut is very small, and there is no indication of a large body at this point.

About 2 miles east of the above locality, on a tributary of Spring Creek, there are a couple of small areas on the hillside carrying some bowlders of phosphate. The slopes are covered with chert and yellow clay, in which the phosphate is embedded. No prospecting has been done at this point, but the limited extent of the territory covered by the float indicates that the deposits are small in extent. Numerous outcrops of limestone show that the solid rock is near the surface, which precludes the possibility of finding extensive deposits of phosphate here.

The next deposits to the north are on the hillside facing the Tennessee River near the mouth of Parish Branch, and about a mile from the river on the south side of this branch. Both these localities have been thoroughly prospected. The phosphate is somewhat more abundant than at the locality first described, but it is evidently limited by the shallowness of the clay which covers the limestone. The phosphate appears to be of excellent quality, being made up entirely of the lamellar variety, white or pink in color, alternating with zones slightly more massive and somewhat porous, which have a gray or greenish color. The phosphate occurs, so far as can be seen, only in bowlders disseminated through the clay, but most abundant near the surface of the limestone. It does not form a continuous layer as at Toms Creek, and the amount of clay to be removed would be considerable compared with the amount of phosphate obtained. These deposits may contain a few hundred tons, but from present indications the amount would scarcely exceed that.

The white phosphate has been found at three points on Lick Creek. The first is about 2 miles from the Tennessee River, on the Sparks place. It is near the top of a spur on the south side of the creek. The surface of the limestone is covered with a thin layer of cherty clay, and within an area about 50 by 100 feet numerous fragments of phosphate occur on the surface and are shown in a few shallow pits. The smallness of the area within which the float rock is found indicates that no considerable deposit occurs here, although there may be a pocket of some depth. About 5½ miles from the river, also on Lick Creek, the phosphate shows in the roadside as a ledge in place about 2 feet in thickness. Its lateral extent can not be determined, but it is probably not great. Little if any float rock appears on the surface, and the presence of the ledge would not be suspected except for the accidental exposure in the road cutting. About a mile farther up the creek on the south side of the valley, on Tom Young's place, several large bowlders of phosphate occur on the cultivated hillside. No prospecting has been done here, but the scarcity of float would indicate that the deposit is small.

The distribution of the phosphate deposits on Toms Creek has already been described, and thorough prospecting has failed to reveal any considerable amount between the main deposits near the mouth of Wilsdorfs Branch and the Tennessee River.

On Roan Creek, which is next north of Toms Creek, white phosphate has been found at one point about 5½ miles from the Tennessee River. A prospect pit in the creek bottom has brought to light a small amount of the breccia variety. The phosphate forms a matrix in which partially rounded chert pebbles are embedded. The latter are in every way similar to the gravel forming the bed of the creek. As already stated, this creek does not cut down to the limestone, except at its mouth, and therefore the conditions favorable for the formation of the lameller variety are nowhere present in its valley. The same conditions prevail in the next creeks to the north, Crooked Creek and Blue Creek. Numerous leases have been taken on the farms in these valleys, but they afford no indication whatever of deposits of phosphate. Occasional bowlders of chert breccia cemented by limonite are found, and these are locally regarded as indications of phosphate. They, of course, afford no indication whatever of the presence of such deposits.

Little can be added to descriptions of the Toms Creek deposits east of Wilsdorfs Branch contained in the former report.[1] They have not been opened to any extent, and while conditions at a few points are favorable for the existence of extensive deposits, their extent can be determined only by further systematic prospecting.

Some prospecting has been done in the vicinity of Beardstown at points noted in the 1896 report. The lamellar phosphate here occurs more or less intermingled with clay, and the test pits have not yet revealed a continuous bed such as appears at Toms Creek. It is by no means impossible, however, that such a bed may not occur at greater depth than the pits have yet reached. This locality affords better promise than any other in the district except Wilsdorf, and is worthy of more systematic exploration than it has yet received.

VARIETIES OF PHOSPHATE.

In the former report on the Tennessee white phosphates the following classification of the deposits was adopted: (1) Stony, (2) lamellar, (3) breccia.

The first variety consists of a siliceous skeleton, the cavities in which were originally filled with lime carbonate, but are now filled with lime phosphate. The latter forms from 27 to 33 per cent of the rock. This stony phosphate is found in considerable abundance in the northern part of Perry County, on Terràpin and Redbank creeks. No attempt has yet been made to utilize it, and unless some inexpensive method is devised for concentrating the lime phosphate, it is too low grade to compete with the other varieties.

The third variety, the breccia phosphate, which forms most of the surface outcrops in the Toms Creek district, appears to be confined

[1] Seventeenth Ann. Rept. U. S. Geol. Survey, Pt. II.

almost exclusively to the surface. Its importance, therefore, is relatively small, and it is questionable if it exists in sufficient quantity to justify the development of machinery for separating the phosphate from the chert, even if this separation were found to be practicable.

Only the lamellar variety, therefore, has thus far been developed. Fortunately this variety, which is the highest grade and the most easily prepared for market, appears to be also the most abundant. Selected specimens of the thin plates contain 85 to 90 per cent of lime phosphate. The less dense, greenish material, which is associated with the white and pink plates, contains some ferrous iron and runs slightly under 80 per cent of lime phosphate. There appears to be no difficulty, however, in getting from such deposits as are being worked on Wilsdorfs Branch a uniform product which will run between 79 and 81 per cent of lime phosphate.

REPORT ON THE GEOLOGY OF THE PHILIPPINE ISLANDS

BY

GEORGE F. BECKER

FOLLOWED BY A VERSION OF

UEBER TERTIÄRE FOSSILIEN VON DEN PHILIPPINEN (1895)

BY

K. MARTIN

CONTENTS.

ILLUSTRATIONS.

REPORT ON THE GEOLOGY OF THE PHILIPPINE ISLANDS.

By George F. Becker.

SOURCES OF INFORMATION.

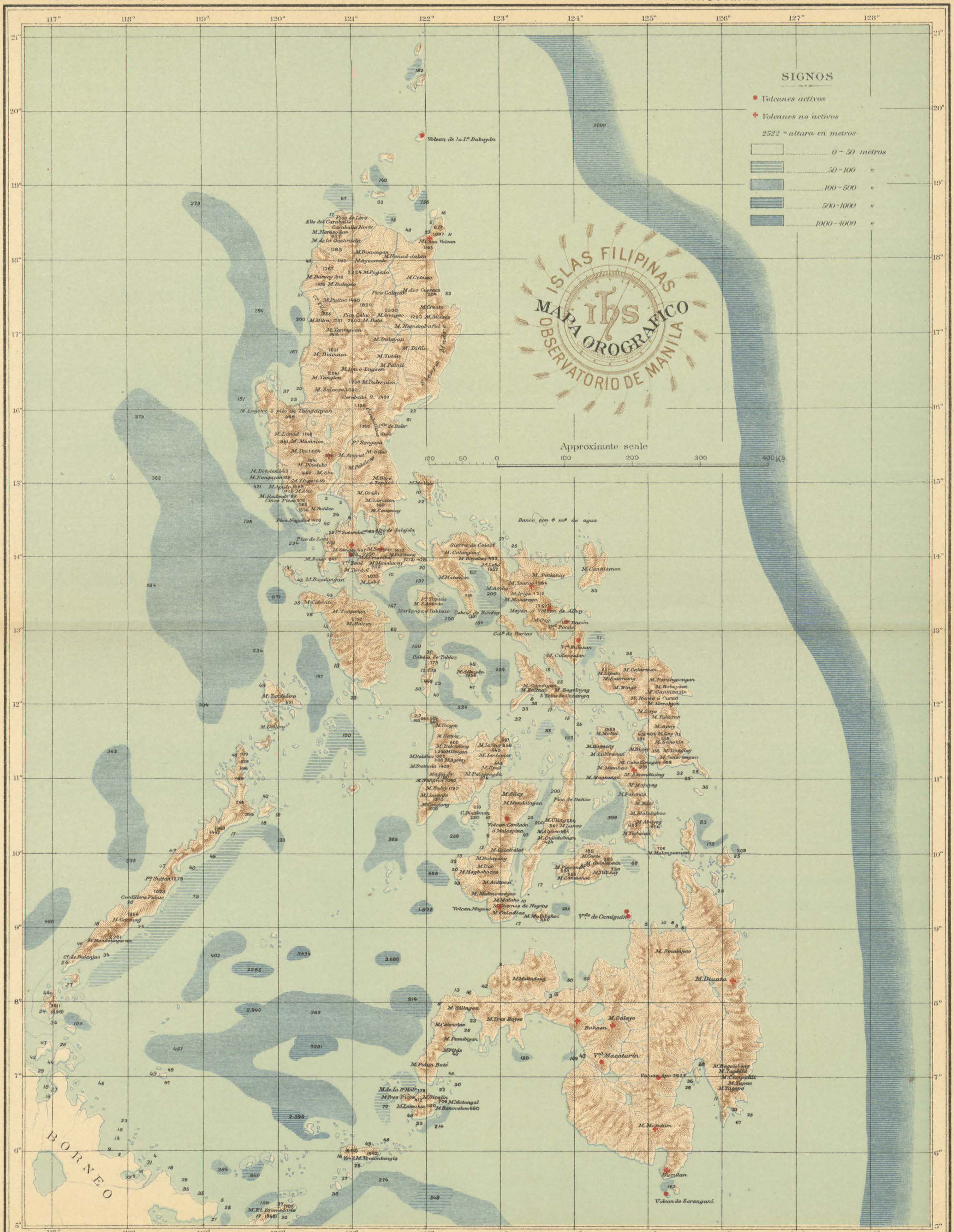
An attempt will be made in the following paper to bring together, so far as is practicable, all that is known of the geology of the Philippine Islands. The report is intended as a vade mecum for geologists in the field and a guide to the literature in the office. Doubtless something has escaped which should have been included, especially among the shrewd remarks of early Spanish travelers, but research in that direction is curious rather than profitable. If here and there they caught a glimpse of truth, with which it would be pleasant to credit them, most of their views on geological matters were of a grotesque falsity, with which it would be unkind to reproach them.

In the bibliography will be found references to about 100 papers touching on the Philippines. The greater number of them are of very subordinate value, containing only casual observations, or compilations which sometimes show careless preparation. Some errors I have noted; many more I have simply ignored.

Serious work began late in the fifties, with a group of German and Austrian geologists and explorers. Ritter von Hochstetter spent a few days in the Philippines, but his chief work was done elsewhere in the Far East. Baron von Richthofen, though but a short time in Luzón, was fortunate enough to discover nummulites at Binangonan. Carl Semper spent years in toilsome travel in the archipelago, almost completely cut off from civilized intercourse. His labors were zoological, but his studies of coral reefs are of great geological importance, and his geological collections are most valuable. They enabled Mr. Oebbeke, in 1881, to make his important study of massive rocks, and they furnished the material for Mr. K. Martin's paper on the Tertiary fossils of the Philippines (1895). Mr. Martin's paper seems to me so exactly suited to the end here aimed at that I have translated it as a complement to this report. Jagor was in the Philippines at the same time with Semper. He was not a specialist, but a very intelligent traveler, and he made many geographical observations. His collection of rocks was worked up by Roth, who took occasion to compile everything then known of the geology of the Philippines. Jagor's human skulls were studied by Virchow, and both these important papers appeared in 1873 as appendices to Jagor's travels. Mr. R. von Drasche spent a few months in the islands, and explored new ground in 1875–76. His Foraminifera were studied by Mr. Felix Karrer, and threw new light on the stratigraphy. Mr. J. Montano also made some studies in Mindanao in 1879 to 1881, which, however, were mainly ethnological.

The Spanish engineers Sainz de Baranda, Antonio Hernandez, José Maria Santos, and José Centeno have contributed many details to the sum of knowledge. Much more has been done by Mr. Abella, who, under conditions which seem to have been very discouraging, spent many years in geological research. Much the best maps of the islands have been prepared by Mr. Enrique d'Almonte, whose work was largely performed in connection with Mr. Abella. Where Mr. d'Almonte was able to make surveys himself the execution was admirable, as I have reason to know. In much of the area of his maps he was compelled to rely on insufficient information. Besides other favors, I have to thank him for a table of areas of some of the islands, given on pages 496–497. The best map of Mindanao and the Joló Archipelago is that prepared by the Jesuit missionaries. The two maps accompanying this report, Pls. XLVII and XLVIII, are borrowed from the Atlas of the Philippine Islands prepared by the Jesuit Fathers and printed by the Coast and Geodetic Survey, 1901. While they are not wholly satisfactory, I know of none so good on a similar scale. Mr. Luis Espina compiled for me from the archives of the Inspección de Minas a sketch of the mineral resources and the geology of the islands which has been very useful.

In July, 1898, I was ordered to report to the military governor of the Philippines for duty as a geologist, and I accompanied Gen. E. S. Otis to Manila. I remained in the Philippines fourteen months, but could accomplish little geological work because of the attitude of the natives. When the cessation of the rains made it practicable to travel, Mr. Aguinaldo's associates had assumed a threatening attitude and soon afterwards became "war rebels." I was able to do something about Manila Bay as far north as San Fernando, and a little at Laguna de Bai. I had somewhat more success at Negros and Cebú, but geologizing under arms with a military escort is more exciting than profitable. I visited Iloilo, Guimarás, and Joló, and had excellent opportunities of studying from the decks of vessels the terracing of Bohol, Mindanao, and other islands. The military authorities afforded me all the facilities practicable without deliberately risking troops for the sake of information which can wait. I have to thank them for much kindness and for many privileges which rarely fall to the lot of a geologist. If the positive results of my stay in the islands are small, it has



Longitud E. del Meridiano de Greenwich

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enabled me to get a better grasp of the geological situation than I could have acquired without an inspection of the country, and it is to be hoped that the digest here presented will aid my successor in making better headway.

The Spanish geologists have dealt in much detail with earthquakes and with mineral springs. These subjects are not included here, but the reader interested in them will find the literature cited in the bibliography (p. 594). It is intended that in most cases this report should enable the field geologist to dispense with other papers; but for field work in either Panay or Cebú, Mr. Abella's memoirs on those islands will be requisite.

It appears certain that Malaysia forms a single geological province. I have therefore made the attempt to draw upon Borneo, Java, and the Banda Islands for instruction and suggestion. Junghuhn, Verbeek, and other Dutch geologists have done a vast amount of work which can not safely be neglected in dealing with the geology of the Philippines. Messrs. Alfred R. Wallace, Dean C. Worcester, and F. S. Bourns also have contributed to geological knowledge of the islands through their studies of the distribution of living forms in Malaysia.

In treating the subjects of the various sections of this report a geographical arrangement of each has been adopted in order to facilitate perusal. The information available is so fragmentary that any attempt to treat separate areas completely would fail. For the purpose of making it practicable to combine data locally I have prepared a special index of provinces (p. 612), by means of which the reader will be able to collect the facts presented for any single province. The latitudes of this index are intended to assist such readers as are unfamiliar with the geography of the country in orienting themselves.

Geographical names in the Philippines are a source of much trouble. This arises partly from the fact that various cartographers have heard native names a little differently. Thus, a river in Mindanao is called on maps both Craán and Gran, which are clearly two attempts to reproduce the same word. Much worse than this is the native attitude toward natural objects, which they regard from what may be called a village standpoint. Thus, a famous mountain is often designated Majayjay for no better reason than that a village near it has that name. To the native, it would seem, a river is merely the water passing such and such a town, so that for him the stream has as many names as there are towns on its banks.

The phonetic Spanish system of spelling native names is a great convenience. All Filipino names are pronounced as if they were Spanish, and, when properly written, there is but one possible way either of pronouncing the syllables or of accenting the words. Spanish names usually follow exceedingly simple rules of accentuation, and, when there is an exception to the general rules, this is indicated by a written accent. The reader must be warned, however, that the accents on native names are often carelessly treated by Spanish printers, no doubt through unfamiliarity with the correct accent. I have tried to write the names correctly in this paper, because it is intended for use in the field, and geologists will find that natives will fail to comprehend geographical names which are mispronounced. It is to be hoped that the present excellent method of name writing will be preserved in Government reports.

In consulting the literature readers will find that maps to which they will need to refer are drawn to different prime meridians. For this reason I have usually given only latitudes. The islands are so narrow that it is little trouble to run down a latitude and find a position marked on the map. Some Spanish maps count longitude from Madrid, others from the observatory at San Fernando, near Cadiz. French authors count from Paris, and the usage in Germany is variable. In dealing with miscellaneous maps and charts of the Philippines, it is convenient to know the following longitudes:[1]

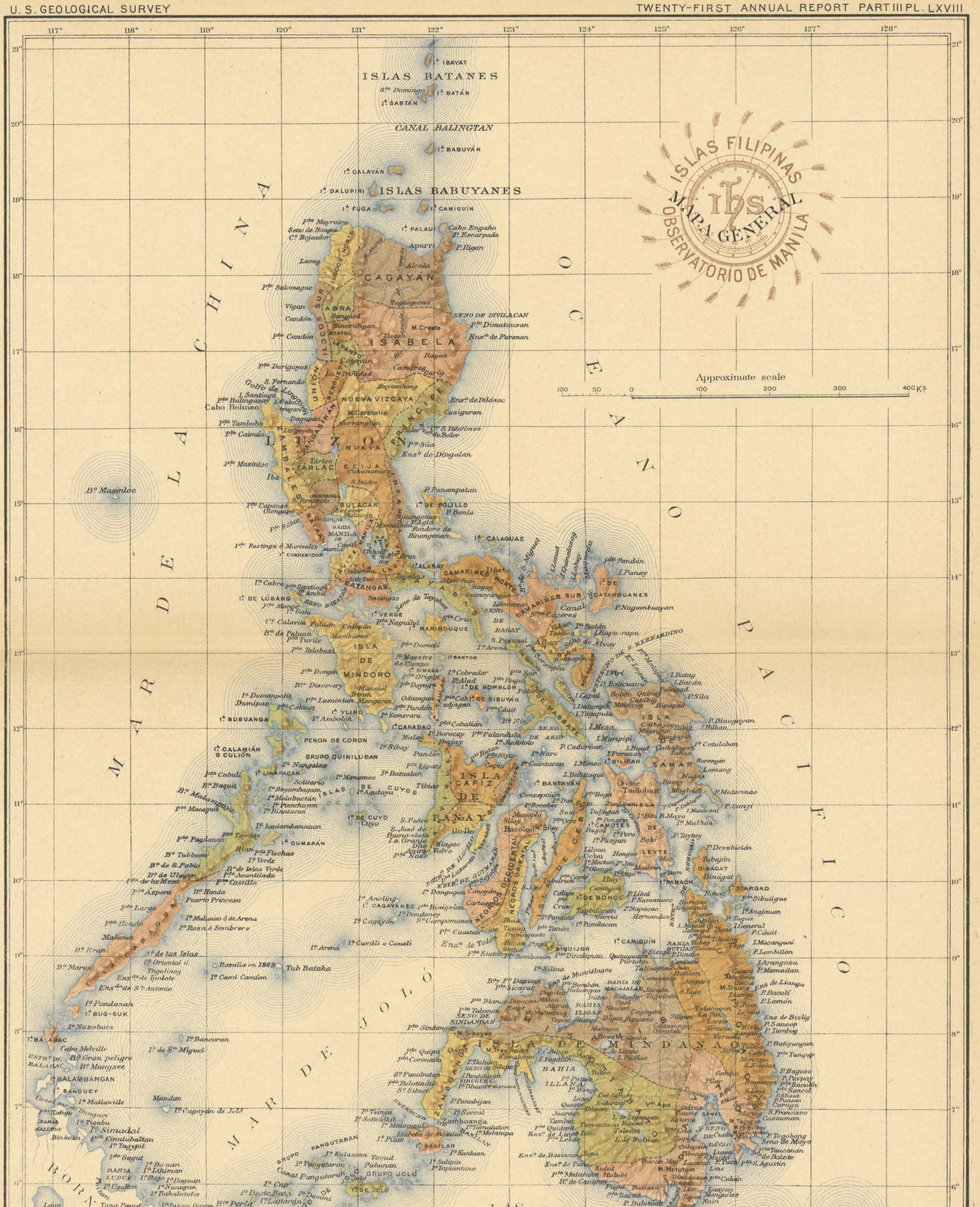
	°	′	″	
Greenwich Observatory	0	0	0	
Madrid Observatory	3	41	21	W
San Fernando Observatory	6	12	24	W
Paris Observatory	2	20	14	E
Berlin (Urania) Observatory	13	36	53	E
Ferro	17	20	0	W
Manila Cathedral	120	58	8	E

NOTE ON SOME AREAS IN VARIOUS PROVINCES AND DISTRICTS IN THE PHILIPPINE ISLANDS.

[By Enrique d'Almonte.]

	Square kilometers.
District of Sámar:	
Island of Sámar	12,606
Island of Capul	40
Island of Daluripi	37
Islets N. of Sámar	140.25
Islets E. of Sámar	24
Tomonjol and Suluan	87.50
Islets W. and SW. of Sámar	189.25
Total	13,124
District of Calamianes:	
Cuyos Islands	149
Culión	388
Busuanga	994
Remainder of Calamianes	395
Total	1,926

[1] The observations are taken from the Nautical Almanac, 1896, p. 492.



Longitud E. del Meridiano de Greenwich

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	Square kilometers.
Joló Archipelago, including Tataran	2,560
Balábac Island and adjacent islets, including Cagayán Joló	604
District of Leyte:	
Island of Leyte	7,109
Island of Panaón	187
Island of Bilirán	512
Adjoining islets	62
Total	7,870
District of Masbate and Ticao:	
Island of Masbate	3,201
Island of Ticao	327
Adjoining islets	136
Total	3,664
Province of Mindoro:	
Island of Mindoro	9,653
Semerara, Ilin, and remaining southern islets	192
Marinduque and adjacent islets	918
Lubang group	215
Other adjacent islets	22
Total	11,000
District of Romblón	1,288
District of Catanduanes:	
Island of Catanduanes	1,720
Adjacent islets	85
Total	1,805
District of Burias	507
District of Cebú:	
Island of Cebú	4,188
Adjacent islands	458
Total	4,646
District of Bohol:	
Island of Bohol	3,685
Adjacent islands	121
Total	3,806
Island of Siquijor	271

CRYSTALLINE SCHISTS AND OLDER MASSIVE ROCKS.

The exposures of crystalline schists and the older massive rocks in the Philippine Islands are neither good nor conveniently situated for study. As a matter of course they are scarcely to be found except in the mountains or in deep ravines. As a rule, they are heavily covered with saprolite, soil, and dense vegetation, while the localities where they are to be found are largely in the possession of uncivilized tribes. The mountain system of northern Luzón and the eastern coast ranges of that island in the provinces of Infanta and Camarines Norte are largely composed of these rocks. They are also found on Lubang Island, in the sierras and seacliffs of Panay, and in the deep ravines of Cebú. On the east coast of Leyte there is a limited occurrence of crystalline schists, and the series is probably represented in Sámar. In the great southern island they appear in the provinces of Misamis and Surigao. The occurrence of metallic ores is suggestive of a still wider distribution of these formations.

The older rocks of the islands appear to embrace crystalline schists and gneiss, granites in small quantities, and possibly some syenite, while diorites and diabases and gabbros are abundant. The most important contributions to knowledge of these rocks are due to Messrs. Jagor, von Drasche, Montano, and Abella. It is a little difficult to correlate the information, which is fragmentary and not altogether accordant. Mr. von Drasche, who began his studies in the Zambales Range, compares the rocks which he met in the Caraballo Sur, the Cordillera Central, and the San Mateo Mountains with those of Zambales. Mr. Abella's most elaborate studies were made in Panay, but during his long residence in the archipelago he became familiar with many areas. His determinations in some cases fail to agree with Mr. von Drasche's. Mr. Montano's examinations were confined chiefly to Mindanao, where Mr. Abella also had made studies.

Aside from somewhat vague and casual mentions,[1] the first statements concerning the older rocks with which I have met are by Meyen and Itier. The former about 1832 observed that the limestones in which the somewhat famous caves occur near San Mateo, Manila Province, rest upon diorite.[2] Itier[3] a few years later drew attention to the character of the stream pebbles at Angat, in the Province of Bulacán. This locality lies at the eastern edge of the great central plain of Luzón, and in the mountains a few miles farther east is an important iron mine. Seemingly on the strength of these facts, Mr. von Drasche lays down on his map an area of crystalline schists directly east of Angat.

In his studies of the Zambales Range, which lies to the west of the Province of Pangasinán, Mr. von Drasche reached the conclusion that this sierra is composed chiefly of gabbroitic and dioritic rocks. What he calls diabase-gabbros are more or less peculiar, but are closely related to ordinary gabbros. The best exposure appears to be along

[1] Dana did not land in northern Luzón, but states that it is said to be covered with granite, gneiss, etc. (Wilkes Expl. Exp., Vol. X, 1849, pp., 539-545.) He cites no authority. Humboldt, in Cosmos, makes a similar statement on Dana's authority (Vol. IV, 1858, p. 404), and other writers have frequently cited Cosmos on this subject.

[2] Reise um die Erde, Part II, 1835, p. 237.

[3] Bull. Soc. géog., Paris, 3d series, Vol. V, 1845, pp. 365-389.

a trail across the range just to the northward of the coast town of Santa Cruz. This path follows a river called by Mr. von Drasche the Santa Cruz River, but which appears on Mr. d'Almonte's map as the Nayon. It crosses the divide in latitude 15° 51'. Most of the western slopes of the range consist of the gabbro in thick layers (Baenke) with northerly strike and western dip. In connection with the gabbro occur dioritic schists, but whether these are uralitic derivatives of the gabbro is not discussed. The green dichroitic hornblende lies in irregular patches among the plagioclases. The gabbro is granular, and to the naked eye shows olive-green and light-brown grains, both of which turn out under the microscope to be augite. This augite, he says, "exhibits a not inconsiderable dichroism between reddish brown and olive green." It seems probable that Mr. von Drasche was dealing with a mixture of green augite and brown rhombic pyroxene. The augite showed a tendency to a single cleavage. Portions of the rock are sharply banded. An analysis of this rock is given below. A similar rock was found on the eastern slope of the range, well down toward the plain of Pangasinán. It, too, was analyzed, and its composition is remarkable for the excessively small percentage of soda and potash. Among the gabbros on the western side, Mr. von Drasche found one which was olivinitic, the diallage being green and quite free from dichroism. This I take to mean that the appearance of olivine was accompanied by the disappearance of hypersthene. Serpentines were found along this trail. Farther south, on the Bucao River Pass (latitude 15° 13'), Mr. von Drasche also found gabbros and serpentines. In the latter he detected remnants of olivine and bronzite.[1]

In examining the mineral springs of the country Mr. Abella encountered compact argillaceous, ancient-looking slates at the eastern base of the southern end of the Sierra Zambales. They occur in the township of O'Donnell, at a place called Canan. It is noteworthy that they strike ENE. and have a northwesterly dip of 25°.[2]

On the San Mateo River in Manila Province access is afforded to the foothills of the eastern ranges, and here the rocks appear to have a marked similarity to those of the Zambales Range. It has already been mentioned that Meyen found diorites beneath the limestones. Near by Mr. von Drasche found coarse-grained gabbros on the Poray, a small tributary of the San Mateo. They contain hornblende as well as diallage, form thick layers, and dip to the eastward. Higher up the stream he met beds which are stratified, resemble sandstone, and are dark green. They consist of crystal fragments, mostly rounded and much decomposed. Mr. von Drasche had this material analyzed, and its chemical and mineralogical composition led him to regard it as a diabase tuff. It is unfortunate that the term tuff should be used

[1] Fragmente zu einer Geologie der Insel Luzón, 1878, p. 21.
[2] Manantiales, 2d study, 1893, p. 144.

by so many geologists to denote waterworn sediments derived from eruptive rocks. By a slight extension of the usage, arkose would be denominated granitic tuff, which would certainly be a retrogression in nomenclature. The excuse is, of course, that it is sometimes difficult to say whether such fragmental masses are pyroclastic or hydroclastic. In these days of microscopical study, however, so important a point should not be left uncertain, and tuff should be limited to essentially pyroclastic material.

At Maínit, on the Payaguán River, 6 kilometers from Boso-boso, Mórong Province, is the center of an extensive area of ancient slates. They are described as diabasic and are accompanied by diabasic conglomerates. The strata at Maínit strike N. 10° W., and dip eastward almost vertically.[1]

The following are the analyses made for Mr. von Drasche. I is the gabbro from the Santa Cruz or Nayon River, on the western slope of the Zambales Range; II is the gabbro from the eastern slope of the same range on the same section; III is the so-called diabase tuff from Poray Creek, San Mateo River. The analyst was Dr. Berwerth.

Analyses of gabbros and diabase tuff.

	I.	II.	III.
SiO_2	50.52	48.93	51.69
Al_2O_3	20.12	21.12	20.11
FeO	4.38		
Fe_2O_3		6.95	9.36
CaO	9.75	11.99	6.26
MgO	11.30	9.54	4.85
K_2O	2.76	.05	1.21
Na_2O	2.48	.41	1.97
Ignition	.36	.59	7.07
Total	101.67	99.58	102.52

Older massive rocks occur also in the Caraballo Sur and in the Caraballo Central or Cordillera Central of northern Luzón. The first definite statement known to me on the subject is by Centeno in 1875. The range which forms the eastern limit of the valley of the Abra River, or the northeastern branch of the Caraballo, he says is pyrogenic, in consequence of which the tributaries of the Abra which come from the eastward carry larger quantities of volcanic and plutonic rocks, such as trachytes, diorites, and various species of porphyry, granite, syenite, etc.[2] Semper traveled in this region, but was little impressed

[1] Abella, Manantiales, 2d study, 1893, p. 75.
[2] Memoria geológico-minera, 1876, p. 19.

with the presence of ancient rocks.[1] Among the specimens which he collected, however, Mr. Oebbeke found a quartz-porphyry from Cabayan, a village in the Province of Benguet, and a quartz-diorite from the Agno River, near the same place.[2] Mr. von Drasche crossed the Caraballo Sur, and made trips through the provinces or districts of Unión, Benguet, Lepanto, Bontoc, and Ilocos Sur, which lie along the Caraballo Central. The basal rocks in this last range, in his opinion, consist of diorites, diabases, protogine-gneiss, and chloritic schist.[3] Some details are as follows: To the northeast of Trinidad, the capital of Benguet, is a large area of diorite, and in seams in this rock occurs gold, exploited by the Igorrotes.[4] A portion of this diorite is quartzose. At the village of Amlimay, on the Agno, in Benguet, the lowest formation is quartzose schist.[5] At Vigan, the capital of Ilocos Sur, there are chlorite-schists and protogine-gneiss.[6] Both on the Agno and on the Abra plagioclase-hornblende-chlorite rocks underlie a formation named by von Drasche "the Agno beds,"[7] which is also found in the Caraballo Sur, on the Pinquiang River. The lowest portion of this formation consists of coarse breccias and conglomerates of the dioritic rock. The overlying strata are of finer grain, with transitions to sandstone, which are again succeeded by green and purple beds, these consisting of thoroughly decomposed rock and being filled with calcite veins. The Agno series is very coarsely bedded, and often faulted. Mr. von Drasche counts the Agno beds among the primitive rocks (Grundgebirge) of the region. No fossils were found in them.

Mr. von Drasche crossed the Caraballo Sur from Carranglán, in Nueva Écija, to Bambang, in Nueva Vizcaya. A few miles south of the crest lies the refuge which he calls Camarín Santa Clara. This he found surrounded by a beautiful, typical, fine-grained, massive syenite in place. From this point to the summit of the pass, a six hours' ride, he found everywhere in place a beautiful coarse-grained rock almost identical with the gabbro of the eastern slope of the Zambales Range.[8]

Mr. Abella's observations differ markedly from Mr. von Drasche's. In a paper dated in 1881, but seemingly written before he had read the Austrian geologist's memoir, Mr. Abella strongly insists on the predominance of diorites in northern Luzón. In a trip from Carranglán to Bambang and to Solano, a few miles north of Bambang, he found that not only the crest of the range consisted of diorite, but the underlying rock all the way from Camarín de Salazar (doubtless von Drasche's Camarín de Santa Clara) to Solano,[9] a distance of over 30 miles. In 1892, Mr. Abella again referred to this subject. He then examined his suite

[1] Die Philippinen und ihre Bewohner, 1869, p. 99.
[2] Neues Jahrbuch, Beil.-Band I, 1881, pp. 495, 497, 498.
[3] Fragmente, 1878, p. 42.
[4] Ibid., p. 33.
[5] Ibid., p. 35.
[6] Ibid., p. 41.
[7] Ibid., pp. 34, 37.
[8] Ibid., p. 27.
[9] Apuntos físicos y geológicos, 1884, p. 30.

of specimens collected in 1881, this time under the microscope, and found neither syenite nor gabbro, but only diorite. The diorites of the region are in part quartzose and so crystalline and granular, he says, that to the naked eye they resemble rocks of the granitic family.[1] As Mr. von Drasche appears to have relied on megascopical inspection, the weight of evidence is on the side of Mr. Abella.

In the Caraballo Central also Mr. Abella is very positive that diorites are the oldest exposed rocks, agreeing only partially with Mr. von Drasche. The peak of Mount San Tomás, or Tonglón, in Unión Province, famous as the site of a great earthquake in 1641, is a holocrystalline, somewhat quartzose, hornblendic, chloritic diorite. This rock in various facies extends far to the north, south, and east of Tonglón and is probably continuous to the Agno River. Some of its facies are augitic and others porphyritic. At Galiano is a rock which Mr. von Drasche describes as unquestionably a hornblende-trachyte tuff.[2] Mr. Abella has examined this material at various points and studied its relation to the diorite massif of Tonglón, which it surrounds on the south and west. He pronounces it simply a sandstone composed of material derived from the dioritic area. Mr. Abella also gives many notes on a formation which would appear to be that named the Agno beds by Mr. von Drasche. It is extensively developed throughout Unión Province and in Benguet. It rests on diorite. The basal beds are conglomerates with more or less rounded dioritic pebbles, often of enormous size. The middle portion consists of sandstones, and the upper strata of clays containing lignite and fossil shells of species now living in the Philippine seas.[3] The supposed tuff at Galiano belongs to this same series. Such partial information as was available to Mr. Abella in 1893 concerning the Cordillera Central of northern Luzón, including its branches reaching to the China Sea on the west and to the Cagayán Valley on the east, led him to believe that it consists of a core of ancient diabasic and dioritic schists together with massive rocks belonging to the same type and epoch, which is cut at some points by very modern trachytes and andesites and is overlain, to the west at least, by the same limestones, conglomerates, sandstones, and clays which constitute the post-Tertiary formation of the central part of Luzón.[4]

Semper seems to be the only naturalist who made public any notes on the Sierra Madre of northeastern Luzón. Two of his specimens represent pre-Tertiary massive rocks. Of these, one comes from the range near the coast town Palanan, latitude 17° 5′. It is described by Mr. Oebbeke as a peridotite containing diallage, enstatite, and pikrite. The other specimen probably comes from the western foothills of the same range. It was a pebble in the brook called Dicamuni, and this

[1] Terremotos de 1892, 1893, p. 32.
[2] Fragmente, 1878, p. 31.
[3] Terremotos de 1892, 1893, p. 33.
[4] Manantiales, 2d study, 1893, p. 18.

brook is said to be "in the land of the Minangas." Semper's map shows Minanga in latitude 17°, at or about the locality of the settlement named Malunú on Mr. d'Almonte's map.[1] This pebble, according to Mr. Oebbeke, is a norite.

The cordillera of Baler and La Infanta, lying to the east of the great plain of Luzón, is described by Mr. Abella in much the same terms as the Caraballo Central. It consists of diabase and diorites, in part schistose, pierced by modern volcanics.[2] To this range belongs the spur containing the San Mateo caves and the gabbroitic area near by them examined by Mr. von Drasche, of which mention has already been made (p. 499).

The foregoing notes cover all the occurrences of ancient massive rocks and crystalline schists known to me north of Laguna de Bai. Immediately south of the lake neo-volcanics appear to stretch quite across Luzón. In the southwesterly prolongation of the island, however, there are patches of the rocks in question. Of these the most northerly is in Tayabas Province and was visited by Mr. von Drasche. This very small area lies just to the west of Antimonan, in latitude 13° 59′. The rock is a greatly decomposed, green talc-chlorite schist with a high easterly dip.[3]

One of the most important areas in the whole archipelago surrounds the ports of Paracale and Mambulao, in Camarines Norte.[4] This is the most promising auriferous district known in the islands, and the rock is also of special lithological interest. Roth describes it as follows:

> On the northeast coast of the province, the country between Paracale[5] and Mambulao consists of gneisses and hornblende-schist in which there are rich quartz veins. The mountain lying a quarter of a league north of Mambulao, and the mountain north-northeast of Mambulao (divided by the Mount Dinaan Brook), consist of gneiss, in which the white layers are separated by thin, discontinuous, uneven layers of tombac-brown mica. The white layers are composed of a mixture of fine-grained quartz, some orthoclases, and plagioclases. The rock is said to contain gold. The mountain half a league northwest of Paracale, Mount Dinaan, and the stretch between Paracale and Mambulao consist of hornblende-schist. The fresh rock from Mount Dinaan is dark colored through the preponderance of rather coarse hornblende, narrow discontinuous white stripes being due to aggregations of plagioclase in small crystals. Besides these minerals there is some pyrite and brown mica. The magnet extracts no magnetite from the powdered rock. The weathered rock between Paracale and Mambulao strikes east and dips to the south at 40°, is gray-green, soft, intersected by stringers of magnetite, and converted sometimes into serpentine-bearing talcose schist, and sometimes into talcose serpentine-schist.[6]

[1] For further details as to this locality see footnotes to Mr. Martin's paper which follows this report.
[2] Manantiales, 2d study, 1893, p. 16.
[3] Fragmente, 1878, p. 59.
[4] Till within a few years there were two provinces, called Camarines Norte and Camarines Sur. Early in the last decade they were united into a single province, Ambos Camarines. About the same time the southeast end of Albay was separated from it, and designated the Province of Sorsogón.
[5] Roth writes Paracali, which is not now the accepted form.
[6] Jagor's Reisen, 1873, p. 344.

This quotation contains the second unquestioned reference to orthoclase among the pre-Tertiary massive rocks discussed in this notice. Judging from the distribution of gold and iron mines on Mr. d'Almonte's map, this area of ancient rocks should stretch from Mambulao to near Daet. Between Paracale and Mambulao Mr. von Drasche found a layer (dike?) of peridotite, about a hundred paces in width, which projects into the sea.[1]

In Camarines Sur there are diorites on the southwest coast just to the westward of the port of Calbajan. They are not schistose, the grain is variable, and the feldspar is relatively anorthitic, since it is completely decomposed by hot chlorhydric acid. The hornblende is black. The rock contains magnetite and some pyrite.[2]

In Sámar Jagor found no ancient rocks in place, but sediments which he collected on the north coast appeared to Roth, after panning, to be derived from gneiss or mica-schist. From the Basey River, on the south coast of the island, Jagor brought home pebbles which Roth considered an oligoclase porphyry.[3]

In Leyte, on the east coast, half a league north of Tanauan, Jagor observed a projecting rock consisting of chloritic quartz-schist.[4]

At Culión, in the Calamianes, Paleozoic schists and quartzite are said to occur.[5]

The Island of Lubang lies to the northwest of Panay, about latitude 13° 50′. Dana[6] reported, "Luban contains copper pyrites in talcose and chlorite slate, and the same formation extends into Mindoro, where it passes into serpentine, specimens of which were contained in the cabinet of Señor Roxas." At San José too, on the coast of Panay, the same geologist saw pebbles of talcose schist. This island has since been investigated by Mr. Abella, not exhaustively, yet with much care.[7] The commonest ancient rock of Panay is a quartz-diorite of granular texture, or a tonalite, in which labradorite is the predominant feldspar, and the quartz is in part granular, in part interstitial. The ferromagnesian silicates are reddish biotite and green fibrous hornblende. Magnetite is absent. This rock of granitic type is associated with others which are semi-porphyritic and contain no mica. There are also quartzless diorites connected with the other varieties by transitions and carrying some magnetite. Mr. Abella further describes rocks containing both augite and hornblende, which he classifies with the diabases, but he does not discuss the question how far the green fibrous hornblende of the diorites may be uralitic.

The diabases are less abundant. They also are labradorite rocks. "The crystals of augite are individualized and well characterized, but what chiefly distinguishes these diabasis from the diorites is that, both

1 Fragmente, 1878, p. 62.
2 Jagor's Reisen, 1873, p. 348.
3 Ibid., pp. 352–353.
4 Ibid., p. 220.
5 J. E. Tenison-Woods, Nature, Vol. XXXIII, 1886, p. 231.
6 U. S. Expl. Exp. 1849, Vol. X, p. 539.
7 La Isla de Panay, 1890, p. 97.

in the groundmass, and especially as inclusions in the pyroxene, there is a great abundance of ferrous iron, and above all of magnetite, which was not found in the diorites." Whether the structure is ophitic is not stated, but I infer from the absence of mention of minute augites that the groundmass is feldspathic, so that the rock might perhaps be classed as an ancient, holocrystalline pyroxene-andesite. At one locality (Mount Násog) much decomposed gabbro was found. Certain picrites, though accompanying the rocks described above, may possibly, in Mr. Abella's opinion, belong with the neo-volcanic group, while the serpentines met he classifies with the older group. Tuffs appear to have accompanied the diorites and diabases, and stratified rocks, including the lignitic beds, intervened between the eruption of these rocks and the neo-volcanic andesites and basalts.[1] In Mr. Abella's map of Panay the ancient and neo-volcanic rocks are not differentiated. The massive rocks are mainly confined to the range which forms the eastern boundary of the Province of Antique, and to the divide which forms the western boundary of Concepción. Excellent tonalites, fit for quarrying, Mr. Abella says, occur on the shore, on the west coast, at Tinanagan, in latitude 11° 44′ 30″, some 5 miles westerly from Pandan; and also on the east coast at Colasi, in latitude 11° 4′ 30″. He suggests this rock as a substitute for Hongkong granite, which is largely employed for paving in Manila.

In the Island of Negros I did not chance upon any ancient rocks. I should expect to find such in the watershed of the southwest coast of Negros, a region which I was unable to visit, rather than in the main volcanic sierra of the island.

Cebú is covered for the most part by a mantle of coral, 100 or more feet in thickness, which reaches from the crest of the island to the sea. In some localities, however, the coral is absent, a condition due, at least in part, to stream erosion. One such exposure occurs in the foothills of the main range, to the west of the capital town, also named Cebú, and extends for several miles both up and down the island. A similar exposure lies on the western slope of the central range nearly opposite that just mentioned. Other areas of minor extent are found toward the ends of the island. A portion of these denuded areas is occupied by schists and pre-Tertiary massives. They have been examined by Mr. Abella, and his specimens were determined microscopically by Mr. José MacPherson. At a single point, Bagbad,[2] Mr. Abella found an amphibolic slate, and he inclines to the opinion that the geological foundation of the island is of this character. The oldest massive rocks are almost exclusively diorites, often much jointed, and sometimes exhibiting traces of schistosity. Dioritic tuffs accompany the diorites. The only exceptional specimens noted are felsophyres,

[1] La Isla de Panay, 1890, p. 109.

[2] I have not been able to find this point on the map, or any note as to its precise locality, in Mr. Abella's memoir on Cebú.

which appear in this case to be porphyritic diorites, a single actinolite rock from the hot springs of Cagbao,[1] and a single granite. The granite comes from the upper part of the Panoypoy Brook, and therefore from a point 3 or 4 miles to the northwest of Consolación, a town lying 8 miles or so to the northeast of Cebú. Of these specimens Mr. Abella says: "Until other more detailed investigations disclose the part played by these rocks we can only consider them as accidental."[2]

On the Guadalupe River, which empties into the sea at the town of Cebú, I met with a rock which is probably allied to Mr. Abella's granite. It occurs in the stream bed about three-quarters of a mile above the point at which the river debouches into the coastal plain, or some 4 miles from Cebú. It is a fine-grained, greenish-gray rock, containing chlorite and some pyrite. It has been much crushed and jointed. Under the microscope it appears thoroughly granular, and is composed of striated and unstriated feldspar, quartz, hornblende, iron ore, and other minor constituents. It is somewhat decomposed. A considerable portion of the feldspars is unstriated. The predominant plagioclase is oligoclase, but there are a few grains of labradorite, one of them neatly inclosed in oligoclase. A few individuals might possibly be interpreted as albite, but these were not so oriented that they could be certainly determined. The unstriated feldspars have a smaller index of refraction than balsam, and are on the whole more decomposed than the plagioclases, being largely filled with sericitic mica. The quartz is interstitial, and is much cracked, no doubt by pressure. The hornblende also appears to be of somewhat later development than the feldspars. It is green and fibrous, but there seems no evidence that it is uralitic. The abundant chlorite and epidote are certainly in part derived from the hornblende. There is a moderate quantity of magnetite and seemingly a little ilmenite, surrounded by leucoxene. A few apatites and zircons were observed. To make certain of the proper classification of the rock the following partial analysis was carried out by Mr. George Steiger:

	Per cent.
CaO	2.66
K_2O	1.07
Na_2O	6.19

Estimating the amount of hornblende at 5 per cent, and supposing a tenth part of this mineral to be CaO, the analysis is compatible with the following hypothetical composition:

	Per cent.
Quartz	25
Hornblende	05
Labradorite (Ab_1An_1)	07

[1] This place is 3 or 4 miles northwest of Minglanilla, a town 6½ miles southward of Cebú. Possibly, and indeed probably, this specimen is identical with the amphibolic slate from Bagbad, which may be a small village near the springs.

[2] Rapida descripción . . . de Cebú, 1886, pp. 96–101.

	Per cent.
Oligoclase (Ab_4An_1)	42
Albite	15
Orthoclase	06

The amount of unstriated feldspar, however, is much in excess of 6 per cent; and I am forced to the conclusion that the rock is composed largely of soda-orthoclase. It can not, however, be classed otherwise than as a diorite. It seems not improbable that Mr. Abella's granite may be a rock with a larger percentage of a similar orthotomic feldspar.

Mr. A. F. Renard found among the specimens of the *Challenger* expedition a pyroxene-olivine rock which he compares to a basalt, but inclines to think pre-Tertiary and a melaphyre. It was collected in a river bed near Cebú, Cebú.[1]

The late Mr. William Ashburner, a well-known American mining expert, examined a gold-quartz vein on the Island of Panaón in 1883. This island lies immediately to the south of Leyte, from which it is separated only by a channel a few hundred yards in width. The mine lies just south of Pinutan Point and is marked on Mr. d'Almonte's map. Ashburner reported the walls of the vein as greenstone-porphyry.[2] This term would not exclude "propylitic" neo-volcanics, but in all probability points to diorite or diabase.

Concerning the great Island of Mindanao, only scattered observations are available. Sainz de Baranda[3] noted the occurrence of serpentine on the east coast of the island at Canmahat and in Misamis Province at Pigtao. Mr. Centeno states that at Pigholugan, near Cagayán, in the Province of Misamis, there are quartz veins in talcose schists. The auriferous districts of the Province of Surigao may, he points out, be regarded as a continuation of the Misamis district. The most notable deposits here are in the mountains of Canimon, Binuton, and Canmahat, a day's journey southward from the town of Surigao. The terrane is here composed of much altered talcose slate and serpentine.[4] Mr. Semper collected on the Maputi, which is an upper tributary of the Agusan River in Surigao. Here he found a uralitic gabbro and a chloritized, aphanitic, augite-plagioclase rock, containing a few plagioclase phenocrysts. The specimens have been described by Mr. Oebbeke.[5] They are probably facies of the melaphyres found by Mr. Montano. Mr. Ashburner examined a slate belt in the extreme northern portion of the island, about 8 miles to the southward of the town of Surigao, at the headwaters of the Cansuran River. It contains auriferous quartz stringers. Mr. Montano collected melaphyres

[1] Voy. of *Challenger*, Vol. II, pt. 4, 1889, pp. 160–175.
[2] Manuscript report of Mr. Ashburner, 1883, shown me by his clients.
[3] He also mentions crystals of rutile from an island called Bigat, which is unknown to me. Anales de Minas, Madrid, Vol. II, 1841, pp. 197–212.
[4] Memoria geológico-minera, 1876, p. 49.
[5] Neues Jahrbuch, Beil.-Band I, 1881, p. 498.

at a number of points in eastern Mindanao. Such are the eastern shore of the Bay of Butuan, the eastern coast of the island between Bislig and Catel, and the divide between the waters which flow northward into Butuan Bay and those which flow southward into the Gulf of Dávao. The river of this southern drainage basin Montano calls the Sahug. Other authorities give it different names. In its headwaters he found float consisting of melaphyre and quartz-porphyries. Melaphyre he found again at Pujada Bay near Cape San Agustín. Quartz breccias also occur on the divide between Pujada and the Gulf of Dávao. Serpentine accompanies the melaphyre to the south of Bislig.[1]

Mr. Minard visited the gold-bearing region of Misamis, the northwestern province of Mindanao. The sandstones and conglomerates of the Iponan Valley, dipping 12°, are said to be broken through at many points by diorite and serpentine. The pebbles of the conglomerates include diorites, augite-porphyry, serpentine, jasper, and marble.[2] Some years later Mr. Abella made a reconnaissance of this region, examining the gold deposits along the courses of several rivers, all of which empty into Macajalar Bay. They are the Iponan, the Cagayán, the Bigaan, and the Cutman. In this region he found two considerable areas of old slates. One of these touches the Iponan River 10 or 12 miles from the sea. The other is intersected by the Cutman and approaches the sea within 2 miles, near the town of Agusan, which lies at the mouth of the Cutman River. Alluvial deposits fringe the shore of the bay and follow the streams. Otherwise the country, as depicted by Mr. Abella, is covered with strata provisionally referred to the Miocene. The slates are described as metamorphic and in part steatitic. The pebbles of the Tertiary conglomerates consist of such slates, serpentinoid rocks, and many varieties of "trachytic rocks." I think that at the date of his memoir, 1879, Mr. Abella used this term for neo-volcanic rocks not basaltic in appearance. The description of the fossiliferous rocks overlying the slate leaves no doubt that they are Tertiary or Recent, a fact which it is difficult to reconcile with Mr. Minard's statement that they are cut by serpentine and diorite. In the placer at the Bigtog, tributary to the Cagayán, Mr. Abella found slightly rounded, large pebbles of orthoclase.[3]

A few miles northwest of Zamboanga (in southwestern Mindanao), at Caldera, Dana observed hornblendic and talcose schist in pebbles,[4] and on Malanipa, about 13 miles E. by S. from Zamboanga, the *Challenger* expedition collected serpentinized peridotite, studied by Mr. Renard.[5]

[1] Mission aux îles Phil., 1879–1881, pp. 272–277.
[2] Bull. Soc. géol. France, 5th series, Vol. II, 1874, pp. 403–406.
[3] Mem. acerca de los criaderos auríferos . . . Misamis, 1879, pp. 4, 18, 32, 45.
[4] U. S. Expl. Exp., Vol. X, 1849, p. 539.
[5] Ibid.

The foregoing fragmentary notes cover all the information available concerning the crystalline schists and pre-Tertiary massive rocks. There is, however, a second line of evidence on this subject which is perhaps not without value, although it is inconclusive. In all cases in the Philippines of which details are known, crystalline schists accompany gold-quartz veins, copper ores, iron ores, and galena. It is therefore probable that where nothing is known of the geology except the occurrence of these ores crystalline schists exist. This deduction leads to the inference that the northern end of the Cordillera del Norte, being auriferous, consists in part of such schists, and the gold of northern Zambales may be taken into account in considering the massive rocks there. A belt of iron ores over 40 miles in length and presumably accompanied by schists passes east of Angat in the same direction as the trend of the neighboring sierra. The islands to the eastward of central and southern Luzón would seem to be composed in part of schists, and with them may be considered the peninsula of Caramoan, which, as well as the islands Polillo, Luhuy, Catanduanes, and Rapurapu, contains gold. To the southward of Luzón the islands Capul, Masbate, and Marinduque contain copper, while Sibuyan and Masbate produce some gold. Southern Negros has gold deposits; copper is reported from Balábac, and gold from Joló. Thus, if this class of evidence is admissible, crystalline schists occur in all the more important portions of the archipelago except Palawan or Paragua, of which next to nothing is known.[1]

A mere inspection of any chart would lead to the inference that such must be the case, for most of the platform on which the islands stand is exposed, while wherever the earth's surface is sufficiently incised crystalline schists or allied granular rocks are laid bare. Of the age of the rocks under discussion nothing is known directly, and it is probable that several eras are represented. When the neo-volcanic rocks come to be discussed it will be found that they belong for the most part to the same chemical and mineralogical types as the pre-Tertiary massives. There appears to have been in earlier times one period at least of volcanism very similar to that still progressing in the archipelago. Very probably it, too, was accompanied by an important uplift of the region. It is noteworthy that the older massives are very deficient in potash. The only orthoclastic rocks noted are a specimen of quartz-porphyry from Cabayan in Benguet; a gneiss from Paracale, Ambos Camarines; a granite from Cebú, and some pebbles from Misamis. Among the neo-volcanics, also, lime-soda feldspars vastly predominate over sanidine.

In Borneo the central portions of the mountain ranges are composed largely of crystalline schists. These are older than slates, which there

[1] On chart 1731 of the Hydrographic Office, which is from a British survey in 1851 by Commander W. T. Bate, Mount Kapoas, on Palawan, in latitude 10° 48′, longitude 119° 17′, is marked granite. Without further information I hesitate to accept this as a lithological determination, though it is not improbable.

is some paleontological evidence for considering Devonian, and they may be Archean. Both in Borneo and in Sumatra the older massive rocks appear separable into two groups of different ages, an older granitic-dioritic group and a younger diabase-gabbro series. The granites, quartz-porphyries, syenites, diorites, tonalites, etc., are intimately associated with the crystalline schists, which are doubtless in part dynamometamorphic forms of these rocks. There are also some later intrusions or extrusions of these rocks. On the other hand, the greater part, if not all, the rocks of the gabbro-diabase series are younger than Carboniferous strata. In most places in Borneo there are no strata between the Carboniferous and the Eocene, and many of these pyroxenic rocks may be of any intermediate age. At Mount Tamban, in South Borneo, however, Mr. Verbeek found gabbros which appeared to be partly Eocene and partly Miocene.[1]

There is nothing in these relations inconsistent with Mr. Abella's generalization that the dioritic rocks are the oldest in the Philippine Islands.[2] That geologist would unquestionably include as dioritic the schists of similar composition which accompany them. In so far as the older orthoclase rocks exist in the Philippines they certainly belong chronologically with the diorites. As for the diabase-gabbro series, their age relatively to the diorites in the archipelago has not yet been worked out in detail. It would seem probable that some at least of these pyroxenic rocks are much younger than the great mass of the diorite.

LITHOLOGICAL NOTES ON THE VOLCANIC ROCKS.

It will surprise no one to learn that the lithology of the volcanics occurring in the archipelago is in a very imperfect condition. Baron von Richthofen's paper of 1862 was published before the introduction of the microscope into the study of rocks. The first microscopical work done on Philippine collections was, I believe, that of Roth on Jagor's specimens, and was published in 1873. It is of great value, but many modern methods of determination were still unknown. Mr. von Drasche's notes on rocks, excepting gabbro, are meager. They appeared in 1878. Prof. Carl Semper's collections, made early in the sixties, were examined after the publication of Mr. von Drasche's memoir by Mr. K. Oebbeke in the laboratory of Professor Rosenbusch, and, with analyses by Mr. A. Schwager, were described in 1881. This is a very thorough investigation, but the number of localities represented is not large. Mr. Abella gives microscopical

[1] T. Posewitz, Borneo, Geology of the Mountain Land, pp. 137-172.
[2] Apuntos físicos y geológicos, 1884, p. 30.

determinations in his memoirs on Cebú, 1886, and on Panay, 1890, but does not appear to have made use of the microscope in his earlier papers concerning Luzón. Mr. Joseph Montano's rocks (1885) were examined by Mr. Ch. Velain, but few details are given in his memoir.

In compiling what is known of these rocks and their distribution it will perhaps be most perspicuous to begin by lithological descriptions derived from study of my own very imperfect collections and culled from the memoirs just mentioned. The distribution of the lavas can be more conveniently discussed by itself. In examining thin sections I have endeavored to take full advantage of the methods of feldspar determination so ably developed by Mr. Michel Lévy, and not less attention has been paid to the microlites of the groundmass than to the phenocrysts.

The Island of Talim, in Laguna de Bai, furnishes a series of thoroughly typical basalts, some of them resembling obsidian in appearance, though in reality nearly holocrystalline. They are characterized by ophitic structure and the predominance among the feldspars of anorthite ($Ab_{11}\ An_{200}$). The phenocrysts are usually zonal, the outer zone approaching or reaching calcic labradorite in composition. The microlitic feldspars vary in composition more than the phenocrysts, and range from anorthite to sodic labradorite, showing, as do many rocks, either that the residual mother liquor was very far from being homogeneous or that the rock inadequately represents the magma, being, perhaps, a fractional precipitate. All of these basalts contain olivine, chiefly in large crystals, and in none of these could I find rhombic pyroxenes. The augite appears to be younger than the olivine, and is in no way remarkable.

Basalts which are probably in every respect similar to these are described by Mr. Oebbeke from the Island of Basilan, at the town of Isabela, and from an islet off the coast about 6 miles due west of Isabela, called Lampinigan.[1] A somewhat decomposed specimen containing glass gave Mr. Schwager the following composition:

Analysis of basalt containing glass.

	Per cent.
SiO_2	51.32
Al_2O_3	15.48
Fe_2O_3	4.48
FeO	6.70
MnO	0.39
CaO	8.68
MgO	6.54
Na_2O	3.06
K_2O	1.11
H_2O	1.10
Total	98.86

[1] Neues Jahrbuch, Beil.-Band I, 1881, p. 489.

Mr. A. F. Renard[1] describes a decomposed rock from a river bed near Cebú, Cebú, which may be a basalt or a pre-Tertiary melaphyre. He inclines to the latter hypothesis because the rock contains epidote, but points out that this fact does not exclude its reference to the basalts. The specimen was collected by the *Challenger* expedition.

The next well-defined group of rocks should, in my opinion, be classed as labradorite-basalt. I collected specimens of such a rock in the ravine just east of Paete, which lies on the east side of Laguna de Bai, about 2 miles to the northward of Santa Cruz. It contains abundant olivine but no rhombic pyroxene. As is well known, these minerals are rarely found together. The olivine is older than the augite. The slide contains an unusual number of determinable feldspar phenocrysts, almost totally devoid of zonal structure, among which I found only calcic labradorite. The microlites, on the other hand, include both labradorites and a little andesine. The phenocrystic feldspars are not sufficiently numerous to produce ophitic structure, but the microlites do form such a network, filled in with minute augites. The groundmass differs so essentially from that of the andesites that to call this rock an olivine-andesite would seem to me misleading. Near the same spot I found a very coarse porphyry, with feldspars half an inch in length, embedded in a fine-grained dark paste. It reminded me at once of the material of Tuolumne Table Mountain, which has been so interestingly discussed by Mr. H. W. Turner. As seen under the microscope, the same description given to the foregoing specimen applies, except for the great size of the phenocrystic feldspars and the absence of andesine in the groundmass. I also collected a labradorite-basalt in the Island of Negros, about 16 miles northeast of the volcano Canlaón, on the Talabe River. In this rock, however, there is hypersthene as well as olivine, and the feldspar of the groundmass consists only of the two labrodorites. With these rocks I place that of the mountain just to the southeast of the town of Joló (Tumantangis). In this the only phenocrysts are olivines, while the ophitic groundmass consists of calcic labradorite, the interstices between them being filled with augite, magnetite, and a little olivine.

In Panay Mr. Abella[2] has discovered leucite-nepheline-basalts.

A very curious rock defying strict classification comes from southern Negros, about 3 miles west of Dumaguete, the massif to which it belongs being andesitic. The specimen originally contained hornblende as the sole phenocrystic ferromagnesian silicate, but this has been completely converted into the ordinary "black border" of magnetite and augite. Outlines remaining leave no doubt of the original mineral. The inner portions of the somewhat sparsely distributed feldspar phenocrysts are sodic labradorite ($Ab_1\ An_1$), but they

[1] Bull. Acad. roy. Belgique, 3d series, Vol. XI, 1886, pp. 95–105; and Voy. of *Challenger*, Vol. II, pt, 4, 1889, pp. 160–175.

[2] Isla de Panay, 1890, p. 107.

show a strongly marked outer zone which, instead of being more silicic, is less silicic than the kernel. These outer rims give the angles of extinction of calcic labradorite, of course, for the same crystallographic positions found for the sodic labradorite of the interior portions. The rims also seem to differ otherwise from the ordinary zonal structure, their inner boundaries being more rounded than the periphery and apparently disregarding crystallographic form, just as if the outer portions of sodic labradorites had been changed to the calcic species by external attack. Some small feldspars are embedded in the hornblendes. These are sodic labradorite and are not inclosed in the more anorthitic mineral. The groundmass contains a large number of microlites suitable for determination. Many of them show nearly square cross sections and can be determined by a method which I have indicated in my report on the gold fields of southern Alaska.[1] Some of these microlites show albite twinning and are demonstrably bounded by the base and brachypinacoid. The long sections of microlites in this rock are also in many cases determinable. The result is that the majority of the microlites are anorthite and the remainder calcic labradorite, which is certainly a very curious state of affairs. This groundmass contains nearly equal quantities of feldspar and augite with a moderate amount of magnetite, but its structure is not ophitic. The specimen came from a brecciated flow and must have been formed under abnormal conditions, most likely, I should say, at the periphery of a moving mass of magma. The position in which it was found seems to show that it is a facies of andesite.

A somewhat similar rock, from the new volcano of Camiguin de Mindanao, has been described by Mr. A. F. Renard. The rocks there collected by the *Challenger* expedition are pyroxene- and hornblende-andesites, the former predominating, and including as constituents bronzite and augite. Olivines are found occasionally. In the pyroxene-andesite he found the feldspar phenocrysts composed of species ranging from andesine to labradorite. They show zonal structure, and the outer zones extinguish at greater angles than the inner ones, in contravention of the ordinary rule. The microlites are labradorite. Mr. Renard comments thus: "We have, then, to admit that the acidity of the magma decreased in proportion to the development of the feldspar."[2]

There are many specimens in my collection which seem to me normal andesites, some of them from the same neighborhood as the aberrant rock just described. One such, collected somewhat south of Valencia, from the same massif, is a very fresh hornblende-andesite, containing a little augite, but no hyporsthene, the phenocrystic feldspars being chiefly calcic labradorite, while the microlites are chiefly sodic labradorite, a few being andesine. There is the usual quantity of iron ore,

[1] Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. III, p. 32.

[2] Bull. Acad. roy. Belgique, 3d series, Vol. X, 1885, pp. 734-751, and Voy. of *Challenger*, Vol. II, pt. 4, 1889, pp. 160-175.

apatite, zircon, much glass, and no suggestion of ophitic structure. The Island of Corregidor and the neighborhood of Mariveles, at the mouth of Manila Bay, was the only volcanic region which I was able to study without being armed and guarded, and I have a better suite of specimens from that region than from other localities. Excepting a dike (which is dacite), all the rocks I could find along the shore or in the foothills of the Mariveles Range, or among the pebbles brought from higher altitudes by the streams, are andesites. In texture they vary from the basaltic to the trachytic type, and there are agglomerates and tuffs in abundance; but they are all essentially labradorite rocks without ophitic structure. For the most part they are pyroxene-andesites, containing augite and a dichroic rhombic pyroxene, but one gray rough rock, which is quarried for use in Manila, is hornblendic. In one specimen only from this region I was able to detect a single minute square crystal, which gave an extinction of 41° and must be anorthite. As a rule the phenocrystic feldspars are Ab_3 An_4, while the microlites are more sodic, ranging downward to andesine. Nearly all these rocks are more or less glassy. I found no olivine. I am rather explicit about the rocks of this locality because Roth[1] calls the rock of this region dolerite.

On the west coast of Negros the country is alluvial, and the beautiful volcanic range ending to the southward in the ever-steaming volcano of Canlaón is distant; but the streams near Bacólod bring down volcanic pebbles which appear to be exclusively andesite, and chiefly hornblende-andesite. A slide shows a glassy rock in which hornblende, in phenocrysts and microlites, is the only ferromagnesian component. This is greenish brown in tint, very dichroic, and extinguishes at a low angle. The feldspars, large and small, are labradorite, chiefly of the sodic variety. Magnetite, apatite, and zircon complete the components of this simple rock. On the Talabe River, on the east side of Negros, nearly opposite Bacólod, I also found vast quantities of andesite pebbles, brought down from the volcanic range. One is a glassy pyroxene rock in which the only notable feature is an interesting variation in the zonal structure of the feldspars. In two phenocrysts a zone of anorthite (Ab_{11} An_{200}) was sharply determined inclosing calcic labradorite and inclosed by calcic labradorite. It is difficult to make sure how such fluctuations can occur. Near Dumaguete, in southern Negros, I also found an otherwise normal andesite which contained one phenocryst and a microlite which were anorthite. Underlying the corals in eastern central Cebú, about 2 miles west of Naga, and again on the Guadalupe River to the west of the town of Cebú, I found very normal hornblende-pyroxene-andesite with labradorite feldspars.

[1] Jagor, Reisen, 1873, p. 341. I think Jagor's labels must have gone wrong.

Mr. Oebbeke[1] gives descriptions of various andesites, with analyses of rocks, and sometimes of components as well. In Mr. Semper's collection he found far more augite-andesites than hornblende-andesites. Of the latter, one is of especial interest. It is a white pumice from Magalang in the Pampanga, just to the west of Mount Aráyat. The feldspars appear megascopically very like sanidine. The hornblende is green. The rock also contains some scales of very dark mica, the angle between the optic axes of which is relatively large. The microscope and analysis show that the phenocrystic feldspars are Ab_1An_1, but near the oligoclastic limit of that species. The groundmass is glass with a sprinkling of magnetite. A specimen of hornblende-andesite from the small Island of Limasaua,[2] just south of Leyte, examined by Mr. Oebbeke, contains feldspars which do not give sharp extinctions, as Mr. Fouqué observed in certain sanidines, the dark tint passing across the section as the slide is revolved. This rock also contains a somewhat abnormal quantity of potash for an andesite. The analysis is given below.

The rocks of the Semper collection from Mariveles correspond with my own in most respects, being labradorite rocks, more or less glassy, without ophitic structure. Portions of the Mariveles rocks examined by Mr. Oebbeke were found to carry hornblende in addition to augite, and some grains were detected of a mineral which is probably olivine. In one respect my results differ from Mr. Oebbeke's. He found the augites strongly pleochroic. Such crystals, when isolated and examined separately, gave finite extinctions. Their analysis gave Fe (Mn): Ca : Mg=1 : 1.2 : 3, and the conclusion is drawn that the mineral is not a rhombic pyroxene. In my slides all the pleochroic pyroxenes cut parallel to the axis give zero extinction and seem to me unquestionably rhombic, while in the individuals which gave sensible extinction angles I could detect no dichroism.

Mr. Oebbeke finds the rocks of Taal volcanic augite-andesite, while Mr. von Drasche[3] regarded them as dolerite, except certain ejecta which "might perhaps be classed as augite-andesites." According to Mr. Oebbeke, all the specimens have a silica content of between 56 and 58 per cent, and the olivine is accessory only. He states, however, that in the case of certain specimens a doubt might arise as to which group they belonged with. The main mass of the crater is a labradorite rock containing phenocrysts of augite and plagioclase in a groundmass which is not ophitic and is largely glassy. Whether certain decomposed yellowish grains were referable to olivine could not be determined. An analysis is given in the table below, as well as of the essentially similar rock of Great Binintiang, a small crater at the northwest end of the Taal Island.

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[1] Neues Jahrbuch, Beil.-Band I, 1881.
[2] Oebbeke writes Limansaua, which appears to be incorrect.
[3] Fragmente, 1878, p. 51.

Analyses of andesites.

[Analyst, A. Schwager.]

	I.	II.	III.	IV.
SiO_2	54.48	54.62	58.42	56.02
Al_2O_3	19.44	16.96	17.64	16.52
Fe_2O_3	1.80	4.50	5.66	5.02
FeO	4.90	4.27	4.00	5.51
MnO	....	.35	.48	.36
CaO	7.08	8.56	4.50	4.20
MgO	3.72	5.20	2.54	4.67
Na_2O	3.58	3.26	4.44	5.83
K_2O	3.32	1.80	2.52	1.66
H_2O (ignition)	1.70	.73	.42	.47
TiO_2	....	Trace.	.31	....
Total	100.02	100.25	100.93	100.26

I. Somewhat abnormal hornblende-andesite from Limasaua Island, just south of Leyte.
II. Augite-andesite from Mariveles Point.
III. Augite-andesite from main crater of Taal.
IV. Augite-andesite from Binintiang crater at Taal.

I found an interesting dacite on the Island of Corregidor, at the entrance to Manila Bay. It forms a wide, irregular dike crossing the island from north to south just east of the little settlement, San José, and terminates in a bold white cliff, visible from the south passage, or Boca Grande. This rock is affected by a system of rectilinear pressure joints, and some considerable dynamic action has occurred since its intrusion. It is blindingly white, and shows to the naked eye, besides feldspar, only some small quartzes and minute, opaque mica scales. Under the microscope the mica is brownish green, unusually opaque, and extremely dichroic. There are no other ferromagnesian silicates. There are few phenocrystic feldspars, and these are sodic labradorite. Two or three quartzes also appear. The bulk of the rock is made up of feldspar microlites, with just a sprinkling of magnetite and a little apatite. The slide contains hundreds of microlites of almost exactly square cross section. They seem divisible into two groups, one giving angles of extinction relatively to the sides of about 43°, while the other gives angles of about 38°. If the bounding faces of these microlites were the base and brachypinacoid, these angles would indicate anorthite and calcic labradorite. On closer examination I found that a fair proportion of these little crystals showed truncation of two corners and that a smaller portion were twinned, the plane of contact, however, running diagonally across the squares. It is thus evident that the bounding faces of the square microlites in this rock are the hemidomes, *n* and *e* or (021), instead of the base and brachypinacoid. Hence the determining angles of extinction are about $\frac{1}{2}^{\circ}$ and $4\frac{1}{2}^{\circ}$ and the corresponding feldspars are the two oligoclases, Ab_3An_1 and Ab_4An_1. This result is confirmed by examination of the long sections of the microlites, all of which extinguish at extremely small angles. Not having hitherto seen microlites bounded by hemidomal faces alone, I was particularly careful to test the development of the feldspar microlites in the andesites and basalts described in this paper, but found no similar cases among the more anorthitic feldspars of these rocks. So far as I know, dacite has not been discovered elsewhere in the archipelago, but it occurs in the Moluccas.

Besides basalt, the andesites, and dacite, there is reason to suppose that trachyte and rhyolite occur in the Philippines. Baron von Richthofen determined as trachyte a rock which is found in contact with the nummulitic limestones on the peninsula of Binangonan, and Mr. von Drasche concurs in the determination. Among Jagor's specimens Roth describes a white pumice containing a little dark mica and feldspar which seems to be sanidine. It was collected between the villages of Yriga and Buhi in the Province of Camarines Sur. Mr. von Drasche describes as trachytic a tuff which occurs over most of the western portion of the inland plain of Luzón from Mount Aráyat westward to the watershed. At Pórac, in Pampamga, he found in a tuff fragments of which he says:[1] "The rock of which these lumps consist is an uncommonly foamy, pumice-like, blindingly white, sanidine trachyte. In the cavities there are numerous white, large, cracked sanidines and thick, short, columnar hornblende crystals." Farther westward he found this pumiceous rock passing into "sanidine-hornblende-trachyte, with a compact groundmass which is sometimes white and sometimes brick red." At the Canan hot springs in O'Donnell, Tárlac Province, Mr. Abella found dikes of a very pretty sanidine-trachyte, of porphyritic texture, cutting ancient-looking slates.[2] At Galiano (Unión) Mr. von Drasche found a trachyte tuff which was microscopically examined.[3] "In a powdery, brown groundmass lie numerous scraps of dichroic hornblende and rounded feldspar grains. Both ingredients are fairly fresh. The feldspars seem to be of two kinds, one orthoclastic and the other plagioclastic." Mr. Semper's specimen from Magalang, which Mr. Oebbeke determined as hornblende-andesite, certainly came from the area regarded by Mr. von Drasche as trachytic tuff. It must also have resembled the Pórac specimen strongly in external appearance. Mr. von Drasche's description of the Galiano specimen seems to leave it open to question whether it is a potash rock, while Mr. Abella denies that it is a tuff at all, pronouncing it a sedimentary rock derived from the degradation of an adjoining diorite

[1] Fragmente, p. 12. [2] Manantiales, 1893, p. 144. [3] Fragmente, p. 31.

area.[1] Without further study this rock can scarcely be accepted as trachyte. Of the trachyte in the Binangonan area I find no lithological description, and Roth, judging from Jagor's specimens, thought the occurrence dubious. Mr. Semper's collections seem to have contained no trachyte. Mr. Abella describes a single trachyte from Panay at Barbaza, Province of Antique, which he inclines to regard as an accidental local facies. "In a decomposed and completely amorphous magma [devitrified glass?] together with granules of augite, there are to be seen in this rock feldspars which show most clearly Carlsbad twinning, and although there are also visible some plagioclases, they are less abundant and not so characteristic as the orthoclases." This passage reads as if Mr. Abella depended upon Carlsbad twinning to differentiate orthoclase, but he may, of course, have employed some other and really applicable test.[2]

Mr. von Drasche found rhyolites in the Province of Bontoc (Luzón). Of such an occurrence he writes:[3] "It is a hard, white rock with splintery fracture. In the dense groundmass are visible sanidines with glassy luster, and gray, opaque feldspar prisms, quartz in formless grains, and small augites, certainly a rare combination of minerals. Under the microscope the groundmass resolves itself into a confused mass of crystals, in part colorless, in part brown, the latter being perhaps augite (?). Those gray feldspars consist of the same mixture, very strange to say, and are separated from the rest of the groundmass by a dark border. There are few augites; magnetite occurs in very pretty crystals. All the phenocrysts are rendered very impure by groundmass and contain numerous glass pores." It is not impossible that hard, white, splintery dacite, such as I collected in Corregidor, may sometimes have been mistaken for rhyolite, while it seems highly improbable that Corregidor should be the only point on the line of the Sierra Zambales at which dacite exists.

The basalts and andesites of our Asiatic province might have come from Alaska or from the western Cordilleras of North America, so far as their composition and structure are concerned. There is the same unexplained adherence of the feldspars to definite types, only emphasized by cases of exceptional composition. There is the same general uniformity in the groundmass of the rocks, accompanied by the occurrence of numerous exceptional microlites and not very infrequent reversals of the ordinary rule of deposition, according to which the more calcic feldspars are precipitated before the more sodic species. There can be little doubt that detailed field study in the Philippines will reveal most of those variable associations of massive rocks which of late years have claimed so large a share of the attention of lithologists. The principles which underlie rock formation are clearly worldwide, and I do not doubt that they extend to other planets.

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[1] Terremotos en Luzón durante 1892, 1893, p. 33.
[2] Isla de Panay, 1890, p. 103. [3] Fragmente, p. 39.

Bunsen showed that magmas, so far as they are homogeneous liquids, are to be regarded as solutions. Considerable latitude, however, is permissible in defining that portion of such a magma which is to be regarded as the solvent. The simplest relations appear to me to result when the eutectic mixture of the substances involved is considered as the solvent. This mixture is definite and, at any given pressure, has a constant composition, inalterable by partial solidification. At temperatures above its point of solidification a eutectic mixture is capable of dissolving a greater or smaller excess of any of its constituents, so that with a single given eutectic solvent, solutions of variable composition may be produced in infinite variety. For instance, there is a well-known and technically important eutectic mixture of lead and silver which, when superheated, will dissolve further quantities of either lead or silver and may serve as the base for an endless variety of alloys. If we knew all about magmas, it seems fairly certain that we could define a number of eutectic mixtures, each, when heated above its melting point, yielding an infinite variety of solutions corresponding to rocks of an infinite variety of compositions. Thus, if a labradorite-basalt is conceived as a eutectic mixture, capable at sufficiently high temperatures of dissolving more feldspar and olivine, it is easily conceivable that rocks of this class should be found containing many large feldspars or no feldspathic phenocrysts, much olivine or none at all, while the groundmass, representing the eutectic mixture, would maintain a nearly uniform composition and character, independent of the phenocrystic composition.

From this point of view the groundmass of rocks would be more interesting and important than the phenocrysts, while it has usually been studied with less care, because of the greater difficulties in the way of mineralogical determination. The groundmass would either consist substantially of the eutectic mixture or afford a closer approximation to it than does the whole rock.

It is difficult to imagine that the comparatively small number of elements which enter largely into the composition of massive porphyritic rocks should form any very great number of independent eutectic mixtures; and it seems to me that it would be possible to elaborate a eutectic classification of those rocks which have consolidated from the liquid state—I mean the porphyries—each rock group representing a series of solutions in one eutectic liquid. Such a classification would also have certain geological advantages over others, for the composition of the groundmass of rocks largely determines their orogenic significance. The capacity of a magma to flow during injection or after ejection depends chiefly on the viscosity and the latent heat of the groundmass or, approximately and in the most important class of cases, on the properties of the eutectic solvent. Commonly the phenocrysts are mere flotsam in the stream of liquid rock, and do not seriously interfere with its capacity to flow.

Even among the rocks which represent solidified fluids there is a class not subject to such a classification as is here proposed. It seems an inevitable conclusion from the laws of precipitation that there must be many rocks which have been formed by fractional crystallization. There is no difficulty in seeing how this process might go on, but the greatest difficulty in comprehending how it could be obviated altogether. Especially must this be true of dikes and laccoliths, where convection currents (incomparably more effective, except at distances within a few centimeters, than any process of molecular flow) must feed the crusts growing on the containing walls with saturated or supersaturated solutions.[1] Now, such fractional precipitates are essentially impure. Either in nature or in the laboratory, they represent neither the substance dissolved nor the solvent or mother liquor, but only fortuitous mixtures of the two—crystals of precipitate, including and entangling variable quantities of mother liquor; crusts, which vary in composition from millimeter to millimeter. Rocks of such origin appear to me insusceptible of any strict classification and fit only to throw a dim light on the qualitative composition of the magma, which they represent, indeed, but only partially and irregularly. Were a eutectic classification worked out, it would probably be easy to recognize these impure partial precipitates, which would then receive the scant attention they deserve. It is hoped that the laboratories of the United States Geological Survey will be able to throw some light upon rocks of eutectic composition within a moderate time.

NOTE ON THE DISTRIBUTION OF THE VOLCANIC ROCKS.[2]

Anything like a comprehensive description of the distribution of volcanic rocks in the Philippine Islands is as yet quite impossible. The interior of northern Luzón is little known, but is supposed to consist mainly of crystalline schists, broken through at some points by intrusives and volcanics; and a similar statement is true of the eastern range of Luzón, the Sierra Madre, as far south as the Province of Príncipe. Crystalline schists appear again in Camarines Norte. But to the north, the west, and the south of this area volcanic rocks are abundant. The southern portion of the Zambales Range and the greater part of the territory between the Bay of Manila and the Strait of San Bernardino are occupied by volcanic rock. In the Visayas volcanic rocks are not rare, but Negros only is remarkable in this respect. Nearly the whole of the range, which extends from one end

[1] Am. Jour. Sci., 4th series, Vol. IV, 1897, p. 257.
[2] References already given in the preceding section are omitted in this note.

to the other of that exquisite island, is volcanic. According to Semper, all of the larger Visayas show extinct volcanic cones except Cebú and Bohol. Of Mindanao it is known that there are crystalline schists along the eastern coast and Macajalar Bay on the north coast, but the island contains at least three active volcanoes, not to speak of the more numerous extinct ones. Finally, much of the Joló group is volcanic, and Palawan is known to contain volcanic peaks. Thus, while it is by no means true, as has sometimes been alleged, that the archipelago is of volcanic origin, volcanic areas are distributed at short distances from the Batanes to Tawi-Tawi.

The rocks which have been more or less inadequately determined as trachyte are of limited distribution. One doubtful specimen comes from Panay, at Barbaza, in the Province of Antique; the remainder are all from Luzón. In that island, near the southern end, in Camarines Sur, between the villages Yriga and Buhi, a pumice-like tuff was considered trachytic by Roth. Mr. von Drasche found the rock at the base of Maquíling, not far to the southward of the town of Calamba, on Laguna de Bai, which he regarded as trachyte. Baron von Richthofen discovered trachyte on the peninsula of Binangonan, on the north side of the same lake; and Mr. von Drasche, on his map, colors the western half of the peninsula as trachyte. On that shore I collected basalt, but was obliged to remain under cover of the guns of the *Napindán* and could not get inland. The trachytes recur on the San Mateo River, near the caves about 5 miles above the town of San Mateo, in Manila Province. Mr. von Drasche found a large area of trachyte farther north. He encountered this rock at Pórac in the Pampanga, and to the westward of that town in the foothills of the Cordillera de Mabanga; again close to O'Donnell in Tárlac, and once more in the Province of Pangasinán, among the foothills of the Sierra de Zambales, not far from the town of Aguilar. He summarizes his observations thus: "On the eastern slope of the southern half of the Sierra there are superposed on these rocks [gabbros and diorites] thick masses of trachytic tuff, which include numerous fragments of trachyte. These tuffs can be followed to the watershed at an altitude of 3,000 feet, and on the east stand in close relationship with the plain of Pampanga, the surface of which consists principally of their decomposition products. The crystalline rocks must be pierced by numerous intrusions of trachyte, for one finds great quantities of such rock species in all accumulations of pebbles derived from the Sierra."

In the provinces of Lepanto and Bontoc also Mr. von Drasche found trachytes abundant, but closely associated with andesites and basaltic rocks. The important copper deposits of Mancayan occur, he says, in a quartz lens embedded in sanidine-trachyte.

Mr. Abella recognizes the very general distribution of trachytes in the Cordillera Central and the mountains east of the great plain of

Luzón, but the only precise locality I find mentioned is at Canan, on a tributary of the Patlin River, about 2 miles to the westward of O'Donnell, in Tárlac Province. Here dikes of porphyritic sanidine-trachyte make their appearance "on the one side in the slopes of the hills Maranglá and Cospién, and on the other between the town and the river Capatían, forming the volcanic line of the hills Dayagdag, Taoagan, and Patlín."[1] I am not in possession of maps showing these hills by name, but they will doubtless be identified with ease from O'Donnell.

Mr. von Drasche also found rhyolites, or, as he calls them, quartz-trachytes, in these northern provinces. He met with this rock a short distance to the northwest of Mancayan, the central town of the copper district in the Province of Lepanto. The rhyolite lay in blocks along the Abra River. On the road from Sabangan to Bontoc, capital of the province of the same name, he also found rhyolite, which, in this district, appears to occupy an important area.

Basalts and andesites seem to be closely associated in the Philippines, as they so frequently are elsewhere, but the quantity of pyroxene-andesite probably far exceeds that of any other volcanic rock in the archipelago. Most of the notes on these rocks refer to isolated localities or volcanic cones, and they can not be delimited areally until a geological survey of the islands is made. Some of these notes will be reserved for the remarks on volcanoes, which will claim attention presently. The Island of Talim, in Laguna de Bai, is basalt, and much of the shores of the lake is also basaltic. The Mariveles district, forming the north headland of Manila Bay, was pronounced basalt by Roth on the strength of Jagor's specimens, and this determination was accepted by Mr. von Drasche, who did not visit the locality. I suspect that some of Jagor's labels were displaced, for my personal examinations and Mr. Semper's specimens show that the region is andesitic, the pyroxenic variety predominating.

The chain of extinct and active volcanoes which stretches from Laguna de Bai to the extreme southeastern point of Luzón appears to be mainly andesitic, but not devoid of basalts. In his interesting study of Panay Mr. Abella finds that the mountain system, the skeleton of the island, is composed largely of massive rocks of two eras. The older is characterized by diorites and diabases, the younger by andesites and basalts. This later period may be regarded lithologically as a repetition of the earlier one. In the Samaráquil Peak of Anini-y, at the southwestern extremity of the island, Mr. Abella found nepheline-leucite-basalts. He considers the basalts as generally younger than the andesites.

In Negros a magnificent range extends from near the northern end of the island to the active peak of Canlaón. At the first glance this

[1] Manantiales, 1893, pp. 18, 19, 144.

range resolves itself into three mountains of most unusual similarity, and there can be no substantial doubt that the two more northern masses are extinct volcanoes of the same type as Canlaón. I was unable to reach the main range, but the streams on both coasts bring down such a mass of pyroxene and hornblende-andesite as to indicate that these are the principal rocks. In the eastern foothills, on the Talabe River, I found basalt in place which seemed to be older than a portion of the coral reefs, and is certainly older than the later ejecta of Canlaón. To the southward of the volcano the range is lower and less striking than to the northward, but at the southern end of the island the Dumaguete Peaks, or Cuernos de Negros, again rise to an altitude of several thousand feet. In this region, near Dumaguete and Valencia, Tanjay and Bais, I saw only andesite rocks.

In Cebú most of the country is covered with a blanket of coral, but where the streams have cut through this Mr. Abella found some decomposed andesites. I, too, found on the river above Naga, about 2 miles from the town, a considerable sheet of hornblende-pyroxene-andesite.

In the Island of Leyte, at Mount Dagami, according to Roth, Jagor collected fresh hornblende-andesite. Dagami is the name of a town in northeastern Leyte which Jagor visited, but he probably collected his specimen on Mount Manacagan, as he calls it, a few miles south of Buráuen. He speaks of the rock of this mountain as "a very hornblendic trachyte."[1] On the Island of Limasau, just south of Leyte, Mr. Semper found hornblende-andesite, and Mr. Renard has determined the rocks of Camiguín de Mindanao as pyroxene and hornblende-andesites.

In Mindanao, the great Apo Võlcano, according to Mr. Joseph Montano,[2] is andesite. He also found andesite north of Lake Dagum on Mount Bunauan. This locality is in the valley of the Agusan, in eastern Mindanao. In much the same region he found andesites at the western foot of the coast range, on the river Miaga. A few miles upstream from Butuan, at the mouth of the Agusan, he found decomposed dolerite. Mr. Semper also collected augite-andesites from several points along the Agusan, as well as close to Zamboanga, at the southwest extremity of Mindanao. Basalts this naturalist found near Isabela, on Basilan, and on the neighboring islet of Lampinigan. J. Itier[3] states that from Mount Pico, in the center of Basilan, basaltic ridges, not over 500 meters in height, run E. and WNW.

Near Joló, on the island of the same name, I found basalt. This island is mentioned by Mr. Kotô[4] also as basaltic, as are the Calamianes.

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[1] Jagor's Reisen, 1873, p. 221.
[2] Rap. sur une mission aux îles Philippines, 1879–1881, p. 287.
[3] Descrip. des îles Solo: Bull. Soc. géog., Paris, 3d series, Vol. V, 1846, pp. 311–319.
[4] Geol. structure Malayan arch.: Jour. Coll. Sci. Tōkyō, Vol. XI, 1899, pp. 114, 117.

Vast quantities of pyroclastic tuffs and volcanic sediments accompany the more solid flows almost everywhere in the Philippines. They are especially abundant in the great central plain of Luzón, and seem to stretch in an almost unbroken, nearly flat area from near Lingayén Gulf southward past Manila, past Taal to the seacoast of Batangas. Mr. von Drasche regards these tuffs as trachytic from the north coast of Manila Bay northward, and as doleritic to the southward, but Mr. Oebbeke shows that some of the northern tuff is andesitic. In the more southerly area, along the Pásig, I am confident that andesitic tuff is abundant. Unfortunately my specimens are lost. On the other hand, much of the basaltic rock of the Laguna de Bai region is tuffaceous. In a large proportion of cases the tuff is so decomposed that a determination of its original lithological character would be very difficult. There can be no question that this tuff area has been laid down in water. So uniform a distribution and such flat surfaces could not have been attained under subaerial conditions. Evidence of aqueous rearrangement of material is frequently visible, and plant remains, or even traces of lignite in minute seams, are not rare.[1] The light scoriaceous material of which the tuffs are composed may, as is well known, be carried to almost indefinite distances by river or oceanic currents.[2] There is no doubt that since the close of the Tertiary the sea has flowed freely from Tayabas Gulf to Lingayén Gulf, and such a channel must have been traversed by currents sufficiently strong to account for the wide distribution of the tuff. Father Zúñiga seems to have been the first to see in ancient eruptions of Taal the origin of the greater part of the material forming the southerly tuff area. He has been substantially followed by all who have expressed their opinion on this subject; but Mr. Abella points out that all the volcanic vents from Aráyat to Banájao must have contributed material to this accumulation,[3] in which opinion I entirely agree with him.

The volcanic rocks of the Sunda Islands and the Banda Islands are seemingly in all respects similar to those of the Philippines. In the Dutch and English possessions in the Far East there is the same preponderance of pyroxene-andesite accompanied by hornblende-andesites and basalts. Leucite rocks, rare in Asia, occur on the small Island of Bawean, to the south of Borneo, and in eastern Java, as well as in Panay,[4] and dacite accompanies andesites in the islands of the Uliasser group,[5] while trachyte seems to be rare. The similarity extends beyond specific names. Mr. Oebbeke[6] made direct compar-

[1] Dana obtained many specimens of plants from the tuff, mostly palms, seemingly of recent species. No vertebrate remains have been detected so far as I have been informed, though the Spanish geologists have been on the watch for them.

[2] Sir A. Geikie notes that at one eruption of Sakurajima (Japan) it was possible to walk a distance of 23 miles on the pumiceous material floating in the sea. Text-book of Geol., 1893, p. 215.

[3] El monte Maquilin, 1885, p. 24.

[4] Kotô, loc. cit., p. 88.

[5] K. Martin, Reisen in den Molukken, geol. Theil, 1898, p. 219.

[6] Neues Jahrbuch Beil.-Band I, 1881, p. 488.

isons between the Semper collection and the specimens in Professor Rosenbusch's cabinet from other parts of Malaysia. He concludes that "there is scarcely a type which is not represented on all the islands alike." Mr. J. L. C. Schroeder van der Kolk examined Mr. Martin's rock specimens from the Moluccas. The only massive rocks were granite, peridotite, dacite, and pyroxene-andesite. The dacites are separated into two groups, one being highly pyroxenic and containing labradorite, while in the other the ferromagnesian silicates are represented by biotite and the feldspars are less calcic. Sanidine enters into the second group of dacites in varying quantities, and there seem to be transitions to rhyolite.[1] The dacite of Corregidor is akin to this second group, and it is probable that other of van der Kolk's types occur in the Philippine Islands.

VOLCANOES, ACTIVE AND EXTINCT.

A considerable number of mountains in the Philippines have ejected ash or lava recently, or since the occupation of the country by the Spaniards. Many other cones are plainly volcanoes of no ancient date, and concerning some of these it is doubtful whether or not they have been active during the last four centuries. The accounts of early Spanish writers, chiefly priests who were intent on other matters, are in part very vague and ambiguous. I shall endeavor to collect here such information as seems important concerning all the volcanoes known with certainty to have been active, and also the available data as to the principal cones which are clearly extinct or dormant volcanoes. The latter group could doubtless be increased almost indefinitely. At the close of this section (pp. 541–542) appears a little tabular statement on the subject.

Beginning at the south, there is at the southern end of Mindanao a group of volcanoes none of which is known to have been in eruption since January 4, 1641. On that date there was a disturbance in the Philippines which extended far and wide. It has been discussed at length by Perry and others, but most satisfactorily by Jagor.[2] The original information is contained in a report to Pedro, archbishop of Cebú, printed by Raymundo Magisa in Manila in 1641. The original is extremely rare. It is reproduced in the Obras Filosóficas of J. E. Nierembergius and in Zúñiga's Estadismo de las Islas Filipinas. This last I have seen. It is alleged that three outbursts took place on this

[1] Sammlungen des geologischen Reichs-Museums in Leiden, Vol. V, 1896, p. 70.

[2] The incident was investigated by order and commission of the archbishop, but the report is anonymous. The document appears among Retana's appendices to Zúñiga's work, and is evidently reproduced with care.

day in different portions of the archipelago, accompanied by earthquakes, which were also felt in Cochin China and Cambodia. A Spanish squadron was off the south coast of Mindanao at the time and some of the ships were almost overwhelmed by volcanic ash. These ships, which were approaching Cape San Agustín from Zamboanga, were then "in the neighborhood of an island called Sanguil, on which the volcano had broken out." The name of this island has led to much confusion. In the original report it appears as Sanguil, while Nierembergius has Sanguiz, and the name appears in various other forms in literature, some of which are probably mere misprints. Perry came to the conclusion that the report referred to the Island of Sanguir, one of the Celebes group, but Semper and Jagor believe the volcano to have been in Mindanao. Even if Sanguil and Sanguir are originally the same word, the identity proves nothing, for in the Philippine Islands a number of geographical names are repeated. According to the Guía Oficial, the Sanguil language is still one of those spoken in the Province of Dávao (southern Mindanao), and the admirable Compendio de Geografía of the Jesuits says "the Sanguils inhabit a small area on the southern coast of Mindanao near Sarangani," which is one of the names of the southernmost cape of Mindanao. On the ethnological map of the Jesuits this area is shown. Most authorities seem of the opinion that this volcano was on the Sarangani Peninsula, in spite of the express statement that it was on an island. On the Jesuit map, however, as well as upon the charts of the Hydrographic Office, a volcano is marked on the island now called Balut, one of the Sarangani Islands. It lies in latitude 5° 25′ and is within 10 miles of the coast. The volcano is said to be now extinct. When this island is visited it will be worth while to observe whether conditions indicate an eruption of considerable violence within two hundred and fifty years. On the peninsula there is also a volcano called Sarangani by Jagor and Semper, but Butulan by Centeno and others. There is no certain record of an eruption of Butulan.

The second eruption of January 4, 1641, is described as occurring near Joló. The report runs: "And although, at the time, the darkness and atmospheric disturbance were so great that the people of Joló could not perceive whence came the stuff which fell from heaven upon them, yet when it became light it was observed that at the same time when the volcano burst forth at Sanguil, Mindanao, the elements there also had become excited, and that a second volcano had opened on a small island which lies opposite the bar of the chief river of Joló, where lies our military station. The crater of this volcano is still open." Semper and Jagor are of the opinion that such an eruption really took place, but no further outbreak is known to have occurred there, and the remains of the crater have not been described of late years, so far as I know.

The third eruption on the same January 4 took place from what was called "a water volcano" by the archbishop's agent. The description makes it clear that by this term he had no intention of indicating thermal phenomena, but merely an outburst of water accompanying what he himself called a frightful earthquake. It took place in Luzón among the Igorrotes, "who relatively to the Ilocos live five days' journey eastward and inland." Three hills and several villages are said to have been thrown into the air in fragments and utterly annihilated. This locality has been regarded as Mount San Tomás, or Tonglón, some 15 miles from Aringay, in Unión Province. This identification does not appear accordant with the original description, and how it was reached I have not succeeded in ascertaining.[1]

A group of volcanic cones exists a little to the northward of the Bay of Sarangani. They are extinct or dormant, so far as is known. Indeed, excepting their position, which is doubtless only approximate, I know nothing of them. Their names are Magolo, Matutum, and Malibato. Of these the first is entitled a volcano on the map of Mindanao in the Compendio de Geografía, and the second is similarly designated on Montano's map. Matutum is said to be visible from the sea at a great distance.

Mount Apo is the highest mountain in the Philippine Islands. It was ascended in 1880 by Mr. Montano[2] and Governor Joaquín Rajal, who found the altitude 3,143 meters, or 10,311 feet, and in 1882 by Messrs. A. Schadenberg and O. Koch,[3] who determined the height at 3,280 meters, equal to 10,761 feet. Mr. Velain determined Mr. Montano's specimens as andesite. The latter describes the mountain as in the solfataric stage, the cone being covered from about the 7,500-foot contour to the summit by a mantle of sulphur. An enormous crevasse opened in the flank of the mountain emits jets of sulphurous acid, which escape with a strident roar. According to the Guía Oficial, the summit consists of three peaks, of which the present crater forms the most southwesterly. There is a lake on the ridge from which issues a cold stream, while another ravine carries hot water. Though Apo is well known to be active, there is said to be no record of its eruptions. It is sometimes called Dávao, from the name of the gulf near which it lies. This gulf on old charts appears as Tagloc Bay.

[1] San Tomás is not volcanic. Mr. von Drasche says of it (Fragmente, page 30): "It is usually considered an extinct volcano, because a passage in a report on the simultaneous eruption of three volcanoes in January, 1641, points to it. Jagor gives a literal translation of this document, from which, however, it appears that (1) this outburst can be referred to any possible mountain in northwest Luzón, and (2) nothing whatever is said of a true eruption. The pertinent passage reads," etc. In the Spanish translation Mr. von Drasche's statement is represented by this phraseology: "Being in reality an extinct volcano, as is established by the following account which Jagor copies from a document dated in January, 1641, and referring to the simultaneous eruption of three volcanoes at that date." Mr. Abella, supposing the Spanish translation to be correct, comments thus: "If, indeed, the account of 1641, which Drasche copies, is confused, that which this geologist himself gives of the geological character of Tonglón is not less so."—Terremotos, 1893, page 30. A careless translation is an unconscionable thing!

[2] Rap. sur une mission aux iles Phil., p. 287.

[3] Cited by F. Blumentritt in Bull. Soc. acad. indo-chinoise de France, 1882-83.

Macaturin lies over 20 miles to the northeastward of Pollok Point, in Illana Bay. Berghaus called this mountain Illano. Semper called it Pollok or Sujut, and this last is the name given it on Jagor's map. Centeno alleges that this volcano has "ejected enormous blocks of conglomerates of various igneous rocks, like those which are to be seen to-day in the port of Pollok, distant seven leagues from the volcano." As appears from Perry, an eruption of Macaturin occurred in 1765, and the Guía Oficial notes eruptions in 1856, 1865, and 1871. The last was preceded by earthquakes which destroyed many villages. Mr. Centeno[1] gives on his map a volcano, Cottabato, just south of the Rio Grande and a few miles from the town. He observed many conical hills like Cottabato along the course of the river, but was prevented from making an examination of it or any of them. He gives no record of eruptions or of other details concerning this mountain.

One of the most interesting of Philippine volcanoes is on Camiguín, or, more specifically, Camiguín[2] de Mindanao, for there is another volcanic islet of the same name in the north. This one is close to Mindanao and in latitude 9° 12′. According to "information from Manila," reported by Jagor, this island up to 1871 consisted of three ridges. On the summit of one of them, Catarman, there was a crater lake the water level of which was subject to great fluctuations. Sometimes it dried up and sometimes, as in 1827 and 1862, it overflowed. Often it was agitated by evolutions of gas. No historical eruption had taken place.[3]

On February 16, 1871, according to Centeno,[4] earthquakes began to be felt in the island, which increased in severity until April 30. They then ceased suddenly, and a volcano appeared 400 yards southwest of the village of Catarman. At 3 p. m. a thick column of black vapor rose, with a strong odor of sulphur. It quickly became incandescent and set the woods on fire. At the end of a week a little volcanic cone 2 meters high had formed and "kept pouring lava into the sea, at the same time gaining in height and width; but such has been the activity of the crater that now, after four years of existence, it already measures some 1,500 feet in height above sea level, in addition to which it has acquired a breadth of half a mile." Roth takes his information from the Spenersche Zeitung, 1871, No. 167. "On May 1, at 5 p. m., a hill above the village of Catarman split, with heavy shocks and thunderous noise. Smoke, ashes, earth, and stones were thrown out. The crater had a length of 1,500 feet, a breadth of 150 feet, and a depth of 27 feet. At 7 p. m. a second eruption took place. No mention is made of a lava flow." The fissure-like shape of the crater here described is interesting and suggestive. As noted above, Centeno reports a

[1] Memoria geol.-min. de las islas Fil., 1876.

[2] The Compendio de Geografia writes this Camiguing. There is reason to suppose that the Spaniards have dropped a final g from a good many native names.

[3] Jagor's Reisen, p. 328.

[4] Ibid., p. 10.

stream of lava. In the Illustrated London News of October 7, 1871 (Vol. LIX, p. 327), there is a sketch of this volcano by Lieut. F. C. P. Vereker, but the editors have confounded the island with Camiguín de Babuyanes, in latitude 19° 10′. The cut represents the island as covered with mountains of impossible steepness and shows the eruption progressing in a depression near the foot of one of the mountains.

Camiguín was visited by the *Challenger* expedition in 1875. It is described as a dome, 1,950 feet in height, without any crater, but still smoking and incandescent at the top.[1]

On the Island of Negros there are two volcanic vents. One of these is a very small affair, at the southern end of the island, some 10 miles from Dumaguete, on the southeastern slope of the Cuernos de Negros. It is called Magaso. I was told in Dumaguete that vapors arise from a small crater-like vent, and that there are cracks in the hot rock in which a stick will inflame. There are sulphur deposits and strong sulphur springs at its base. The Cuernos are largely—so far as I know, wholly—andesitic. The volcano of Canlaón is in the central range of the island, of which it forms a culminating point. It lies in latitude 10° 24′ 35″.[2] The upper part of the mountain has the typical form of a volcanic cone, but this portion rests upon a more irregular mass, which forms a portion of the range stretching northward for some 30 miles. The Spanish hydrographic office gives the elevation at 8,192[3] feet, so that it would rank with Datá, and be exceeded only by Halcon, Apo, and Mayón. It is visible from near Iloilo and can be seen even from vessels cruising on the eastern side of Cebú. From the sea on the western side of this island, called Tañón Passage, Canlaón is a very impressive spectacle, for, in addition to the picturesque form of the cone, steam is always pouring out from at least two vents at the summit. No violent eruptions are remembered, but ash has been ejected from time to time. The last considerable ash fall occurred, as I was informed at San Carlos, in July, 1893. There was also an eruption in 1866.[4] Andesite is the prevailing rock of this region, as shown by the stream pebbles, and I suppose Canlaón andesitic. On some Spanish maps and in Jagor's Travels this mountain appears under the name Malaspina.

The Island of Siquijor is sometimes called Fire Island, and this seems to have led to the inference that there was a volcano upon it. According to Mr. Semper, this inference is entirely false. There are neither craters nor hot springs upon it. He is of the opinion that the spectacle of the natives fishing by torchlight at night led the early Spaniards to christen the island Isla de Fuego.

[1] Voyage of H. M. S. *Challenger*, Narrative, Vol. I, 1885, Part II, p. 653, with a cut.
[2] Derrotero del Arch. Fil., by Capt. C. de Arana, Madrid, 1879.
[3] Bowditch's Navigator and British Admiralty charts.
[4] Mendez de Vigo, Hist. geog. geol. y estad., Vol. II, 1876, p. 173.

According to Mr. Semper, extinct volcanoes exist in nearly all the islands. Cebú and Bohol, like Siquijor, show none; but they exist, he says, on Leyte, Sámar, and in the western mountain region of northern Mindanao, while in the high range of Palawan such extinct volcanoes raise themselves far above the mean crust of the sierra to which they belong.[1] Same of the peaks are said to be more than 2,000 meters (6,561 feet) in height. In the Compendio de Geografía mention is made of a volcano named Calayo and situated in Pulangui. In another passage Pulangui is said to be a town in northeast Paragua (or Palawan). As I have met with no reference to such a volcano in the eastern islands, or to any other town of this name, I suppose the volcano to be in northeast Palawan. According to Mr. Mendez de Vigo,[2] there are two mountains on the Island of Dumaran, close to the northeastern end of Paragua, which often emit smoke and sulphurous fumes, but are not known to have ejected streams of lava. They are called Alivancia and Talasiquin.

The charts show crater-like depressions at the southern end of Cagayán Joló, one of them broken down at the edge and admitting the sea. Capt. Charles S. Perry, U. S. N., who landed there to raise the American flag, informs me that these are unquestionably craters, but that they are to some extent covered with vegetation and can not therefore have been active very recently. They seem first to have been recognized as craters by Mr. F. H. H. Guillemard.[3]

On the line of Palawan, but close to Borneo and to the south of the small Island of Banguey, an islet rose from the sea during the earthquake of 1897, according to Mr. R. M. Little,[4] but the rock is described as grayish-white sandstone, and no indications of volcanic action are noted.

In the Island of Leyte there are two volcanic vents in the solfataric phase from which much sulphur has been gathered. They lie to the southward of Buráuen, in the northeastern portion of the island, and were visited by Jagor.[5] The more southerly is called Mount Danán. The other is called the crater of Kasiboi, and lies, according to Jagor, on a mountain named Manacagan. This mountain, on Mr. d'Almonte's map, is called Himaiacagan. Jagor describes the rock as "very hornblendic trachyte." It is probably the rock determined by Roth as hornblende-andesite. Roth probably refers to Kasiboi when he states that the outflow of the solfatara at Dagami (some miles north of Buráuen) forms a brook with a temperature of 50° R. = 145° F.[6] The Guía Oficial mentions a volcano at Buráuen called Caolangojan, which, I suppose, is another name for one of those just referred to.

The Island of Bilirán is well known for its sulphur deposits, the best in the archipelago. The sulphur occurs in solfataras, some of which

[1] Die Phil. u. ihre Bewohner, pp. 16, 31.
[2] Hist. geog., geol., y estad., Vol. II, 1876, p. 23.
[3] Cruise of the *Marchesa*, 1889, p. 175.
[4] Geog. Jour., 1898, p. 298.
[5] Reisen, 1873, p. 220.
[6] Ibid., p. 354.

are extremely hot, Mr. Abella[1] getting temperatures of no less than 115° C., which would show that the water is a strong solution of some salts. These hot springs contain pyrite of recent formation "produced by the reducing action either of an excess of sulphur or of vegetable remains, brought by water or wind, on the iron sulphate which had previously formed." Mr. Abella says nothing of craters, but refers the solfataras to still existing volcanic action. He compares the phenomena on Bilirán to those near Buráuen in Leyte (writing Buranen, however, doubtless by mistake), and calls attention to the fact that the volcanic range continues southward through Panaón to Surigao, Mindanao, while to the northward it is connected through Maripipi and other small volcanic islands with Bulusán on Luzón. Maripipi, by the way, is represented by Mr. d'Almonte as a conical island, almost round, about 3½ miles in diameter and 3,000 feet high. Its plan is very much like that of a volcanic cone. The chief rock of Bilirán is described by Mr. Abella as containing greenish and black hornblende and phenocrystic feldspars in a feldspathic groundmass, while augite and magnetic iron are sometimes visible. This description makes it substantially certain that the rock is hornblende-andesite.

In Panay a few warm springs seem the only present manifestations of volcanic activity. There is a peak on Mindoro, the elevation of which is 2,700 meters (8,858 feet). It is called Halcon or Alcon, but I can ascertain nothing further about it.[2] Near the port of Galera, according to Mendez de Vigo, there is a small, very deep lake, which smells of sulphur and may be a crater.[3]

The southeastern portion of Luzón is famous for its volcanoes, active and extinct. Of these the most southerly is Bulusán. It lies on the Strait of San Bernadino, and Jagor calls attention to the striking similarity of its shape to that of Vesuvius. According to the Guía Oficial its height seems comparable with that of Mayón. "At present it is nearly extinct, but sometimes emits aqueous and sulphurous vapors." The Estado Geográfico, page 314, states that it began steaming in 1852, after long seeming extinct.

Mayón, or the volcano of Albay, is, next to Taal, the most famous Philippine volcano. It is possibly the most symmetrically beautiful volcanic cone in the world, and at times its crater is almost infinitesimal, so that the meridional curve of the cone is continuous almost to the axis. The height has been variously determined, and appears to change with each eruption. Since the crater always remains small the height should tend to increase, but the determinations are probably not sharp enough to develop this tendency. Jagor's barometrical measurement in 1859 was 2,374 meters. The Spanish Hydrographic Commission, according to Mr. Abella, gives 2,522 meters. Mr.

[1] La Isla de Bilirán, 1885, p. 10.
[2] Kotô speaks of it as a volcano, but without citation; Geol. struct. Malayan arch., 1899, p. 119.
[3] Hist. geog., geol., y estad.

d'Almonte's map of 1883 gives 2,527 meters. Mr. Abella himself gives 2,734 meters, but he did not reach the summit, because his visit was made during the eruption of 1881–82, and he does not state his means of determining the height. Mr. d'Almonte, however, made a sketch map of the mountain for Mr. Abella's memoir,[1] and I fancy that he measured the height by triangulation. In English measure Mr. Abella's elevation would be 8,970 feet. The rock of Albay is described by Roth and von Drasche as dolerite, but Mr. Oebbeke regards it as an olivinitic augite-andesite.

Albay has had a vast number of eruptions. Father Coronas[2] gives some details as to eruptions in 1616, 1766, 1800, 1814, 1827, 1835, 1845, 1846, 1851, 1853, 1855, 1858, 1868, 1871, 1872, 1873, 1881, 1885, 1886–87, 1888, 1890, 1891, 1892, 1893, 1895, and 1896, and he describes the eruption of 1897. According to the newspapers, there was an eruption early in 1900. Some of these eruptions have been very serious. In 1814 about 1,200 lives were lost (Jagor, by error of transcription, says 12,000), and the country was covered with ash. Many picturesque details may be read in Perry or elsewhere. Of more permanent interest than the destruction of life and property is the character of the emanations. Mr. von Drasche, adopting Stöhr's[3] hypothesis of three periods in the life of a volcano (first, that of lava flows; second, that of agglomerate flows; third, eruptions of ash), considers Mayón in the second stage, and says that the ash eruptions are seldom interrupted by small lava flows from the summit. Mr. Abella states from observation that the ash ejections are small and preliminary to extensive flows, and Father Coronas gives a map of the flows of 1897, when lava from the summit poured down in various directions, even reaching the sea at a horizontal distance of about 6 miles from the crater. In 1897, however, there was much ash as well as flowing lava. An area of about 4 square degrees was covered with ash, which, nevertheless, formed an orogenically insignificant layer at points considerably removed from the foot of the mountains. At Tabaco, less than 10 miles from the crater, the inhabitants were reasonably in fear of smothering, but the ash which fell was only 3 or 4 centimeters in depth. Per contra, on the mountain side the fall was heavy; the village of San Antonio, more than 4 miles from the crater, was so buried under lava and ash that the ridgepoles of the houses were hidden. It would appear from the descriptions that a very considerable part of Mayón consists of a solid framework of lava flows, which alternate more or less irregularly with ash eruptions, but that the external form of the mountain is determined by showers of ash and coarser fragmental ejecta. I can hardly believe that there is ordinarily any such

[1] El Mayón, 1885.

[2] La erupción del volcán Mayón en 1897, Manila, 1898.

[3] Emil Stöhr, Der Vulkan Tengger auf Ost-Java, Naturwiss. Verein der Rheinpfalz, Dürkheim, 1868, p. 200.

regularity in the life history of a volcano as is implied in Stöhr's hypothesis. Study of the history of Mayón and comparison with other volcanoes show that the form of the vertical cross section is a definite one[1] (depending on the resistance of the material to crushing), and it follows that the material ejected during any considerable eruption is so distributed that the vertical depth of the added layer is substantially uniform from the summit to the base. Of course, more material falls near the top than near the bottom, but more rolls down from the steeper slopes of higher portions than from the gentler slopes near the foot. If each particle were to remain where it fell the slope would become steeper at each eruption and the mountain would tend toward the shape of a cylindrical column.

A large number of extinct or dormant craters exist between Mayón and Laguna de Bai. Only one of these has certainly been known to break out since the occupation of the country by the Spaniards. The magnificent cone of Banájao, 7,382 feet in height, towers over Laguna de Bai, and is visible from Manila Bay. Its crater, now 700 feet deep, was occupied by a lake till 1730, when, according to the Estado Geográfico, a violent eruption took place, bursting the southern side of the crater and pouring out both water and incandescent lava. Since then it has been dormant. The Estado Geográfico also alleges that Iriga, in the Province of Camarines Sur, underwent eruption in 1641, but Jagor gives seemingly good reason for believing that this statement, not to be found in earlier works, is a mistake. Many of the extinct cones retain traces of solfataric action, or at least give vent to hot springs, but there seems to be little of special interest known about them which can not be included in the table on pages 55–56, where they are catalogued.

Solfataras and hot springs are numerous throughout this region. One of the more remarkable occurrences of this nature is near the base of Mount Malínao, in the Province of Albay, a short distance from the town of Tiui and at a small settlement called Naglabong. Some of the springs here deposit siliceous sinter, similar to that of the Yellowstone, Iceland, and New Zealand, in various fantastic forms, and pyritous deposits of recent date are also found. The water was analyzed by Rammelsberg for Roth and Jagor. In 100,000 parts he found 7.5 silicic anhydride, 25.4 lime with a trace of iron, 0.2 magnesia, and abundant chlorides, but no sulphates. The occurrence is enthusiastically described by Jagor and has been discussed by Mr. Abella among the subordinate volcanic emanations of Malínao (1885). Mr. Abella found still more silica in this water, viz, 0.28 per thousand parts, or 28 per hundred thousand. He compares his results with Rammelberg's on the erroneous assumption that the German chemist's results are per

[1] The vertical outline is the hyperbolic sine curve. A discussion may be found in my report on the gold fields of southern Alaska: Eighteenth Ann. Rept. U. S. Geol. Survey, Pt. III, 1898, pp. 20-25.

thousand parts.[1] Mr. Abella confirms the absence of sulphates in this water. He found the temperature of the water at various vents from 52° to 106° C.[2]

The hot springs at Los Baños on Laguna de Bai, at the base of Maquíling, are very well known, largely because they are so accessible from Manila, and have long been supposed to possess remarkable curative properties by the natives.[3] I shall not attempt, however, to include in this paper any account of the numerous hot and mineral springs of the Philippines. They form the subject of two memoirs by a special commission, of which Mr. Abella was chairman.

The Taal Volcano is a very peculiar one and, when order prevails among the natives, is readily accessible from Manila. It has consequently often been described, both by Spaniards and by others. Chamisso visited it in 1818, Hofman in 1825, the Wilkes exploring expedition and Delmarche in 1842, Semper in 1859, and von Drasche in 1876. Of the accounts published by these travelers, Semper's is the most instructive, and he collected the specimens from which Mr. Oebbeke determined the lava as andesite. Most of the accounts, however, leave much to be desired, because the travelers did not remain long enough to make any detailed surveys. The most complete account of Taal is to be found in Centeno's memoir, written in 1883, and accompanied by maps and sections.

Taal lies on a small volcanic island in the lake of Bombón.[4] The island has an area of some 220 square miles. There is a relatively large central crater and several smaller extinct ones. Of these latter, that at the northwest corner of the island is known as Great Binintiang, or Binintiang Malaquí, and that at the south end as Little Binintiang, or Binintiang Munti. The central or main crater is nearly round, its diameter on a north-south line being 1,900 meters (6,233 feet) and the east-west diameter 2,300 meters (7,546 feet). The edge of this crater is somewhat irregular, but is nowhere broken through, its highest point standing at only 320 meters (1,050 feet) above sea level and its lowest at 130 meters (426 feet). It is said that Cosima in Japan is the only other volcano of similarly low altitude. Within the rim are two hot pools, known respectively as the yellow and the green lake, and a little active cone about 50 feet in height from which escape steam and sulphurous gas in varying quantities. The level of the interior pools, according to Centeno, is by measurement, at least very approximately, that of Bombón Lake itself. The following analyses by Mr. Centeno show the composition of the solid residue in one liter of water from (I) the yellow or more northerly lake and (II) the green lake. The

[1] Perhaps another case of careless translation. I have not seen the Spanish translation of Jagor.

[2] Emanaciones volcánicas subordinadas al Malinao, 1885.

[3] The precise locality is called Maínit, a name which occurs at many hot springs in the Philippines and is said to be the Malay word for hot. The French traveler, de la Gironière, called Mount Maquiling Maínit because it is close to this hamlet.

[4] Old writers use the form Bombong.

temperature of the yellow lake is 100° C.; that of the other pool is high, but it could not be approached on account of its steep banks. The soil of the crater is heated to about 50°. The inner walls of the crater are so steep as to make descent into it very difficult.

Analyses of solid residue in hot waters from crater of Taal Volcano.

Constituent.	I.	II.
	Grams.	*Grams.*
Sodium chloride	15.9412	30.8588
Potassium chloride	0.7095	3.4716
Ferric chloride	4.1907	9.6736
Ferrous sulphate	0.5693	1.6772
Aluminic sulphate	0.9360	....
Magnesic sulphate	1.3200	3.0600
Calcic sulphate	0.5100	0.4644
Sodic phosphate	0.5867	0.7620
Free sulphuric acid	1.5855	1.4888
Free chlorhydric acid	....	7.8264
Silica	0.6400	0.7400
Total	26.9889	60.0228

The concentration and acidity of these waters seem remarkable. I know of none elsewhere closely resembling them.

Taal has had some violent eruptions since the beginning of the Spanish occupation, the worst being in 1754. The earliest known record is by Father Gaspar de San Augustín, who wrote in 1680. His account is given in full by Centeno for the light it throws on the condition of the volcanoes prior to the more recent eruptions, and I have examined the original work. Father Gaspar[1] says: "In this lake of Bombón there is a small island upon which is a fiery volcano, wont at times to eject numerous and very large burning stones which destroy and lay waste many cultivated fields which the natives of Taal possess on the slopes of the said volcano." Father Alburquerque, priest of the town of Taal, which lay on the shore of Bombón but is now destroyed, proceeded to the volcano in order to exorcise and sanctify it. He had himself let down into the crater, "which had two mouths, one of sulphur and one of green water which is always boiling. To this place now come many deer, which are attracted by the saline deposits (salitrales) existing about the lake of the volcano. The opening which lies toward the town of Lipa [SE] has a width of a quarter of a league, and through the other, which is smaller, the volcano

[1] Conquistas de las Philippinas, Madrid, 1698, p. 254. This book may be seen in the Boston Public Library.

began to send out smoke in such quantities that" a fresh exorcism was clearly requisite and was duly solemnized. From that time up to 1680, the date of writing, no fire or smoke had issued from the volcano. It appears from this description that Taal over two hundred years ago must have been very much in the same condition as it is to-day, excepting that deer would perhaps find a visit to the salt deposits in the crater more difficult now than in the days of Friar Gaspar.[1]

Eruptions are recorded at Taal in 1709, 1715, 1716, and 1731. From the account of Father Francisco Bencuchillo, quoted by Centeno, it appears that the outbreaks of 1709 and 1715 were confined to the island, doing no damage on the outer shores of the lake. Incandescent stones were thrown out, "and a great fire ran like a river all across the island" (corrio por toda la isla). Mr. Centeno finds no trace of continuous lava flows on the island which are anything like so recent as the last century, and believes that the accumulation of red-hot ejecta on the slopes of the volcano must have conveyed a false impression to the inhabitants watching the destruction of their property from a distance. In 1716, according to Father Francisco Pingarrón, rector of Taal, as quoted by Centeno, a more serious eruption took place. After sounds mistaken for discharges of artillery had been heard, fire was descried bursting from the volcano on the island at the side toward Lipa, on a point called Calavite. This point is now called Calauit, and is the southeastern corner of the island. The fire then shifted into the lake in the direction of Mount Macolod, throwing up water and ashes in immense, bubbling masses, rising like towers into the air. The water grew hot and black, fish were strewn on the beaches as if they had been cooked, and the air was so full of sulphurous smells and the odor of dead fish that the inhabitants sickened. This state of things lasted three days. In 1731, so Father Bencuchillo writes, "fire broke out in the lake in front of the point which looks to the east, obelisks of earth and sand so large and high raising themselves from the water that in a few days an islet was formed with a quarter of a league of coast line." Centeno thinks the Father referred to the northeastern point of the island, and that the islets which now exist there were formed at this eruption. Possibly, however, an island of pumice may have been formed at Calauit and have been washed away at a later date. It

[1] Le Gentil (G. J. H. J. B. le Gentil de la Galaisière), in his Voyage dans les mers de l'Inde, a l'occasion du passage de Vénus, 6 Juin, 1761, Vol. II, 1781, p. 18, translates this account, quoting the author as Gaspard, and stating that "at present many wild boars [sangliers] come to the neighborhood, to which they are attracted by the saltpeter which they find about the lake." The dictionary meaning of salitral is saltpeter deposit, but the term is still used for almost any deposit of efflorescent salts, very much as alkali is employed in the far West for deposits bearing little resemblance to hydrated oxides of the alkaline metals. In Father Gaspar's day chemical distinctions were almost unknown, and the use of the word salitral can not have been more definite than it now is. Perry (ibid., p. 66) still further improves on Gaspar, and states that many wild boars come to the neighborhood, attracted by the sulphur! Perhaps he thought even such a preposterous assertion credible of a country where the horses still insist on having molasses.

would be interesting to examine the existing islets with a view to estimating their age.

I have given somewhat full details of these eruptions because Mr. Semper thus summarized the early history of Taal: "Two doubtful eruptions are mentioned in the years 1634 and 1645 without statement of the name of the craters. From 1707 to 1733 the two Binintiangs alternated with one another till at length, in 1749, the middle crater burst out, silencing the other two. From this time on it has assumed the rôle of bringing to the inhabitants of the neighboring villages, in the smothering ashes, death and at the same time a blessing." The benefaction, he explains, is the fertile soil into which the ash is transformed. He gives no authorities for the eruption of the Binintiangs, nor do Perry and Centeno refer to any. Mr. Semper is a careful writer, but possibly he has confused the accounts of eruptions on the eastern side of the island with indications of past eruptions on the western side afforded by the little craters with long names. Mr. Centeno states that Little Binintiang is now base-leveled, and though geologically recent is very ancient. Great Binintiang still emits hot steam, but Centeno does not appear to consider its last eruption very recent.[1]

The greatest eruption of Taal took place in 1754. It consisted only of fragmental ejecta, but these were sufficient to destroy four villages lying about the lake. This ash, Semper says, has now indurated and a new growth of bamboo and palms has sprung up round the projecting ruins. The eruption began, according to Bencuchillo, on May 15, and continued with intervals till December 1, when it ceased and a typhoon supervened, lasting two days, and destroying all the volcano had left. In the tropics nature has wonderful powers of recuperation. "In spite of the terrible lessons of the last century," comments Centeno, "all of these localities have been repopulated. Their fertility, their surpassingly beautiful topographical situation, and their unimprovable healthfulness charm the people into a prompt forgetfulness of past disasters." No great eruption has occurred since 1754. In 1808 and in 1873 there were outbreaks, but the damage done seems to have been confined to the island itself.

Lake Bombón has a rudely oval form with a mean diameter of about 12 miles. I have not been able to ascertain its level, but the surface can not stand many feet above the sea, for the Rio Pansipit, which connects the lake with the Gulf of Balayan, is only about 6 miles long and has no cataracts, and it was formerly navigable. It cuts through a low mass of tuff. The other portions of the lake are encompassed by a crest considerably higher than the surrounding country. At some points this crest comes close to the shore of the lake, while at others a narrow strip of lowland intervenes, but, as Mr. von Drasche pointed out, the watershed is everywhere so near the

[1] The Guia Oficial, however, speaks of vague reports of eruptions of Binintiang Malaquí.

shore that the lake has not a single affluent. The entire surrounding region is composed of volcanic material, almost altogether tuff. Father Zúñiga regarded the lake as originating in the collapse of a volcanic cone, and to this theory von Hochstetter, von Drasche, and Centeno assent. The theory of volcanic collapse seems to imply that an empty space beneath the earth's surface is formed by the eruption of lava and that the intervening rock is too weak to bear the load put upon it; so the country over a mine sometimes subsides. I doubt this theory as applied to volcanic cones, excepting when invoked to account for local details of structure. It seems to me very improbable that a considerable cavernous subterranean space is left when lava is extruded, nor can I think the foci of volcanic activity so close to the surface that such a cavern, if formed, could be filled by means of mere subsidence of the cone. If the focal distance from the surface is many miles, such a cavern would be filled in immediately by molded or fractured rock from its own sides, and even this would most likely only partially relieve the tendency to upheaval which so usually accompanies active volcanism.[1] On the other hand it is well known that craters of vast size have been formed by explosions, and I can see no reason to doubt that Bombón may have been, probably has been, formed in this way, in spite of its large dimensions.[2]

From the southern edge of Bombón to the Gulf of Batangas, and again from the northern edge of the lake to the northern end of Manila Bay, stretches a great area of tuff, to which reference has been made in discussing the distribution of volcanic rocks. The area to the north of the lake slopes with extreme gentleness toward the bay, decreasing in elevation only 500 to 600 meters in 30 kilometers, on a wonderfully steady slope. All observers seem to be forced to the conclusion that most, at least, of this tuff comes from Taal. Under subaerial conditions I should say that this would be impossible; such masses could not be projected to distances so great or distributed in such a manner along so flat a country. Nothing is more certain, however, than that Luzón stood at a considerably lower level than it now does in recent times. Taal and Bombón must have been immersed, and a channel then passed from Batangas Gulf to the eastward of the Zambales Range into the Gulf of Lingayén. In such circumstances the actual distribution of tuff from the Taal vent would be intelligible.

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[1] Pepandajan or Papandayang, at its eruption in 1772, has been regarded as a prominent instance of collapse. Lyell wrote: "It was estimated that an extent of ground of the mountain itself and its immediate environs, 15 miles long and fully 6 broad, was by this commotion swallowed up in the bowels of the earth." (Principles, 11th ed., 1877, ch. 30.) But Junghuhn showed that no collapse at all occurred. Such an area, with 40 villages and nearly 3,000 human beings, was buried under ejecta, raising the level of the country. (Java, Germ. trans., 1854, 2d part, p. 97.)

[2] Mr. von Drasche, while assenting to the theory of collapse, nevertheless speaks of Bombón as "a crater lake," and Mr. Kotô refers to it in the same way (loc. cit., p. 119). It might be questioned whether the term crater is properly applicable to mere sinks, even of volcanic origin, but that is a matter of usage. In this particular case the ambiguity of the term leaves me in doubt whether Mr. Kotô shares my view or Mr. von Drasche's.

The conditions, then, seem to point to the hypothesis that at the locality of Lake Bombón there existed a volcano, at least the lower portion of which was below water level; by ordinary eruptions and krakatoan cataclysms vast quantities of scoriaceous ejecta were expelled, and such of these as fell into the Batangas-Lingayen channel, or its drainage area, were distributed as the more or less stratified tuffs now so widely spread along this course; finally, Taal itself is the small inner cone of a great crater of explosion. This hypothesis appears to account for all the facts at present known to me, such as the rim about the lake, the contour of its bed, the steady slope of the northern tuff plain, the distribution and character of the tuff. I am by no means of the opinion, however, that all the tuffs of Manila Province came from Bombón.

Returning to enumeration of volcanoes, there are to the southeast of Lake Bombón two mountains supposed to be extinct vents, but of which next to nothing is known. One of them is called Malarayat, a peak of which is called Sosoncambing, and the other is Tombol.[1] About the same latitude and off the western coast is the alleged volcano Ambil. Mr. Semper investigated this case and could find no evidence that there has been any eruption on this island in historical times. On the charts what appears to be a crater is shown with an elevation of 2,500 feet.

In the Sierra de Mariveles there are no present signs of volcanic activity beyond hot springs, but the range is unquestionably of volcanic origin. Prominent points upon it are Pico de Loro on the southern headland of Manila Bay, the Island of Corregidor, Nagouliat Peak, and Butilao Peak. It has been alleged that there is a crater on Corregidor, but I found none. Mr. von Drasche has suggested that Corregidor and the little island Pulo Caballo are parts of the rim of a large crater, and this appeared probable to me too during a visit to these islands.

North of the Mariveles Mountains lies the Cordillera de Cabusilan, which contains volcanic-looking peaks (sketched by Mr. von Drasche), especially Pinatubo, but I know nothing further about them.

Mount Aráyat is a striking object, even from the mouth of the Pásig River, looming up over an extensive plain in solitary grandeur. The merest glance is sufficient to show that it is a monadnock and in all probability volcanic. There are two peaks, of which only one is visible from the south. It is densely wooded and shows no crater, according to Mr. von Drasche, who regards the rock as dolerite. Mr. Oebbeke, who examined specimens from both peaks, says that the groundmass is chiefly feldspar, and he classes it as an olivine-bearing augite-andesite. Aráyat must have been extinct for a very long time.

It has already been noted that San Tomás, or Tonglón, on the eastern boundary of Unión Province, is not a volcano, either active or extinct.

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[1] Mr. Semper collected augite-andesites from Mount Binay and the mountains of southern Batangas which have been described by Mr. Oebbeke. I can not find Binay on the maps, where it is probably represented by some other name.

On the other hand, Mount Datá is regarded by Messrs. Semper, Jagor, and Espina as an extinct volcano. Mr. Hans Meyer ascended Datá in 1882 and by barometer found the height 2,245 meters. He found a lake some 1,100 yards in diameter on a bench on the eastern slope of the highest part of the mountain.[1] This is perhaps a crater lake. This traveler says nothing of the rock, but at Mancayan, only about 5 miles from the peak, the rock is sanidine-trachyte, according to Mr. von Drasche.

The remaining volcanic mountains of the archipelago lie in one group at its northern end. Mr. James Horsburgh mentions the little island Camaguín de Babuyanes as having formerly been a volcano, and says that on the west end of the Island of Babuyan Claro there is a volcano.[2] Meyen states that in 1831 the latter underwent a violent eruption. Semper says Babuyan Claro seems to be continually in eruption and that Camaguín is now in the solfataric stage. In 1856 a new volcano made its appearance not far from Camaguín, at the Didica reefs, or Farallones. It is called the Didica Volcano. It appeared in September or October, 1856, between two rocks well known to the natives, at first as a column of "smoke." No earthquake attended its first appearance, but in 1857 it underwent a violent eruption, attended by earthquakes. From that time to 1860, when Mr. Semper saw it, the volcano was constantly active, and in four years had reached a height, according to his triangulation, of 700 feet. He was unable to visit the spot. There is, finally, a volcano on the main Island of Luzón, in the eastern coast range, some 25 miles south of Cape Engaño. It was discovered by Mr. Claudio Montero, of the Spanish Hydrographic Commission. In 1860 Mr. Semper, from Aparri, saw smoke ascending from this mountain, and his servant, who went to its base, assured him that it was well known among the natives as a "fire-mountain."[3]

In the following table are collected the principal data available concerning 20 active and 29 extinct or dormant volcanic vents. I may repeat here that San Tomás and Siquijor, or Fire Island, are omitted because it has been shown that they are not volcanoes. Calayo, supposed to be on Palawan, is left out because there are no data as to its position, while I have no means of separating the positions of the two volcanoes said to exist on Dumaran de Paragua. The principal synonyms are given, that which seems most appropriate being put first. The latitude and longitude are only approximate and have been read from maps. So far as possible Mr. d'Almonte's maps have been used to fix positions and elevations. Mr. Abella's determination of altitude has been taken for Mayón and Mr. Montano's for Apo. A number of the heights of Luzón volcanoes are those originally determined by Jagor, but I do not know the sources of all of Mr. d'Almonte's

[1] Weltreise, 1890, pp. 253–287. Meyer had a paper in Globus, 1883, which I have not been able to see.
[2] The India Directory, or directions for sailing to and from the East Indies, 2d ed., 1817, p. 328.
[3] Die Philippinen, 1869, pp. 14, 98.

figures. Many of them are doubtless his own. The longitudes of the table are for the prime meridian of Greenwich. In the section on "Sources of information" the Greenwich longitude of other prime meridians is noted.

Active and solfataric volcanoes.

Name.	Province.	Approximate— Latitude.	Approximate— Longitude E. of Greenwich.	Height in feet.	Rock. *a*	Date of eruption.
		° ′	° ′			
Babuyán Claro..	Batanes	19 30	121 56	....	....	1831, 1860.
Camiguín de Babuyanes.	.....do	18 55	121 52	....	....	Solfataric.
Didica	.....do	19 2	122 9	700	....	1856 to 1860.
Cagua or Caua ...	Cagayán..........	18 13	122 4	3,920	....	Solfataric in 1860.
Taal	Batangas	14 2	120 57	1,050	Andesite *b* ..	1709, 1715, 1716, 1731, 1749, 1754, 1808, 1873.
Banájao or Majaijai.	Laguna...........	14 2	121 27	7,382	Andesite *c* ..	1730.
Mayón or Albay .	Albay	13 16	123 39	8,970	Andesite *b* ..	1616, 1766, 1800, 1814, 1827, 1835, 1845, 1846, 1851, 1853, 1855, 1858, 1868, 1871, 1872, 1873, 1881, 1885, 1886, 1887, 1888, 1890, 1891, 1892, 1893, 1895, 1896, 1897, 1900.
Bulusán..........	Sorsogón	12 47	124 1	....	....	1852. Solfataric.
Guinon (Bilirán Island).	Leyte............	11 32	124 28	....	Andesite *d*..	Solfataric.
Kasiboi or Caolangojan?	.....do	10 55	124 53	....	Andesite *e* ..	Do.
Danán	.....do	10 54	124 53	....	Andesite *e* ..	Do.
Alivancia........	Paragua	10 30	119 48	....	....	Do.
Talasiquin	.....do	10 30	119 48	....	....	Do.
Canlaón	Negros Oriental ..	10 25	123 6	8,192	Andesite? *f*.	1866, 1893.
Magasu	.....do	9 15	123 9	....	Andesite? *f*.	Solfataric.
Camiguín de Mindanao.	Misamis	9 12	124 42	1,950	Andesite *g* ..	1871, 1875.
Macaturin, or Pollock, or Sujut, or Illano.	Cottabato.........	7 36	124 26	....	....	1765, 1856, 1865, 1871.
Apo or Dávao	Dávao	7 3	125 17	10,311	Andesite *h* ..	Solfataric.
Sanguil or Sangir (Balut Island?).	.....do	5 25	125 19	3,117	....	1641.
Joló	Joló	*i* 6 5	*i* 120 58	....	Basalt? *f*....	1641.

a The queries indicate that the composition of the volcano is inferred from specimens collected near it, but not on it.
b Oebbeke.
c v. Drasche.
d Abella.
e Roth.
f Becker.
g Renard.
h Velain.
i Uncertain.

Extinct or dormant volcanoes.

Name.	Province.	Approximate— Latitude.		Approximate— Longitude.		Height in feet.	Rock.
		°	′	°	′		
Datá	Lepanto	16	57	120	55	7,364	Trachyte? *a*
Aráyat	Pampanga	15	13	120	42	2,880	Andesite. *b*
Pinatubo	do	15	9	120	19	6,050	
Butilao	Bataan	14	43	120	21	4,376	Andesite? *c*
Nagouliat or Mariveles	do	14	31	120	26	4,678	Andesite? *c*
Corregidor	do	14	23	120	32	640	Andesite, dacite. *c*
Pico de Loro	Cavite	14	13	120	36	2,270	Andesite? *c*
Talim	Mórong	14	20	121	13	1,519	Basalt. *c*
Maquiling	Laguna	14	8	121	10	3,724	Basalt. *d*
Cristóbal	do	14	3	121	24	5,288	Basalt? *d*
Malarayat and Sosoncambing.	Batangas	13	58	121	11	....	Andesite? *b*
Tombol	do	13	49	121	10	....	Andesite? *b*
Ambil	Mindoro	13	48	120	16	2,500	
Loboo	Batangas	13	39	121	16	3,451	Andesite? *b*
Labo	Camarines Norte	14	1	122	46	5,092	Andesite. *a*
Colasi	do	13	58	122	59	....	Andesite. *d*
Isarog	Camarines Sur	13	41	123	21	6,450	Andesite. *d*
Iriga	do	13	26	123	26	3,976	Basalt and andesite. *a*
Malínao	Albay	13	26	123	34	....	Basalt. *d*
Mazaraga	do	13	18	123	35	4,442	Basalt. *d*
Pocdol or Bacon	Sorsogón	13	5	123	54	....	
Mainit or Sapongan	Surigao	9	28	125	33	1,115	
Cottabato or Taviran	Cottabato	7	6	124	18	....	
Cagayán Joló	Balábac	6	59	118	30	....	
Magolo	Dávao	6	19	125	6	....	
Matutum	do	6	11	125	10	....	
Malibato	do	6	8	125	2	....	
Butulan or Sarangani	do	5	42	125	18	....	
Balut or Sanguil (?)	do	5	24	125	20	3,117	

a v. Drasche. *b* Oebbeke. *c* Becker. *d* Roth.

VOLCANIC BELTS.

So large a portion of the Philippines consists of volcanic rock as to make it manifest that there must be in the archipelago a considerable number of volcanic belts. Such zones form one of the most prominent features of Malaysia as a whole, and when these are passed in review it appears that the volcanic structure of the Philippines must bear complex and interesting relations to that of the entire region. J. D. Dana[1] was, I believe, the first to call attention to the linear disposition of the volcanic islands of the Pacific and to refer this arrangement to geotectonic principles. Naumann,[2] Perry,[3] Suess,[4] Junghuhn,[5] Centeno,[6]

[1] U. S. Expl. Exp., Vol. X, 1849, pp. 11–23, 415–436.
[2] Lehrb. der Geognosie, Vol. I, 1858, p. 93.
[3] Phén. volc.: Mém. Acad. de Dijon, Vol. VIII, 1860, p. 31.
[4] Antlitz der Erde, Vol. II, 1888, pp. 213–217, etc.
[5] Java, Vol. II, 1854 (German trans.), p 807.
[6] Memoria geológ.-min. Fil., 1876, p. 7.

Wichmann,[1] Verbeek,[2] Martin,[3] Molengraaf,[4] Kotô,[5] and others have contributed to the subject, which, however, still requires much study, especially with reference to the Philippines.

The Nicobar Islands, Sumatra, Java, and the Little Sunda group lie along the edge of a vast submarine precipice, or, in other words, at the very abrupt limit of the continental plateau. Lines of folding and volcanoes, Tertiary and modern, accompany the course of this southern limit of Asia. Some of the most active and remarkable volcanoes of the world are here. Papandayang, in West Java, had a great eruption in 1772, destroying 40 villages. Galung Gung in 1822 destroyed 114 villages; and it is some measure of the violence of the Krakatoa explosion of 1883 that over 36,000 people perished. Off the eastern coast of the Philippines there is also a rapid deepening of the sea bottom, marking the eastern edge of the continental plateau, and here, too, there is a series of active or extinct volcanoes which stretches from close to Formosa southward to the Moluccas. According to Naumann, these two great lines meet in the volcanic island of Nila, about latitude 6° 30′ S., longitude 129° 35′ E., but later studies show that, while in a generalized way this statement represents the distribution of the main volcanic lines, the volcanic systems of the Banda Sea are very complex. In this neighborhood submarine elevations connect Malaysia and Australia, and complexity of structure is therefore to be expected. As many as three curved folds appear to exist here with a common center near the middle of the Banda Sea. They certainly serve to connect the Sunda volcanic line with the Formosa line; but, though considerable study has been devoted to the subject, the evidence is not sufficiently full to unite geologists as to the actual linear connections between volcanic localities. The Formosa line seems clearly to continue along the eastern coast of the Philippines southward through Gilolo, in the Moluccas, but Kotô and others regard Buru and Ceram as a recurved portion of one of the concentric Banda Sea arcs, and as running in this locality perpendicularly to the Formosa line. For the present purpose it is not needful to enter into minutiæ concerning the Banda Sea area.

Within the region outlined by the submarine cliffs of the continental plateau and by the great volcanic arcs lie Borneo, Celebes, and the western portion of the Philippines, as well as the peninsula of Malacca and its continuations, Bangka and Billiton. These latter are closely connected, structurally and otherwise, with the Nicobars and Sumatra, and they are of minor interest so far as the Philippines are concerned.

[1] Gesteine von der Insel Kisser: Beiträge zur Geologie von Ostasien, Vol. II, 1887, p. 197. Neues Jahrb., 1893, pt. 2, p. 176. Petermanns Mitteil., 1893, p. 18. Zeitschr., D. geol. Gesell., 1893, p. 543.

[2] Verbeek et Fennema, Descrip. géol. de Java et Madoura, 1896, p. 993.

[3] Reisen in den Molukken, geol. Th., 1897, p. 57.

[4] Petermann's Mitteil, Vol. XLI, 1895, p. 203.

[5] Geol. structure of the Malayan archipelago: Jour. Coll. of Science, Tōkyō, Vol. XI, pt. 2, p. 83. This is in part a very convenient review.

On the other hand, a glance at such a map as Stieler's physical map of Asia is sufficient to show that Borneo, Celebes, Gilolo, and the Philippines are very nearly related from a structural point of view. The southwestern ranges seem to gather in toward the eastern edge of the Philippines as do the branches of a tree to its trunk. The eastern coast range of Mindanao is continued southward, by the Talaut Islands and others, to Gilolo in the Moluccas. Near the center of our own Island of Leyte there is a fork in the mountain system, and the westerly branch is seemingly continued southward, through Mount Apo and the southernmost point of Mindanao, by way of Sanguir Island to Celebes. In the Visayas, at Masbate, it would seem that a second branch is thrown off, extending through Negros and western Mindanao, Basilan, and the Joló group to the Bornean coast. More obscure is a line which starts apparently in Panay and is marked in the Joló Sea by the Cagayanes, including Cagayán de Joló, for which the Government of the United States is now negotiating with Spain. A very important line is represented by the Calamianes and Palawan, continued in Borneo by the range one point of which is the lofty Kina Balu, which is not volcanic. This range extends through Borneo to its southwest coast and, in the opinion of some geologists, not including Mr. Verbeek, there connects with Bangka. In northern Luzón the coast range or Sierra Madre is clearly continued by the Babuyanes and Batanes to the neighborhood of Formosa (or Taiwan), but the relations of the Zambeles Range and the Caraballo del Norte are not evident on mere inspection.

The interpretation of these topographic features is more or less difficult and uncertain. Lines of folding must of course be discriminated from ranges due to erosion, and while volcanic outbursts are apt to mark anticlines, this is not an invariable rule. The question of continuity is sure to arise in discussing volcanic belts, and it is sometimes assumed that where any considerable gap occurs between areas of volcanic ejecta the fissure system connecting vents is also lacking. This does not seem to me a correct inference. As I read them, volcanoes represent points on a zone of active dislocation where a powerful resistance leads to the dissipation of epeirogenetic energy. Dislocation without attendant volcanism is common enough even in volcanic regions, for active volcanoes are characteristically accompanied by inactive or extinct ones, and from this association it is only a step to volcanic zones in which spots exist where there neither are nor ever have been volcanic vents. These gaps I suppose to mark portions of the fissure system so related to the zone as a whole that resistance to dislocation is never intense enough to supply the latent heat of fusion to the hot rocks on the isobathic surface of melting.

It follows as a matter of course, from these and similar considerations, that minute study of the structure and lithology of a country is needful to a satisfactory elucidation of its volcanic and tectonic system, a topographic sketch being quite insufficient for the purpose. Nevertheless, when it is distinctly understood that a discussion of the subject is intended only to be tentative and suggestive, speculation may lead to the accumulation of facts which otherwise would be overlooked.

Perry[1] proposed to classify the volcanoes of Luzón into three lines nearly parallel to one another. The three trend northwesterly. One includes Mariveles and Taal, a second Aráyat and Banájao, the third Mayón. The Mariveles-Taal system, in Perry's opinion, passed southward through Siquijor and Mindanao, including the volcanoes Macaturin and Sanguil; it took in Ternate and probably reached the Banda group. Mr. von Drasche[2] called attention to the fan-shaped disposition of the islands and to the forking of Masbate, one prong of which is parallel to southern Luzón and the other to Negros and Cebú. Mr. Centeno, in his Memoria,[3] distinguished two systems, one passing through Aráyat, Taal, central Mindoro, Canlaón, and Macaturin; the other through Mayón, Buráuen (in Leyte), Camiguín de Mindanao, Apo, and Butulan. He regards the two systems as uniting to the south of Mindanao, their prolongation passing through Sanguir and to the Moluccas. He also refers to the northerly continuation of the volcanic system of the Philippines toward Formosa, but without specifying the relations of the northern portion to the more southerly lines. Mr. Abella[4] called attention to the continuity of the volcanic phenomena in Leyte northward through Bilirán, Maripipi, etc., to the volcano Bulusán, and to Mayón in southern Luzón, as well as southward to the eastern coast range of Mindanao. Mr. Kotô[5] gives the Philippines a single belt of active volcanoes. From the Babuyanes and Cape Engaño it passes out to sea, reaching land again in Camarines Norte and including Bilirán and Camiguín de Mindanao in its course. In the Gulf of Dávao it forks, one branch reaching Sanguir and Celebes and the other Talaut and Gilolo. This scheme omits the active volcanoes Macaturin, Magaso, Canlaón, and Taal. Mr. Kotô, however, adds tectonic lines. Two of these diverge from Masbate; the eastern branch crosses the volcanic belt in Leyte and follows the eastern coast range of Mindanao; the other branch follows Negros and western Mindanao to Joló. A third tectonic line follows the Sierra de Zambeles; leaving the shore at Mariveles, it intersects Ambil and follows Palawan to Kina Balu, in Borneo, reaching the center of that great island.

These notes suffice to show that, so far as details are concerned, there is considerable diversity of opinion. To my thinking, too much effort has been made to show unbroken continuity of volcanic zones. Fissures occur far more often in parallel systems than singly, and just as dikes frequently jump from one fissure of such a system to another,

[1] Documents, etc., 1860, p. 35. [2] Fragmente, p. 3. [3] Mem. geológ. min., 1876, p. 8. [4] Isla de Bilirán, p. 11. [5] Geol. struct. Malay arch., p. 112.

so I think do the greater volcanic phenomena. Fissures, furthermore, commonly occur in two systems, cutting one another at a large angle, and there are somewhat clear indications that such is the case with the volcanic belts in the Philippines south of Manila. These two systems are approximately parallel to the two prongs of Masbate, but each is curved, the centers of curvature lying in the China Sea, one of them much to the southward of the other. I should consider, provisionally, that the elevations of northwesterly trend, such as the mountains of eastern Mindanao, Leyte, Tayabas, Mindoro, northwestern Panay, and perhaps the northern extremity of Palawan, belong to the one system, but represent a considerable number of different though associated fissures. The trends of the northeasterly character also seem to belong to one system. The western fork of Masbate appears to continue to northeastern Panay, but to be interrupted with an offset in the southwestern portion of that island. The southerly prolongation, it seems to me, is to be found in the Cagayanes. Of course Palawan, Negros, excepting the southern end, and the Basilan-Joló group belong in this system. So nearly as I can make out by plotting, the two systems intersect at pretty constant angles of about 60°. A fairly consistent and satisfactory scheme of short arcs can be arranged in this way for the ranges south of Manila, but I hesitate to print my diagram, because a map conveys an impression of certainty and definiteness which in this case would be erroneous.[1]

To the northward of Manila the same scheme of ranges seems less plausible. I am almost inclined to think that the Sierra Madre and the Caraballo del Norte, which are composed largely of crystalline schists, are each made up of short arcs belonging to each system. Some support for this guess is to be found in Mr. d'Almonte's large map of Luzón, where the watersheds show several zigzags. This region is perhaps a "horst" in Mr. Suess's sense. As for the Sierra Zambales, it seems to me most probable that it continues southward through Pico de Loro and Cape Santiago to the lofty Alcon Peak, in Mindoro, and so into Panay, for a series of hot springs extends southward from Mariveles through Pico de Loro to Balayán, near Cape Santiago, in Batangas Province.[2] The western range of middle Luzón would thus be affiliated with the system with a northwesterly trend. Mr. von Drasche, however, calls attention to the fact that the Sierra Zambales exhibits a remarkable double repetition of the two main directions of Luzón, one northerly, the other northwesterly.[3] With Aráyat I can do no better than leave it in its impressive loneliness.

It is not only in the matter of volcanic zones that the Sunda and Banda islands are homologous with the Philippines. The volcanic

[1] Dana called attention to the symmetry exhibited in the trends of the islands. "Thus the body of Luzón is at right angles with the southern extremity; Palawan is at right angles nearly with Mindoro," etc. He also points out that both of the two systems of trends are curved.

[2] Abella, Man. min., 2d study, 1893, p. 70.

[3] Op. cit., p. 21.

rocks of the southern islands, as has been pointed out above, are substantially indistinguishable from those met with in the Asiatic dependency of the United States. These islands are occupied to a large extent by Tertiary strata, and have undergone slow, recent uplift marked by raised coral reefs. Even their older massive rocks seem much the same as in Luzón, but they also contain Paleozoic and Mesozoic strata, not yet discovered in our possessions.

NOTES ON HISTORICAL GEOLOGY.

Pre-Tertiary strata are entirely unknown in the Philippine Islands. Whether they are absent or merely undetected is questionable. If they are absent, it must either be because the elevation throughout the Paleozic and Mesozoic was as least as great as it now is, or else because the sediments of those periods have since been removed by erosion. In either event it might be expected that the archipelago would stand on a very extensive submarine plateau, built up of sediments derived from the land area. Such is not the case; the islands now stand high, and about three-quarters of the total platform area is dry land. Furthermore, the greater part of the submerged territory lies either immediately west and south of Sámar, and thus between the Visaya Islands, or about the Joló group; while a rise of 100 fathoms[1] would add very little to the area of either Luzón or Mindanao. There is thus no physiographical reason to suppose pre-Tertiary strata absent.

Still less does analogy point to the absence of Paleozoic or Mesozoic beds, for both are fairly abundant in the Sunda Islands, while manifold similarities show that they and the Philippines belong to a single geological and to a single zoological province. If such strata exist, it may be that they are so folded up with the greatly disturbed Eocene that they have not hitherto been differentiated. From the descriptions of Surigao and Misamis, it would seem, too, that considerable areas of slate are there exposed and that portions of these rocks are not highly metamorphosed. This region may possibly yield fossils. In carrying on geological investigations in the Philippine Islands, the indications afforded by the constitution of neighboring islands should evidently be borne in mind, for if the similarities which might be expected do not manifest themselves, the cause of difference demands elucidation.

In Borneo pre-Tertiary strata appear to be somewhat extensively developed. Of the supposed Devonian, Mr. Posewitz[2] writes as follows:

On the islands of the Malay Archipelago the oldest slates, in which up to a short time ago no fossils had been found, are included in the so-called "old slate-formation," to distinguish them from the "younger slate-formation," which, in Sumatra, is

[1] This is, of course, not a mere arbitrary depth, but approximately the lower limit of wave action.
[2] Borneo, Its Geological and Mineral Resources, p. 164, London, 1892.

included by Verbeek in the Culm Measures. Their distribution is very extensive, as they occur in all the islands. In Borneo they contain gold; in Bangka and Billiton, tin. With regard to the age of these phyllites, it was only known up to quite lately that they were pre-Carboniferous, as the Carboniferous strata in Sumatra are underlaid by them. In recent years, however, fossils have been found in west Borneo, which, however, are so badly preserved that up to the present an exact determination of their age has not been made. But the fossil evidence is not against the view that the formation might be Devonian.[1]

It is perhaps from analogy with these slates that Mr. Montano pronounces the ancient massive rocks of the Philippines "principally Devonian."[2] It would certainly be surprising if none of the older schistose rocks of the Philippines should turn out to be equivalent to the old slate of Borneo. In Sumatra, Verbeek considers this old slate as Silurian or Devonian, or a mixture of both.[3] The Carboniferous is known to exist on Borneo and other of the Sunda Islands. It seems to pass by insensible gradations into the underlying slates, but to be separated by a sharp unconformability from the overlying rocks. It is composed of sandstones and limestones, often standing on edge. It is extensively developed in north Borneo.[4] The Upper Jurassic (weisser Jura) has been detected in west Borneo in rock previously supposed to belong to the "old slates,"[5] and from the same region Liassic fossils have been described.[6] In Sarawak, too, an Oolitic fossil has been found.[7]

The Cretaceous is also represented in the mountains of west Borneo. Specimens collected by van Schelle near Sajor, on the River Seberuang, were determined by Boettger and Geinitz as Upper Cretaceous. The extent of the Cretaceous is unknown.[8]

Most of the area of Borneo is occupied by Tertiary strata, and there seems no doubt that all three divisions of the Tertiary are represented. Their delimitation is not so certain.

In the Island of Timor occur both Permian and Triassic strata, fossils from which have been identified by Mr. Rothpletz.[9] With them are found nummulitic limestones containing *Alveolina*, and capped by reef limestones. This island further contains a series of massive rocks very like that of the Philippines. On this subject and for further information the reader will do well to consult Mr. B. Kotô's excellent review.[10]

The age determination of the Malaysian formations, both Mesozoic and Tertiary, is a matter of extreme difficulty, and has led to much

[1] Jaarboek van het Mynwezen in Nederlandsch-Indië, 1886, II, p. 122.
[2] Mission aux îles Phil., 1881, p. 272. Montano gives no grounds for his assertion.
[3] Posewitz, Borneo, p. 166. Verbeek, Sumatra's Westkust, pp. 237–238.
[4] Posewitz, ibid., p. 167.
[5] Fr. Vogel, Samml. geol. Reichs-Museums en Leiden, Vol. V, 1896, p. 127.
[6] P. G. Krause, ibid., p. 154.
[7] R. B. Newton, Geol. Mag., 1897, p. 407.
[8] Posewitz, ibid., p. 173.
[9] Am. Naturalist, 1891, p. 959.
[10] On the geologic structure of the Malayan Archipelago: Jour. Coll. Sci., Tōkyō, Vol. XI, 1899, pp. 83–120. This paper contains a few inaccuracies of statement concerning the Philippines.

unavoidable difference of opinion, because the subject can be approached from different points of view. No deposits have yet been discovered which serve to establish a direct connection between Tertiary strata of the East Indies and those of the North Temperate Zone, nor does the configuration of Eurasia give much hope that such a terrane will be discovered. It is to America that geologists must turn for a direct correlation of formations in the two zones, and studies there will doubtless throw much light ultimately on the East Indian faunas of the past. This is no place for a full review of the literature of the Malaysian Tertiary, but a few notes on the subject, and especially on the Eocene, will be useful to those readers of this paper who happen to be unfamiliar with it.

Junghuhn,[1] in his great work on Java, attempted no divisions of the Tertiary, and even expressed doubts as to the validity of Lyell's three sections of that period. In 1858 F. von Hochstetter[2] segregated the Eocene into three divisions, but in 1866 he modified his views so far as to refer the highest of these to the Miocene. The two remaining Eocene series were:[3]

(*a*) Lower group; coal-bearing system. Many exploitable seams of bituminous pitch coal in quartzose sandstone and clay slate. Fossil tree trunks common, but few fossil shells, or none at all.

(*b*) Upper group. Orbitulite and nummulite limestones; with compact limestones and older coral limestones, heavily developed beds, greatly tilted in certain localities.

The Miocene he also divided into two groups of marly, tuffaceous beds.

Mr. Verbeek, in 1875, in conjunction with Böttger, Geyler, and von Fritsch, subdivided the Eocene of Borneo into three stages, as follows:[4]

Stage α, sandstones with indurated clays, clay slate, and coal seams.
Stage β, soft shales and marls.
Stage γ, limestones.

The observations and collections of Mr. Verbeek and others led to much controversy, in which Mr. Martin and Mr. Wichmann, both of whom have made journeys in the Malaysian Archipelago, took an active part. Mr. Martin, in 1879-80, laid down broad principles of correlation which appear very important.[5] He held that mere comparison of species or genera in tropical and boreal rocks could lead to no trustworthy conclusions, the tropical faunas being radically different from the coeval European faunas. Age determinations, in his opinion, should be made by comparison between fossil tropical faunas and the

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[1] Java, Vol. III, 1854 (Germ. trans.), p. 91.
[2] Jahrb. K.-k. geol. Reichsanstalt, Wien, Vol. IX, 1858, p. 294.
[3] Reise der österreichischen Fregatte *Novara* um die Erde., geol. Theil, Vol. II, 1866, p. 149.
[4] Die Eocänformation von Borneo und ihre Versteinerungen, 1875, p. 4.
[5] Tertiärschichten auf Java, allg. Theil, 1879-80, p. 21. See also Sammlungen des geol. Reichs-Museums in Leiden Vol. V, 1899, p. 259.

living fauna in the same region. Yet even this method is held to be inapplicable in the precise form worked out for the European Tertiary, for in the Tropics physical conditions vary so much less than in boreal regions that the extinction of species must be less rapid, and therefore a greater proportion of living species is to be anticipated in a Tertiary formation of Malaysia than in a homonymous formation of Europe. On these grounds he declined to recognize Mr. Verbeek's Stage γ as Eocene, and expressed himself dissatisfied with the determination of Stage β.

In 1883 Mr. Verbeek made a change of no very great importance in his classification of the Eocene by adding at the bottom an unfossiliferous basal conglomerate, and by characterizing his divisions thus:[1] Stage I, breccia stage; Stage II, quartz sandstone stage; Stage III, marl sandstone stage; Stage IV, orbitoide stage. In 1892 fossil evidence forced him to change his opinion as to β and γ, or III and IV, and he referred the lower of these to the Oligocene and the latter of them to the Upper Miocene[2] thus reaching much the same opinion as Mr. Martin had expressed.

While this report was in preparation, Mr. Martin published a paper on the division of the fossiliferous strata of Java, which he classifies as follows:[3]

Quaternary; consisting of fluviatile and marine deposits, the latter rich in Mollusca and at some localities in remains of whales.

Upper Pliocene; represented by the Kenden beds, rich in remains of *Stegodon* and *Cervus*, containing also *Pithecanthropus erectus* Dub.

Pliocene-Miocene, or the Java series, possibly including some pre-Miocene rocks. This constitutes the greater part of the Island of Java and most of the fossils from the island which have been described come from it. Among them are *Lepidocyclina* and *Cycloclypeus*. This series extends northward through the Philippines to central Japan.

Eocene; marine beds of small extent with nummulites, *Alveolina* and *Orthophragmina*. They contain coal.

Cretaceous limestone with *Orbitolina* from Banjumas. This rock is not known to exist at any other point in Java.

For the purposes of Philippine geology it is important to remark that the series which carries the black lignites accompanied by quartzose sandstones, has been regarded by all the geologists cited, and by most others, as Eocene; while there appears to be a gap in the Miocene of the Sunda Islands which may correspond to an unconformability there, and which answers to a very pronounced discordance in the Philippines.

The Tertiary of the Philippines is fairly well developed, but very insufficiently investigated. In presenting his determinations of the

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[1] Top. en geol. Beschrijving van Sumatra's Westkust, 1883, pp. 315 et seq.

[2] Neues Jahrbuch für Mineralogie, etc., 1892, part 1, p. 66.

[3] Die Eintheilung der versteinerungsführenden Sedimente von Java: Sammlungen des geologischen Reichs-Museums in Leiden, Vol. VI, 1900, pp. 135–245.

fossils in the Semper collection Mr. K. Martin has luminously reviewed the whole Philippine Tertiary, and his paper should be in the hands of every student of the geology of the archipelago. For this reason I have translated it in full, instead of attempting a mere condensation, and my version will be appended as a complement to this sketch. While it is possible that future investigations may make minor changes in Mr. Martin's conclusions, they appear adequately to represent the best results which can be reached until much further investigation of the islands has been accomplished.

The Eocene has been recognized, thus far, only in the nummulitic limestones. These were first discovered by Baron F. von Richthofen at Binangonan on Laguna de Bai, in Mórong Province. They were detected in stone quarries northeast of the town, where the limestone projects in a pillar-like mass through trachyte. The nummulites are mentioned as belonging to several species, but no specific determinations are given. He considers the barren limestone of the caves near San Mateo and those of Jala-Jala on Laguna de Bai of the same age. The limestones are crystalline at their contact with trachyte. At Zamboanga (Mindanao) he found similar limestones, though no fossils; and believed that the excellent brown coal found in the Bay of Sibuguey, in Zamboanga Province, belongs to the same formation.[1] Mr. Abella also found nummulitic limestone in Cebú, at Ginagdanan, a gulch within about three-fourths of a mile from the Esperanza coal mining prospect, in the township of Compostela, a few miles to the north of west from the town of that name. This is on the east coast of Cebú, in latitude 10° 25′. The position of the mine seems to be marked on Mr. Abella's map, though not its name. The fossils were so imperfect that the species could not be determined.

Mr. Abella in describing his Compostela section gives the following notes: "In the rocks of this section we found among the lignites and sandstones of the mines only a few fossil plants, which were indeterminable; and among the limestones certain indistinct forms half converted into spar which could afford no certain indication as to their age. Nevertheless, in breaking some pieces of limestone from Ginagdanan, we found included in the compact mass certain forms which, though specifically indeterminable, should be considered as nummulites in the opinion of various competent persons." He adds that such was the opinion of Mr. José MacPherson, who perceived a striking similarity between specimens of these strata and those of nummulitic limestone in the Province of Cadiz, Spain, which he had studied.[2] It should be added that the strata between the mine and the fossil locality are very highly inclined, a part dipping to the northward and a part to the southward; so that the lignite and the fossiliferous limestone

[1] Zeitschr. D. geol. Gesell., Vol. XIV, 1862, pp. 357-360.

[2] Isla de Cebú, 1886, p. 109.

might be of very different ages so far as the stratigraphy is concerned.

Chiefly on the strength of this discovery, Mr. Abella regards a large area in Cebú as Eocene. It consists of "clays and marls in a compact or slaty condition; sandstones, calcareous sandstones, and conglomerates; compact or crystalline limestones and some lignite seams; all of these in beds which have undergone extreme disturbance."[1]

I must confess that the paleontological evidence as to the existence of the Eocene in the Philippines seems to me far from satisfactory. In Borneo no nummulites, it is said, occur in Mr. Verbeek's Stage α, the only beds now considered Eocene, while one species is found in the Oligocene (β) and four in the upper Miocene (γ).[2] In British India, Burma,[3] and Timor, indeed,[4] nummulitic Eocene is recognized, but it would seem probable a priori that the Philippine nummulitic beds would be comparable with those of the adjacent Island of Borneo rather than with the far-away formations of Burma and Timor. I can see no reason as yet why the Binangonan limestones may not be Oligocene or even Miocene.[5] On the other hand, there seem to me structural reasons for correlating the lignitic series of Cebú with Verbeek's Stage α, as will be explained a little later. While desiring further light, however, I fully recognize Mr. Martin's authority on the paleontological question involved.

Two horizons of the Upper Miocene have been detected. The earlier is revealed by the collections of that model explorer, Semper. He found fossiliferous beds in the valley of the Rio Grande de Cagayán, Province of Isabela, Luzón, which are characterized by a typical mullusk *Vicarya callosa* Jenk, var. nov. *semperi* Mart. They occur in the neighborhood of a place which Semper calls Minanga, in latitude 17°, which seems to be the town named Malunú on Mr. d'Almonte's map. It may be that Minanga is the name of a suburb (barrio) of Malunú. A considerable number of species where collected on the banks of the Catalangan River, and on the banks of the Ilaroen, which latter appears to be identical with the Tarretic of the Spanish geographer's map. Another important locality is the brook called by Semper Dicamui and seemingly also Dicamuni. In a note to Mr. Martin's paper I have given reasons for believing that this stream is also near Minanga. The same *Vicarya* was also collected by Semper at Alpacó, in Cebú. This is in the coal region not far from Naga, and seemingly comes from a marl overlying the Eocene limestones, which is referred to by Mr. Abella as cropping at the head of the arroyo Sibod.[6]

[1] Isla de Cebú, 1886, p. 95.
[2] Posewitz, Borneo, 1892, p. 197.
[3] Geikie, Text-book of Geol., 1893, p 981.
[4] See Kotô, loc. cit., p. 92.
[5] While there is little doubt that tropical strata, both in the East Indies and the West, have been regarded as more recent than they are because of the strong similarity of fossil shells to living species, it should be noted that in the Torrid Zone masses of coral limestones are sometimes transformed with great rapidity into masses so dense as to bear great lithological resemblance to rocks of far greater antiquity.
[6] Isla de Cebú, 1886, p. 114.

The occurrence and character of this marl require attention both for its own sake and because of its relations to the other rocks of Cebú. After having described the massive rocks of the island and the contorted lignitic series, which he considers Eocene, Mr. Abella proceeds to describe his Quaternary formation, and, incidentally, certain marls. Extracts from these descriptions had best be given in literal translation because of the importance of the points involved.[1]

Surrounding the rocks hitherto described on every side, lies an essentially calcareous terrane, which, in general terms, may be said to pass over into the coral reefs on the coast and to rise toward the interior, forming masses as high as those in Mount Mangílao. In addition to the limestones, there is exposed at many points beneath them a bed of marl, more or less argillaceous, which must be referred to this formation, since its stratification is always concordant with the limestone and it contains fossils similar to those found in the limestone. This bed can only be seen toward the central portion of the island and toward the south, in its widest portion, generally appearing at the bottom of the deepest ravines. [At Magdagoog, in the district of Consolación, which is on the eastern coast, he found such a marl dipping at 20° to the southeast. It is grayish white, and almost plastic when extracted, but hardens rapidly on exposure.] Among the many fossils found in it, in addition to the species which are mentioned later, we found the genera *Cancer*, *Dolium*, and *Cyclolites*. This *Cyclolites* we also found in the Compestela road where it crosses the first hills near the coast. * * * At Mount Alpacó, again, appears another bed of gray fossiliferous marl, analogous to that at Magdagoog, but in circumstances which are entirely exceptional in the matter of position. In fact, it is found isolated, overlying the mass of compactly crystalline limestone of the old road to the mines, and seemingly with a dip of 50° to the northeast. In it we collected a large portion of the well-preserved fossils, which, when determined, as we shall see further on, have turned out to be identical with living species, demonstrating the recent age of the bed. Moreover, we have found other marls, identical in composition and containing similar fossils, always lying under the limestones with conformable stratification, not only at the bottom of the beds of the rivers Bairan and Sapangdacó, but also in the gulch Jaguimit of the Pandan Valley so close by [the Alpacó locality]. We must, therefore, rationally suppose, as we have previously indicated, that some landslide or other local convulsion has brought this marl bed into a certain sort of association with the nummulitic limestone of Alpacó, at a distance from the coarse limestones of the coast, to which formation it must be referred. [The reference in the last sentence is to the passage[2] noticed by Mr. Martin. At Jaguimit, Mr. Abella says the stratification of the older series is very confused and difficult of elucidation, the dips being 45° to the NE., while a little more to the westward they are 40° to the SE.] Continuing farther toward the valley of Alpacó a trench is crossed which, at that point, is excavated in a rather crystalline limestone. This, judging from its position, would seem to be related to the limestone of Sáyao, but appears to dip in the contrary sense; that is to say, at 55° to the NNE., its stratification, however, being confused and difficult of exact determination. Moreover, to complete the confusion above the limestone, even at the head of (en vertientes de) the Sibod gulch, appears a stratum of fossiliferous marl, which can not be considered as belonging to this terrane either on account of its lithological character or because of the fossils which it contains.

The head of Sibod Gulch seems to be on Mount Alpacó (1,526 feet) and less than 2 miles from the mines, which stand 978 feet above sea level. When Semper visited the mines he must have crossed this marl

[1] Isla de Cebú, 1886, pp. 120 to 126.

[2] Ibid., pp. 113-114.

bed, which contains well-preserved fossils and would seem, from Mr. Abella's description, to be the only known locality thereabout where good fossils occur or are likely to be found. Mr. Abella states that the lignitic series (at least except at this one locality) contains no material resembling this almost plastic marl, and such is certainly my observation both in Cebú and in Negros. In the lignitic series he was never able to find any well-marked fossils. Hence, it is highly improbable that Semper could have found so striking an object as a determinable *Vicarya* excepting in this marl. Mr. Martin in his paper on the Philippine Tertiary made no express mention of the material attached to Semper's specimen, but had this not been compatible with its derivation from marl, Mr. Martin would never have concluded it "very probable that at this point Eocene limestones are overlain by Miocene marls."

In response to a letter of inquiry Mr. Martin has been good enough to write me as follows:

> In the Semper collection, and labeled "fossils from the argillaceous strata of the coal mines at Alpacó," there are fragments of a light-colored, bluish-gray, friable earthy marl, which is full of fossils. After moistening, these last are easily extracted; but the shells were in part fragmentary when they were embedded; others were well preserved, but have been injured by careless handling or remain only as casts. For these reasons I have been able thus far to identify no species and only the genera *Pecten*, *Cardita*, and *Conus* (?). There are, however, also numerous Foraminifera and among them with certainty a few *Orbitoides*. Accordingly, these marls can not be younger than the Miocene; possibly they are still older, a point which there is reason to hope may be determined by examination of the middle chamber. Judging from the adherent matrix, the same beds have yielded a small *Natica* and a small *Ancillaria*, both in a large number of well-preserved specimens. Perhaps the *Vicarya*, too, is from the same beds, for from its state of preservation it must come from strata which are petrographically extremely similar. If the marl with *Orbitoides* should turn out to be Miocene, it will be in the highest degree probable that the *Vicarya* belongs with them.[1]

Taking all these various circumstances into consideration, it is practically certain, to my thinking, that Semper's *Vicarya* came either from the same marl beds where Mr. Abella also collected a considerable number of different species or from a stratum conformably associated with them. These, however, have all been determined by the Spanish geologists as post-Pliocene. Unfortunately, in his list of 29 fossils belonging to living species, Mr. Abella does not give the localities separately. The discovery of living species in the marl does not, of course, preclude its determination as Miocene. Strangely enough, however, not one of the fossils determined for Mr. Abella by Mr.

[1] Later Mr. Martin was so obliging as to write "that the *Orbitoides* referred to belong to *Lepidocyclina*, as has been determined in very interesting sections prepared from them. The strata concerned are therefore post-Eocene and older than the Pliocene. They correspond to an horizon of the Java group and are to be regarded as Miocene."

The inferences drawn in the text are thus confirmed by very weighty evidence. The information reached me only in time for insertion as a footnote, the small type of which will not derogate in minds of professional readers from the importance of the fact recorded.

Gonzalez Hidalgo is specifically identical with Mr. Martin's list of Miocene fossils from near Minanga, unless "Capucimex" is a misprint; but the following correspond generically:

Conus insculptus Kiener.
Fussus [Fusus] colosseus Lam.
Murex capucimex [capucinus?] Chem.
Murex endivia Lam.
Venus magnifica (?) Sow.

I can see no reason for doubting that Mr. Abella is correct in regarding the Alpacó marl as belonging with the series the most striking portion of which is the mantle of coarse coralline limestone. Mr. Kotô, however, infers from the literature that Semper's fossil determines the age of the lignite.[1] Now it is absolutely certain that there is one great unconformability both in Cebú and in Negros. It lies between the lignitic series and the coral mantle. Mr. Abella's observations seem to show that certain marls form the most ancient portion of the coral-reef series. He regards the Alpacó marl bed as exceptional, seemingly, however, only because it is not accompanied by the coarse reef coral. I see nothing incomprehensible in this. In the neighborhood of Mount Úling, a few miles to the northward of Alpacó, I had ample opportunity to observe that the blanket-like mass of reef coral has been cut away, undermined, and dissolved by surface waters. That at some point or points the soft but relatively insoluble marl should remain, after the removal of the superjacent limestone, would not be wonderful, and such I suppose to be the origin of the Alpacó bed. As most of the marl beds occur in the bottoms of water courses, it is not impossible that the Alpacó exposure shows lower beds of the marl than any other with which Mr. Abella met, and that this accounts for the absence of *Vicarya* from his collections.

Mr. Hidalgo's fossil determinations would make the entire coraliferous superjacent series of Cebú Pleistocene. This does not accord with Mr. Martin's conclusions for other portions of the archipelago, where he regards the older coral reefs as Pliocene. It is almost impossible to believe that the vast mass of coral on Cebú, rising as it does to the very crest of the island, and in latitude 9° 45′ reaching 2,362 feet in elevation, does not include representatives of the older reefs. On the other hand, taking Semper's fossil for a guide, considering also the astonishing regular terracing of the southern end of the island, the prevalence of terraces nearly everywhere throughout its extent, and the even, horizontal crest of the northern part of Cebú, the following conclusion might be drawn: Ever since the later Miocene there has been a continuous, very slow, rise of the island and extension of its land area, raising above water successively Upper Miocene, Pliocene, and Pleistocene beds, the total uplift amounting to over

[1] Loc. cit., p. 117.

2,000 feet. Now this is almost word for word the conclusion which Mr. Martin has reached with reference to Java.[1]

The difference between Semper's discovery and Mr. Abella's results seems quite inexplicable if Mr. Hidalgo's determinations are precise. It is therefore most desirable that some colleague should reexamine Mr. Abella's Cebúan fossils, which are doubtless accessible in Madrid. It is an extremely important feature of the foregoing discussion that, if the conclusion is correct, the lignitic series of Cebú is separated by a great unconformability from the lowest Miocene strata yet known in the Philippine Islands. As the upturned lignitic series is also much eroded, a long period also elapsed between the folding of the beds and the epoch of *Vicarya callosa.* Hence also the lignitic series may be assumed to be as old as the Eocene. The analogy of other islands renders it very improbable that it is as old as the Chalk.

That a great upheaval took place late in the Eocene and early in the Miocene, the effects of which were felt from the Pyrenees to the East Indies, is well known. Eocene beds are found in the Himalayas up to an elevation of over 16,000 feet.[2] It is natural to connect the crumpling and upheaval of the strata of Cebú with this great earth movement. On the other hand, I am surprised to find little or no reference to such a convulsion in Borneo. While the α, or sandstone, stage, sometimes dips at angles of over 40°, it is often far less inclined. The later beds, however, seem to lie at still smaller angles, and perhaps unconformabilities will yet be found.[3] It would thus appear as if the thrust which folded Cebú came from the Pacific, and that its effects were most intensely felt at no very great distance from the edge of the continental plateau.

In the Island of Negros, the folding of the lignitic series has been similar to that in Cebú. The predominant rock of this series along the Talabe River is sandstone, which is accompanied by shales and some limestone. The whole series is considerably indurated. The strata are much distorted and faulted. The strike is usually to the east of north, or nearly in the direction of the axis of the volcanic range. The dips are from 30° to 70° or more, and it is clear that the coral-reef formation, which is continuous for some miles from the coast, rests on the upturned edges of the lignitic series.

In the Island of Panay, which has been described by Mr. Abella, the structure is less clear. In the interior of the ranges he found thin lignite seams and strata comparable in their lithological character with those of Cebú. The limestones are in part crystalline, and they contain traces of organisms, probably Foraminifera, but nothing deter-

[1] Neues über das Tertiär von Java, etc.: Samml. des geol. Reichs-Museums, Vol. V, 1895, p. 28. "There can be no doubt that, since the later Miocene, there has been a continuous and very slow extension of the land area, which has laid bare in succession the Upper Miocene, the Pliocene, and the Quaternary strata." Verbeek's Stage γ is found at one point at an elevation of 1,088 meters.

[2] Geikie, Text-book of Geol., 1893, p. 979.

[3] Posewitz, Borneo, 1892, pp. 178, 181, 206.

minable. The strata are disturbed and folded. The strikes are in general northerly and seem, as a rule, to follow the local directions of the ranges. The dips often reach high values, and the strata are sometimes practically vertical. The angles of dip usually decrease from the axes of the ranges. These older rocks, regarded by Mr. Abella merely as Tertiary for lack of fossils, are surrounded by relatively recent, coarse, coralline limestones, containing a few fossils belonging to living species. They pass over into living reefs at some points along the shores. They seem to be confined to much lower altitudes than are the corresponding rocks in Cebú. On Mr. Abella's principal section, in latitude about 11°, they first appear near Janíuay, which has an elevation of 82 meters, and something like 100 meters seems to be their limit.

Nowhere could Mr. Abella discover a discordance between these coarse coralline rocks and the underlying strata, as he is very careful to point out.[1] That there must be an unconformability somewhere in the strata of Panay between the vertical beds of the mountain crests and the flat limestones of the coast, seems almost certain. It is hardly possible to imagine conditions under which such an amount of disturbance and folding could be brought about in the upland rocks without involving unconformability. The most evident trial hypothesis is that the strata immediately underlying the coral rock belong to a formation not earlier than the Upper Miocene, and that the discordance is to be looked for below this horizon instead of at contact with the limestone. The relations of the strata in Panay seem to form a connecting link between the conditions in Cebú or Negros and those of Borneo.

On the reasonable hypothesis that the black lignites of the Philippines are of Eocene age, this formation is very generally distributed through the southern provinces of Luzón and throughout the Visayas. For details the reader is referred to the section of this paper dealing with Mineral Resources, but the localities in question may be enumerated here in general terms. Black lignites seem to occur in Tayabas, Camarines Sur, Albay, and the Island of Catanduanes, in Sámar, Masbate, Marinduque, northern and southern Mindoro, and in Leyte. While nothing definite is known of the various coal seams in eastern Mindanao, it is probable that some of them resemble the Cebúan fuel. On the Gulf of Sibuguey, in southwest Mindanao, there is black lignite of a high quality.

It may further be noted that at the town of Libón, in Albay, there is coal and also a building stone containing fish scales.[2] This locality may afford an opportunity for an important study.

The occurrence of *Vicarya* at Alpacó has led me into a long digression from the enumeration of deposits, but where so little is known

[1] Isla de Panay, 1890, p. 91.

[2] Roth, in Jagor's Reisen, 1873, p. 349.

concerning the stratigraphy and the fossil faunas, a thoroughly systematic treatment of the geology of a region is impracticable.

A higher horizon, though probably also Upper Miocene, is represented by the foraminiferous marls occurring in Zambales Province along the west coast of Luzón up to 400 feet altitude, between Paláuig and Santa Cruz. The Foraminifera of these rocks were investigated by Mr. Felix Karrer.[1] Tuffs occur in the range of hills on the coast of Aringay, Unión Province, Luzón, which Mr. Martin thinks perhaps equivalent to the Zambales strata just mentioned. He considers it possible that both these series belong in the Pliocene. This formation has not been identified elsewhere and the fossils may easily be overlooked, most of the specimens being less than 2 millimeters in length.

In discussing the crystalline schists and older massive rocks, reference has been made to a series called by Mr. von Drasche the Agno beds. They are extensively developed in Benguet and Unión provinces (northern Luzón), and unquestionably represent a basal conglomerate overlain by sandstones and clay. Mr. von Drasche at first classed them as primitive, afterwards as Paleozoic;[2] while Mr. Abella, who seems to have devoted more time to them, says that the upper strata contain lignite and fossil shells of surviving species. There seems nothing in the Spanish geologist's description incompatible with the hypothesis that the lower part of the Agno beds represents the basal conglomerate formed during the Miocene subsidence of the Philippines. It is somewhat tempting to seek in them the equivalent of Mr. Verbeek's breccia stage of the Eocene, which consists of unfossiliferous strata underlying Stage α; but the absence in the region of Benguet of the Cebuan lignitic series and the character of the organic remains appear to indicate that this portion of Luzón was above water during Eocene times.

In Misamis, surrounding the gold fields, Mr. Abella found a large area of sedimentary rocks lying upon ancient slates.[3] It stretches eastward from Iligan for at least 30 miles, and from this line northward to the western headland of Macajalar Bay. Its southern and eastern limits are unknown. The beds consist of conglomerates, calcareous sandstones, marls, and limestones. Mr. Abella compares them to the Nagelflue and the Molasse of Switzerland, but I should regard the likeness as interesting rather than as important. More significant is their resemblance to Mr. Verbeek's Stage β or III. They are somewhat distorted, a dip of 35° to the north being noted at one point. They contain numerous organic remains, especially in the hill ESE. of the town hall (tribunal) of Tagsulip, but the fossils are very imperfect. Mr. Abella thought himself justified in referring one specimen to *Turbinolia*. This fossil and the general character of the deposit led

[1] His memoir is appended to von Drasche's Fragmente.
[2] Neues Jahrbuch für Mineralogie, etc., 1879, p. 265.
[3] Criaderos auriferos de . . . Misamis, 1879, passim.

him to refer the formation provisionally to the Miocene, a step which seems to me reasonable in the circumstances. Mr. Abella was not in Misamis to make paleontological studies, but to report on the gold fields. The region evidently promises results to the paleontologist.

Off Joló Bay, at the little island called Marongas, I found the rocks soft conglomerates and sandstones, containing fragments of coral and basalt pebbles. The strata are considerably tilted, and a heavy basalt dike intersects them. Possibly these strata are of the same age as the Misamis beds just referred to.

Concerning the Pliocene and post-Pliocene, Mr. Martin reaches the following conclusions:

> The beds of the Agusan River (Mindanao) are Pliocene. It is probable that as such are also to be counted the hard, light-gray marls of the River Salac y Maputi (Mindanao) and the clay beds of Paranás (Sámar), as well as the older coral reefs of the Philippines, especially those of Benguet, which are assuredly not older than the Pliocene.
>
> Quarternary are the shell banks which stand 15 feet above the level of Laguna de Bay (Luzón), and those on the beach at Paranas, and again on the south coast of Sámar, where, at Nipa-Nipa, these beds reach an elevation of 60 feet above sea level. Here, too, belong the fossil coral reefs, which are intimately connected with the living reefs and are widely distributed in the Philippines. With them belong the recent limestones of Cebú.

For further details the reader is referred to the accompanying paper by Mr. Martin, but one or two additional localities may be noted. According to Charles Darwin, Mr. Cuming found a large bed of fossil shells on the Rio Grande de Cagayán, in the Province of Isabela, at Cabagan. This town lies in latitude 17° 25′. The fossil-bearing stratum is about 50 feet above the river, and the fossil shells are said to be certainly of the same species as those now living on the shores of neighboring islands.[1] Cabagan is about 30 miles from Semper's localities, near Minanga or Malunú. I am not aware that Mr. Cuming's specimens have been described. Mr. Karrer states that Mr. Hugh Cuming made collections in the Philippines, and that, excepting the Foraminifera turned over to Dr. Carpenter, his "collection of mollusks is reported to have been acquired by the British Museum (Brady)."[2] It is to be hoped that some of the paleontologists interested in the Far East will examine it. Mr. Cuming is said to have spent the years 1837–1841 collecting in the Philippines. When geological explorers can again reach the upper waters of the Cagayán, they will doubtless endeavor to establish stratigraphical relations between Cuming's locality and Semper's.

Mr. von Drasche heard reports of the occurrence of recent shells in the great plain of Luzón, but did not see them. Semper regarded the reports as probable, but did not investigate the matter. Centeno, however, gives details of interest.[3]

[1] C. Darwin, Structure and Distribution of Coral Reefs, 2d ed., 1874, p. 178.
[2] R. von Drasche, Fragmente, 1878, p. 84.
[3] Mem. geológ.-min., 1876, p. 21.

In the townships of Tárlac and [San Miguel de] Camiling, close to the lakes of Canaren and Mangabol, some deposits of marine fossils were found in 1861 by that enlightened naturalist, Father Antonio Llanos. In the former, about half a league north of the settlement, in a place called Malitlit, there appear some beds which abound in fossil species belonging to genera which now exist in warm seas. Among the many species there found, only the following have been determined: *Berinices*, *Trochus*, *Griphea*, *Caryophillea*, *Meandrina*, *Astrea*, *Oculina*, and others. These shells are dug up by the natives to make lime. They sink shafts which cut the fossil beds at a depth of four or five varas [11 to 14 feet], after having passed through a thin bed of clay banded in different colors. The said beds rest upon one of a yellowish, soapy clay. The known extent of these deposits is very small. [Tárlac is on the railway and very accessible from Manila.] In the township of Camiling and, as we have mentioned above, near Lake Mangabol, at some 5½ or 6 leagues from the Gulf of Lingayén, at an elevation above sea level of not less than 250 feet, are found beds of fossils, analogous to those of Tárlac, which also the natives use to prepare lime. In addition to the species noted, there has been found at this latter point *Pholas*. The beds also contain some small mollusks upon which *Pholas* lived, such as *Physa*, *Balanus*, *Cerythium*, *Cytherina*, and others. The rock containing these specimens is a volcanic tuff, which consists of a conglomerate of ash, pumice, and clay. At many points it is found to be covered by a calcareous sediment upon which may be seen some fossil *Serpulas*, and these appear to belong to the species *hexagona*.

The lake here referred to appears on Mr. d'Almonte's map as the *Pinag* de Mangabol, because it contains water only in the wet season.

Semper collected *Potamides palustris* Linn. at Zamboanga. He also found *Potamides sulcatus* in the humus layer of the hill at Sinaan [Dinaan?] on the Island of Cebú.[1] Abella, too, reported this species from the post-Pliocene of the same island.

The coralline limestone which plays so large a part in Philippine geology has a number of peculiarities which are of geological importance. These are due to the mode of growth of the coral polyps, the limitations to their growth, and the solubility of the calcareous mass. It is well known, of course, that living corals are usually but not invariably confined to water not exceeding some 15 or 20 fathoms in depth, that they can not live when exposed to the air even at the lowest tides, that they flourish only when constantly washed by moderate currents of sea water, that fresh water or dirty water kills them, and that dead corals either dissolve away or are converted by a more partial process of solution into crystalline limestone.

While sediments tend to horizontal stratification, corals grow freely on steep surfaces; so that, on a rising island, the coral limestone tends to form an even layer approaching 100 feet in thickness and following the topography which previously existed. Thus in such cases actually coeval corals follow contours instead of surfaces; and if an island rises perpendicularly, the under portion of the highest corals is the oldest. In the Philippine coral rocks there is a very rude sort of stratification, which seemed to me on Guimaras, Negros, and Cebú to be only locally developed. Such a parting might be caused by a

[1] K. Martin, in Sammlungen des geologischen Reichs-Museums in Leiden. Die Fossilien von Java, Leiden, Brill, 1899, 4°, p. 211.

shower of volcanic ash, or by a flood of fresh water, or, perhaps, more frequently still, by mud. The rains accompanying typhoons are tremendous, more so, perhaps, than what is known in the United States as a "cloud-burst," while a typhoon extends over a large area. For example, in October, 1875, according to Mr. Abella,[1] the rains attending a typhoon brought down such torrents of mud from the ashy slopes of Mayón that 1,500 persons were overwhelmed and smothered, while the destruction of property was immense. This storm must have carried into the sea millions of tons of sediment and must have rendered the water temporarily quite unfit for coral growth. This, indeed, was an extraordinary case, but many of these hurricanes pass across the archipelago each year. In my opinion it can not be inferred that any pseudo-stratification of coral rock was ever horizontal unless there are special grounds for that opinion, and the observer must be very cautious in inferring upheavals from inclined stratification.

A marked peculiarity of the corals is that they grow upward to a limiting line or a plane, instead of seeking the lowest possible level, like sediments. Thus the crest of the Cordillera Central in the northern portion of Cebú is an even line many miles in length, which at once suggests base-leveling, but seems to be due in reality to what may be described as the summit-leveling of coralline growth. Similarly, barrier reefs and fringing reefs, when seen from a distance, simulate terraces and may lead to misinterpretation, although, like terraces, their upper surfaces indicate approximately the position of the surface of the water. The details of topography of coral reefs often differ markedly from those of sedimentary terranes. Thus, in northeastern Negros, on the Talabe, I found a series of hills flanking the main range with excessively steep slopes and crests only a few feet in width. They were composed of rough coral and seemed to represent barrier reefs.

Most of the caves in the Malaysian Archipelago are in the older coral rocks of Pliocene or early Pleistocene age, and this leads to a most curious method of geological determination. The swallows which build the edible birds' nests, *Hirundo esculenta*, frequent these caves, and, according to Mr. Posewitz,[2] where these nests are reported, Verbeek's Stage γ may be inferred. Thus, Palawan (Paragua) is famous for its birds' nests, and it is therefore at least highly probable that the island is provided with a mantle of coral reefs of Pliocene age.

I shall not attempt to go into a discussion of atolls, of which I have made no studies. It is well known that Semper was led by his investigations of the corals among the Philippines and the Pelew (Palaos) Islands to dispute Darwin's subsidence theory, seemingly not altogether without success.[3] Semper brought much evidence to bear to show that only the exterior lateral surface of a mass of growing coral

[1] El Mayón, 1885, p. 10. [2] Borneo, 1892, p. 190. [3] Die Philippinen, 1869, p. 100.

flourishes, while the interior dies, decays, and yields to solvent processes. The recent field investigations of coral reefs in all quarters of the globe are, to a great extent, confirmatory of Semper's views. As exceptions to Darwin's theory, Mr. Alexander Agassiz mentions all the reefs which he has studied in Florida, Yucatan Bank, Cuba, Bermuda, the Bahamas, the West India Islands, the Galapagos, the Sandwich Islands, Australia, and the Fijis.[1]

In the Joló Archipelago, the charts indicate several well-developed atolls, such as Simonor Island (latitude 4° 52′, longitude 119° 50′) and Tumindao (latitude 4° 45′, longitude 119° 20′), as well as several in the Tapue group (latitude 5° 30′). The charts of this region also show innumerable coral reefs, which are bare at low tide and must therefore have been uplifted. In the Province of Benguet is a very famous atoll, first recognized as such by Semper, in which lies the provincial capital La Trinidad. It has been described by Semper,[2] von Drasche,[3] and Abella.[4] The elevation of La Trinidad is 3,960 feet (Abella). The atoll is about 2 geographical miles in diameter, according to Semper; the wall varies from 500 to 700 feet in height, the inner side is bare, and the slope is 25° to 35°. A stream passes through the craterlike valley, passing the wall by narrow slits.

The recent plains of the Philippines require little attention geologically, though they form the most valuable and thickly settled portion of the islands, and, indeed, this is the case throughout Malaysia. In large part these plains are areas of marine denudation and deposition, outer portions of the continental plateau which have been lifted above water level in very recent times. Recent unfossilized shells often occur scattered through the earth of these plains, as is the case on the southern outskirts of Manila, where intrenchments effected exposures. Wherever the land has been only peneplained it shows minute terracing, frequently to be seen along the course of the Pásig, and finely displayed on Binangonan Peninsula, Laguna de Bai. The streams, too, are engorged as a natural consequence of uplift. A portion of the lowlands consists of confluent deltas, which are usually composed of very rich land, and country of this description is naturally intersected by bayous, or, as they are called in our Asiatic territory, *esteros*. The environs of Manila Bay to the northward of the city consist chiefly of this delta country.

Laguna de Bai is an extremely shallow sheet of water, dammed back by a low swale of indurated tuff through which the Pásig River has cut its channel. The lake is only about 4 fathoms deep in the deepest portions, which are nearly on a level with the Bay of Manila. The lake bed seems to have changed somewhat since the Spanish occupation,

[1] The islands and coral reefs of Fiji: Bull. Museum of Comp. Zoology, Vol. XXXIII, 1899, p. 41. Interesting comparisons can be made between the geology of this group and that of the Philippines.

[2] Zeitschr. für allg. Erdkunde, Vol. XIII, 1862, p. 84; and Die Philippinen, 1869, p. 18.

[3] Fragmente, 1878, p. 30.

[4] Terremotos de 1892, 1893, pp. 13, 38.

and a small island, Sunuli, which formerly existed near Los Baños, is now united to the mainland. Near the outlet, however, an old settlement, Pueblo de Bai, is now under water, seemingly in consequence of slight earth movements.[1] According to Martinez de Zúñiga, a town, called Tabuco, which existed according to official records on the western shore of the lake in 1603, is now under water, the settlement having been moved to the present village of Cabuyao, a few miles to the northwest of Calamba.[2]

The lake basin is merely a portion of the great plain of Luzón, separated from the main area by a slight undulation of surface. When the country stood at a little lower level it must have been an arm of the sea. Such is also the belief of the natives, among whom there are reports that it contains sharks. These have not been verified, so far as I know. A similar rumor, also unsubstantiated, exists concerning Lake Bombón, which is much lower and much closer to salt water than Laguna de Bai. Bombón, however, is several hundred feet in depth, and, as has been mentioned, I consider it a crater due to explosion.

I have already discussed the Pliocene and post-Pliocene uplift of the archipelago as indicated by the distribution of fossils. It must also be considered from the more striking physiographical point of view. Physical evidences that the islands are rising at the present time, or have been rising within a few years, abound from one end of the group to the other. It is also clear that the amplitude of the movement has been very great. Whether minor fluctuations, temporary subsidences of relatively small amount, have occurred is a delicate question which can not be definitely settled at present; but the distribution of living animals seems most easily accounted for on the hypothesis of oscillation.

Repeated mention has been made of the continuity which sometimes exists between the growing coral along shores of the islands and the coralline limestones on the land, but the distribution of instances exhibiting this relation has not been described. In intimate connection with it is the terracing either of the dead corals or of terranes which, for local reasons, are devoid of coral. It would be useless to set down all the cases noted of transition from living coral to exposed limestone. Semper[3] wrote: "Everywhere on the shores of the islands, on Camiguín to the north of Luzón and on Basilan near Zamboanga, on the eastern coast of Luzón and of Mindanao, as well as on Bohol and (according to report) on the Calamianes and Palawan, occur raised coral limestones, sometimes in long continuous patches, sometimes in isolated ones; and these limestones are continuous with the

[1] Abella, El monte Maquilin, 1885, p. 9.

[2] Estadismo de las Islas Fil., edited from manuscript by W. E. Retana, Madrid, 1893, p. 334. This work and its elaborate appendices are very valuable contributions to Philippine lore, though containing little of a geological nature excepting bibliography.

[3] Die Philippinen, 1869, pp. 18, 99.

living reefs, the two being connected by the waterworn lower portions of the limestones and the upper parts of the reefs, which are exposed at low water and are still rising." A glance at the charts of the archipelago will show how superabundant is evidence of this class. Semper was especially struck with the phenomena on the islet of Lampinigan, close to Basilan, where trachytic (really basaltic) talus above high water is cemented by coral, and a waterworn cave containing a pothole exists over 20 feet above the level of the highest tides. Similar observations have been made by all observers, and especially by Mr. Abella in his studies on Cebú and Panay. Dana long since stated, from information, that on Point Santiago, in the Province of Batangas, coral exists at an elevation of 600 feet. Mr. Abella, in describing the gold fields of Misamis, refers to the raised corals along the Bay of Macajalar as very abundant. The distribution of the localities here noted shows that the phenomena in question have been observed in all areas of considerable extent within the archipelago. Mr. Abella makes the interesting statement that the Caroline Islands are undergoing depression.[1] At Bacólod, in western Negros, the sea is shoal and muddy and there are no corals. The edge of the wide plain of western Negros stands a few feet above high tide, and the sea is encroaching upon it so rapidly that undermined cocoanut trees strew the shore or hang on the ragged edge of the little bluff. At Dumaguete, too, on the southeast coast, there are no raised corals, a fact which, I think, must have a connection with the volcanic nature of the locality, but between Dumaguete and Tanjay (a few miles to the northward) there are well-developed terraces. On the southern outskirts of Tanjay the old burial ground is on a broad knoll of decomposed coral more than 50 feet above tide level, and on the main coast road, a mile south of Tanjay, is a hillock of well-preserved coral. The first hills to the westward of San Carlos, northeastern Negros, are coral, some of which is at least 300 feet above the sea, and the natives say it is found far higher up in the mountains. On the Talabe there are sharp ridges of coral, elevated to at least 600 feet, which have been mentioned above as probably barrier reefs. The Island of Refúgio, lying off San Carlos and Talabe, is all coral, and it rises to 70 or 80 feet. Off the town of Cebú, Cebú, lies the Island of Mactan, on which Magellan was killed. The reefs about it are most interesting, for they are partially exposed, and terrace after terrace, of small altitude, can be studied there, the vertical intervals being only a few feet. One of the most marked levels, forming the tops of some reefs, is about 8 feet above the water, and the exposed portion is worn and dissolved into the most fantastic shapes. Some small masses stand on pedestals, like bowlders on a glacier, and others are cavernous. Mangroves and other plants have already taken possession of the upper surfaces. The lowest terrace appeared to me to correspond nearly to low low water. At Joló, also,

[1] Guía Oficial, 1898, p. 131.

there is evidence of uplift. There is a little island called Marongas, about 5 miles northwest of the town of Joló, composed of tilted sandstone and a basalt dike. It is partly surrounded by reef coral, some of which stands 2 or 3 feet above water. A storm beach about 5 feet in height here incloses a mangrove lagoon. One side of this pond is formed by the sandstone island, while the storm-beach barrier appears to rest upon coral reef. The circumstances seemed to me illustrative of atoll formation. It is alleged by Mr. Espina that in Palawan actual uplifts have been observed by residents.

High terraces, as well as low ones, are abundant throughout the islands. I should say that on the Island of Cebú it would be difficult to find a place from which there are not to be seen either horizontal coral ridges or incised terraces. Especially fine are the terraces on the southern exposures of Cebú and Bohol. Here the rocks as they rose have been exposed to the swell caused by the southeast monsoon, and the terraces are more sharply marked than they are in more sheltered situations. This part of Cebú must approach 2,000 feet in height, and is scored with a vast number of terraces, all of which are sensibly horizontal; nor could I perceive any division between them, such as would answer to a partial submersion followed by renewed uplift. In such a case it might be expected that the upper set of terraces would be less distinct than the lower set, the dividing line corresponding to the greatest temporary submersion, but nothing of the kind is perceptible. In steaming along the coast of Mindanao from Joló to Cebú it is evident that in that great island also terraces form one of the most prominent topographical features.

All the evidence thus far adduced, both paleontological and structural, points to a progressive uplift of the archipelago, beginning in the later Miocene and still proceeding. This evidence, however, is too fragmentary to be absolutely conclusive, and the possibility of minor fluctuations is not excluded. The distribution of living forms is certainly calculated to throw some light on the more recent history of the Philippines, and should be made to contribute all it can. At the same time it must not be forgotten that obstacles which seem geologically of small moment may limit the extension of species, as has been pointed out by Mr. Wallace himself.[1] The Island of Cebú affords a striking example of this fact, as will presently be noted. In dealing with the Philippines, Mr. Wallace regards the greater part of the birds and mammals as descended from Bornean forms, while, in his opinion, there is also evidence that a direct connection at one time subsisted between Luzón and continental Asia. He says: "Absence of a large number of Malayan groups would indicate that the actual connection with Borneo, which seems necessary for the introduction of the Malay types of Mammalia, was not of long duration, while the large proportion of widespread continental genera of birds would seem

[1] Jour. Royal Geog. Soc. London, 1863, p. 231.

to imply that greater facilities had once existed for migration from southern China, perhaps by a land connection through Formosa, at which time the ancestors of the peculiar forms of deer entered the country."[1]

Mr. Dean C. Worcester and Dr. Frank S. Bourns[2] have also examined the former distribution of land within the Philippine Archipelago as elucidated by the present distribution of the avifauna. It would appear that Cagayán Sulu, Balábac, Palawan, and the Calamianes have been more recently connected with Borneo than the remainder of the islands, while the Island of Cebú, strangely enough, seems to have been separated from the eastern islands of the archipelago for a very long period. At first sight it would seem that an induction of this character could scarcely be made from the distribution of winged animals, for other islands of the archipelago are in full view from every point of the shore of Cebú. The peculiarity of the Cebúan fauna is accounted for in Mr. Worcester's opinion by the lack of necessity for periodic migrations on the part of the birds. While in temperate climates most birds are compelled to make long journeys, in order to escape rigors of climate and to find proper food, birds in the Tropics may be hatched, grow old, and die in a single grove without being impelled, except by restlessness, to transgress its limit.

Negros, Panay, Guimarás, and Masbate, according to these zoologists, form a well-defined group of islands. So, also, do the islands from Sulu (or Joló) to Tawi-Tawi. On the other hand, they tell us that the chain of islands on the eastern side of the archipelago, from Luzón to Mindanao and thence to Basilan, show a very close relationship.

It seems impossible to understand such a distribution of the existing fauna unless it can be assumed that land connections formerly existed between islands now separated by considerable channels. It is fairly clear that in the early Miocene the whole area of the archipelago must have been continuous with Borneo, and that partial submergence followed; but if connections had never since existed between land masses which are now separated by water, each island might be expected to exhibit its own peculiarities, as do Mindoro and Cebú. The easiest way to account for the present distribution of life is to assume that at some time, perhaps during the Pliocene, there was a temporary uplift carrying the archipelago somewhat above its present level, so that some of the islands were connected, and that this uplift was followed by subsidence. There is an alternative, however, for it may be imagined that connections which once existed, in spite of a greater general submergence of the Philippines, were eaten away in relatively recent times by waves and tidal currents. This hypothesis,

[1] Geographical Distribution of Animals, Vol. I, 1876, p. 345.
[2] Proc. U. S. Nat. Mus., Vol. XX, 1898, pp. 549–625.

however, is of very dubious value. If, for example, Negros, Guimarás, Panay, and Masbate were now to be depressed, even 100 feet or so, a very wide interval, 30 miles or more, would exist between Negros and Panay, while nearly as great a distance would intervene between Panay and Masbate. It is almost incredible that, in these quiet land-locked waters, connecting isthmian areas of such extent have been cut away by wave action and left no monadnocks to tell the tale. Inspection of the charts seems rather to indicate, in the shoal waters which separate this group of islands, a submerged coastal peneplain.

If a fluctuation such as is here suggested has occurred, it would have produced a nonconformity of erosion which would probably be traceable on minute study. It should certainly be sought when opportunity offers.

Summarizing the foregoing facts and inferences, it would seem that the geological history of the Philippines is something as follows: From early Paleozoic times onward an archipelago has usually marked the position of these islands. Prior to the Eocene nothing definite is known of them, but further investigation will very likely disclose Paleozoic and Mesozoic strata there, as in the Sunda and the Banda islands. During the Eocene it is probable that the lignitic series of Cebú was deposited, and the contorted indurated strata, which in other localities also carry black lignite relatively free from water, should be referred provisionally to this period. Whether the nummulitic limestone found at Binangonan is Eocene seems to me to be an unsolved question. After the Cebúan lignitic epoch a great uplift and folding took place, and this may have been a detail of the late Eocene movement which so profoundly modified Asia and Europe. It must have brought about temporary continuity of land area between Borneo and Luzón. Somewhere about the middle of the Miocene the country sank to a low level. Many of the present islands must then have been far below water, while Luzón and Mindanao were represented by groups of islets. Observations appear to suggest that the Agno beds represent the basal conglomerate formed at this subsidence. A slow rise began again during the later Miocene, and may have continued to the present day without inversion, yet the actual distribution of living forms is such as to give some grounds for believing that, at some intermediate period, the islands were a little higher than they now are, but sank again only to rise afresh. The diorites and associated massive rocks, including their tuffs, may have made their appearance about the close of the Paleozoic. The less siliceous of these rocks seem to have followed the more siliceous intrusions as a whole. The gold deposits, and perhaps other ores, are so associated with these massive rocks as to indicate a genetic relation. The neo-volcanic period began as early as the highest Miocene horizon, and very probably at the post-Eocene upheaval. If the semiplastic marls of Cebú are all Miocene, the earlier andesitic rocks, at least, date back nearly to the great upheaval. Among these rocks, also, there is sometimes a tendency for the basalts to follow the andesites, but the one dacite found at Corregidor is later than the andesites of that island. The relation of the trachytes to the andesites is not certain, but the sanidine rock is probably the earlier. A very large part of the neo-volcanic ejecta has fallen into water and been rearranged as tuffaceous plains. The volcanic vents appear to me to occur rather on a network of fissures than on a single system of parallel diaclases, and the volcanic activity is to be regarded as a thermal manifestation of the energy of upheaval.

Before dismissing the general geology of the Philippines, I may perhaps be excused for calling attention to a particular aspect of that difficult subject, the paleontology of the tropics. From one point of view it is more interesting and more important than that of temperate zones, for it must ultimately be made to contribute to the physical history of the globe. If the solar radiation has been variable during geological time, it must have left some paleontological evidences, however obscure, of change in insolation, especially near the equator; and it seems hardly conceivable that any decipherable record besides these evidences should exist of changes in the sun's thermal emanation. Several other causes, as well as change in solar radiation, would tend to bring about alterations in climate on the earth's surface. Variations in the eccentricity of the earth's orbit, and in the obliquity of the ecliptic, must influence climate; but at the equator only to an insignificant extent. Changes in the distribution of land would influence the distribution of the warm waters flowing from the tropics toward higher latitudes, but would seemingly not considerably affect climatic conditions at the equator. An alteration in the composition of the atmosphere would affect the radiation from the earth's surface; so that if the diathermancy of the atmosphere were decreased, the mean temperature of the globe would increase. How the effect of such a change would be distributed over the earth's surface has not, so far as I am aware, been adequately discussed. It is possible that it would tend rather to a uniform high temperature throughout the world than to an increase of mean temperature at the equator, because of the increased rapidity of atmospheric circulation. There can be little question that this problem can be, and will be, solved; and the light which paleontology is capable of throwing on the former mean temperature within the tropics will then tend to elucidate the history of the entire solar system. Geological exploration in Malaysia is a cause in which many have already laid down their lives, either meeting death with arms in their hands, like George Müller, F. W. Witte, and F. Hatton, or succumbing more painfully to disease, like L. Hörner and others; but the cause is worthy of the sacrifice, and they have afforded the world an example which should be cherished.

MINERAL RESOURCES.

COAL.

True (Paleozoic) coal does not exist, so far as I am aware, anywhere in Malaysia. The nearest approach to it is a black, pitchy lignite, similar to that of Washington. The difference between lignite and true coal lies mainly in the quantity of combined water, which not only diminishes the percentage of combustible material, but requires the expenditure of combustible constituents to convert it into steam or dissociated gases of the temperature of the flame. The black lignite is the most valuable mineral asset of the Philippines, and is widely spread from southern Luzón southward. It is difficult to trace its distribution in detail, because there are also brown lignites of small value at many points, while the reports are in large part not sufficiently explicit to determine which fuel has been detected. The black lignite is probably of Eocene age, like the very similar fuel of Labuan, in North Borneo, well known throughout the Far East, and other Bornean or Javanese lignites. The brown lignites in the Philippines probably correspond, both geologically and in quality, to the late Tertiary lignites of Borneo. The Japanese "coal" is also a lignite, and at least no better than the black fuel of the Philippines, which will do good service for all local purposes, and in case of need will answer for vessels of war. As will be seen later, its heating effect is approximately from two-thirds to three-quarters of that of the best Paleozoic steam coals, such as Cardiff.

Coal seams are recorded at a great number of localities in the Philippines, but in a large proportion of cases the information is insufficient to decide whether the occurrence is one of black Eocene lignite or the later brown lignite. The brown fuel in so heavily wooded a country would, in most cases, be economically worthless, but might be geologically important. To some extent a guide may be found in the mining concessions, for it is improbable that any one would go to the expense of taking up deposits of brown lignite. In the Island of Luzón concessions have been granted only in the extreme southeastern corner, the Province of Albay, but Centeno states that applications were made for concessions in Tayabas, though no work was done. I am not aware of any reason to believe that Eocene coals exist to the northward of Tayabas.

Thus the following localities in Luzón at which fossil fuel has been found[1] are probably, though by no means certainly, late Tertiary lignites. In Cagayán there is an occurrence at a bayou or slough called Calbong, in the township of Amulung. In Abra lignite is found on the river Malauas, in the township of Dolores. In Unión it occurs at Aringay. Mr. von Drasche was unable to learn anything of the deposit when he visited the town, but thought it might be in the tuff. Again,

[1] Guía Oficial, 1898, p. 125.

in the Island of Polillo there is lignite at a place called Burdeos, which is not on the map; so, too, at Norzagaray, in Bulacán, and at Montalbán, in Manila Province. This last is very probably associated with the nummulitic limestone. In Mórong Province there is lignite at Tatauiran Gulch and elsewhere.

In Tayabas a considerable number of coal mines are marked on Mr. D'Almonte's map, and these I am inclined to refer provisionally to the Eocene group. That more is not heard of them may very possibly be due to thinness of seams or other disadvantageous features. A group of these coal prospects centers at Antimonan, a port at the narrowest part of the Tayabas Isthmus. These mines are all within 15 miles of the town. Two are on Alabat, an island to the north. There are also two little islands to the south, Pagbilao Grande and Chico, each of which has coal, and two more prospects lie on the mainland to the southeast. Farther off in this same direction, in the region of Macaleton, is still another so-called mine.

In Camarines Norte there seems to be no coal, while in Camarines Sur it is found near Pasacao, on the southwest coast,[1] and also on the Caramuan Peninsula, which forms the eastern extremity of the province. Jagor[2] heard that coal was found at three localities in this peninsula. On the map a single one is marked. Opposite lies the Island of Catanduanes, which administratively belongs to the Province of Albay. In this island, according to Mr. Espina, there is coal at Bató, in the southeast corner. The localities just mentioned seem to lie at the edge of a field which stretches southward into Sámar and which is extremely promising. About 12 or 15 miles to the southward of Catanduanes lie the small islands of Carraray, Batan, and Rapurapu. Here the lignite is black, resembling bituminous coal in appearance; it is of excellent quality, is found in seams of good thickness, and is close to tide water. Mr. Espina, who has visited the place, gave me the following notes:

The seams are lignite and their thickness is very variable, but is always greater than 0.75^{m}, and never exceeds from 3^{m} to 4.50^{m}. The dip varies from zero to 37° and 40°. The quality of the coal is fairly good, as is shown by the following analyses made in the Inspección General de Minas of seven specimens from the Bilboa mine, Viscaya district, Batan. [Six of the analyses are of the coal, and show very little variation; one is of the bituminous shale underlying the seams. The mean of the six coal analyses is as follows:]

Mean of six analyses of coal from the Bilboa mine, Viscaya district, Batan.

	Per cent.
Hygrometric water	13.518
Volatile substances	37.463
Fixed carbon	44.455
Ash	4.564
Total	100.000

[1] Espina, Ligero Bosquejo, 1898, p. 157.
[2] Reisen, 1873, p. 166.

Carbon equivalent to combustible constituents	0. 68035
Carbon equivalent to volatile constituents	0. 23560
Calories of combustible portion	5, 497. 22800
Calories of volatile portion	1, 905. 02750
Quantity of steam at 100° from water at 40° ....kilos	6. 24918
Fuel requisite to produce 1 kilogram of steam ....do	0. 16656
Mean density	1. 30 to 1. 40

Color, jet black, with iridescence and high luster; hardness, less than steel; texture, laminar and cleavable; flame, reddish white with somewhat dense smoke; odor, very resinous; ash, yellowish, dull white; duration of flame, 1′ 45″.

A coal mine is marked on Mr. D'Almonte's map in western Albay, not far from Libón and a little south of Lake Bató. Roth[1] also says that a bituminous limestone from Montecillo, near Libon, contains fish scales. The stone is used for building. It would be interesting to ascertain whether a connection could be established between the coal and this fossiliferous limestone.

The Batan coal seems to reappear at Gatbó, not very far from Bacon, in Sorsogón Province. Among the seams here Centeno[2] says that one is from 4 to 8 meters in width, nearly vertical, and strikes N. 20° W. This coal was tried on steamers, and found satisfactory. A company undertook to exploit it, but with what success I do not know. The last Luzón locality is near Magallanes, latitude 12° 50′. Beyond its position on the map I have no information.

In Sámar, according to Centeno, the coal deposits of Sorsogón continue. He gives a locality, Loquilocon, and Mr. Abella mentions Gándara and Paranas. The last two towns are on the west coast, at a considerable interval. A line drawn through them would pass near Gatbó, and its direction would be very like the strike of the bed at the last-mentioned place, differing some 60° from the prevalent strike in Cebú.

There is coal at Cataingan, in southeastern Masbate, and two concessions have been granted. In Marinduque Mr. Espina reports coal, and so, too, at Subaan, on the north coast of Mindoro, but without details. In southern Mindoro, at Bulalácao, and on the adjacent islet, called Semerara, there are coal seams which appear to be important and on which there are mining concessions. Mr. Espina reports the quality as similar to that of Batan and the thickness of the beds as from 75 centimeters to 2½ meters. Centeno says that the croppings at Semerara are between high-water and low-water marks.

In Panay Mr. Abella found no important coal seams, but thought that the thin seams found, 8 or 10 inches in width, might perhaps be accompanied by others of more value now covered by soil. He notes especially Balete, Buruanga, and Valderrama, in Capiz Province, and Dingle, in Iloilo Province.[3]

[1] Jagor, Reisen, 1873, p. 349. [2] Mem. geol.-min., 1876, p. 35. [3] Isla de Panay, 1890, p. 201.

In the northeastern portion of Negros coal seams occur, lying 6 or 8 miles from the coast and in a line substantially parallel with it. They are exposed in the channels of the rivers Talabe, Calatrava (or Macasilao), and Luzón. It is said that some of the seams are of good width and quality. I visited that on the Talabe, but found nothing of value. Two seams were exposed; neither had over a foot of fuel, and they carried pyrite. The lignite was jet black, and seemed to belong to the same class as the Cebú lignites. The seams lay between walls of bituminous shale and dipped 30° NW. The stratification in the neighborhood was much disturbed. There were many pieces of float coal in the river, and very possibly there are other seams hereabout, but the natives professed to know of no other exposure. It was my intention to explore the entire belt of deposits, but an attack on my escort by a relatively large body of natives put an end to prospecting. This belt is well worth examination when the natives quiet down. Governor Larena also informed me of a coal deposit in southwestern Negros, to the eastward of Cabancalan. Efforts to obtain detailed information failed.

Cebú divides with Albay and Sorsogón the reputation of being the most important coal region of the archipelago, and it has been examined with care by Mr. Abella. The coal occurs chiefly on the eastern slope of the central range, between Danao, latitude 10° 30′, and Boljoón, latitude 9° 38′. It is also found on the west coast in the townships of Toledo (10° 17′), Balamban (10° 29′), and Asturias (10° 33′). The principal deposits are in the townships of Danao, Compostela (10° 26′), and Naga (10° 13′). In 1899, work was going on only at the Compostela mines, which were supplying coasting steamers in a small way. The existence of coal has been known to the natives for an indefinite period, and a mountain in the Naga district bears the name Úling, which is the Visaya name for coal. The Spaniards first became aware of the coal deposits in 1827. Since then work has been done in a fitful manner from time to time and at various points, but nowhere with energy and method.

While coal occurs in almost every township along the eastern coast, Mr. Abella properly protests against speaking of the region as a coal basin. The strata are sharply flexed, folded, and faulted. As I had occasion to observe near Mount Úling, the coal-bearing series not infrequently stands in a vertical position, and the conditions are such that continuity can not be depended upon. Most careful exploration would be needful in opening any mine, and the expenses of mining can not fail to be seriously increased by the position and fractured condition of the seams. At the same time, labor is cheap, the distance to the shore is only a few miles, and the Cebú coal should be able to compete with Japanese or Australian on the Manila market with a very handsome profit. The seams often reach 4 feet in thickness, and one at Compostela is over 8 feet in width. The strike is characteristically to the east of north, or in the direction of the axis of the island, while the dip is westerly or easterly, according as the seam is on one side or the other of the local axis of folding. The dip is seldom under 30°, and rises to 80° or 90°. Some of the seams are of very good quality, being free from pyrite and standing the weather well. There are pyritous seams, however.

The best idea of the quality is to be had from Mr. Abella's assays. As is well known, the results of coal assays vary considerably with the method employed. For this reason, Mr. Abella very wisely assayed Cardiff coal and Australian coal at the same time and by the same method as his Cebú coals. As the chief point of interest in such tests is to ascertain the relative value of the material tested, the result is entirely satisfactory. Tests of some of these coals were also made on Spanish war vessels and under boilers at the arsenal at Cavite. In these last the quantity of water evaporated per unit of coal was 6.5 units. The conclusion drawn from the tests on the *Santa Filomena*, a government vessel, was that for the ordinary purposes of navigation the coal is acceptable even burned alone, but when mixed with one-third Cardiff coal the results are excellent. For further details of these tests, I must refer the reader to Mr. Abella's memoir, but I reproduce here his table of analyses. Only the first two of them fairly represent the coal below the surface unimpaired by weathering.

Comparative assays of coals from Compostela and Danao, in Cebú, and foreign coals on public sale at Manila in August, 1878.

Source of the fuel.	Density.	Percentage composition.				Flame.		Coke, character.	Ash, color.	Carbon equivalent.		Calories.	
		Fixed carbon.	Volatile matter.	Moisture.	Ash.	Duration, minutes.	Character.			To the volatile matter.	To the combustible matter.	Of the volatile matter.	Of the combustible matter.
Seam of Esperanza tunnel, Caridad mine, Compostela.	1.329	51.96	37.56	7.80	2.68	6	Large, reddish....	Almost fritted	Brick red	0.202	0.721	1,632	5,829
Seam of Caridad tunnel, Caridad mine, Compostela.	1.340	54.56	34.53	9.60	1.31	4½	Regular, reddish .	Pulverulent	Light red.......	0.167	0.698	1,369	5,643
Upper outcrop of Santa Rosa mine, Danao .	1.319	57.94	31.75	9.23	1.08	4	Regular, bluish...	.....do	Reddish	0.083	0.662	671	5,353
Bairán outcrop, Magallanes mine, Danao..	1.305	49.50	35.03	11.18	3.62	4	Regular, light	.....do	Yellowish red ..	0.184	0.678	1,491	5,490
Mantijá outcrop, Legaspi mine, Danao	1.320	47.30	33.43	16.65	2.62	3½	.....do	.....do	Red	0.075	0.625	605	4,642
Upper outcrop, Magliji mine, Danao.......	1.301	37.92	37.34	18.75	5.99	3	Short, dark	.....do	Very red........	0.161	0.540	1,305	4,367
Outcrop Baisabais mine (Cajumay and Jumayán), Danao.	1.315	50.50	30.85	16.12	2.53	4½	Regular, dark	.....do	Yellowish	0.131	0.636	1,058	5,139
Outcrop, Maulincop mine (Tagamacan, Balamban) Danao.	1.262	48.09	31.68	17.20	3.03	5	Regular, reddish .	.....do	Very red........	0.106	0.887	860	4,747
Australian (mixed Newcastle and Sydney). *a*	1.365	71.45	16.25	2.90	9.40	6½	Large, bright, black tipped.	Porous, bright	Reddish gray...	0.053	0.768	432	6,205
English (Cardiff) *b*	1.389	83.00	8.60	4.50	3.90	5	Short and dark...	Almost pulverulent.	Gray...........	0.103	0.932	842	7,530

a We mixed in equal parts coal which we were assured came from the Wollerong mines (Sydney) and the Agricultural company's mines (Newcastle.)
b We were assured that the coal came from Cardiff.

I made a visit to the neighborhood of Mount Úling from Naga. All the mining prospects were abandoned and caved in, and the deep soil concealed exposures, except in the beds of the water courses. I saw several exposures, the best of which was in the bed of a brook called Cambagnao, to the southeast of Mount Úling peak, at an altitude of some 600 feet. Here a thickness of 4 feet was exposed, while the bottom of the seam could not be reached. The coal was bright and free from pyrite; the seam was nearly flat, with a slight southerly dip; the hanging wall was sandy shale. This coal was somewhat jointed. At a quarter of a mile below this exposure the strata in the stream bed are vertical. The crest of the range above the coal deposit is formed by a cliff of coral limestone 100 feet or so in height. It is perfectly evident, however, that the coral rock rests upon upturned and considerably faulted strata. A specimen of Mount Úling coal, from the claims of the Philippine Mining and Development Company, was analyzed in the laboratory of this Survey in June, 1900, by Mr. George Steiger, and gave the following results:

Analysis of Mount Úling coal.

	Per cent.
Moisture	8.74
Volatile matter	43.01
Fixed carbon	46.29
Ash	1.96
Total	100.00
Sulphur	0.36
Phosphorus	0.02

The coke sinters together slightly, but is not firm. The ash is red-brown.

It will be observed that this analysis corresponds pretty well with the analyses of Compostela coals by Mr. Abella. As is well known, the amount of fixed carbon obtained from a coal varies somewhat with the method of manipulation, so that this determination is largely a matter of convention. The method employed in the laboratory of the Survey is given in the report of the committee on coal analysis.[1]

I was not permitted by the commanding officer in Cebú, Colonel Hamer, to visit Compostela and Danao, because the natives were on the eve of a serious outbreak.

Leyte possesses coal, but even the name of the locality is unknown to me. It is said to be in the southwestern part of the island. An analysis made in the Inspección de Minas showed it to be of the same class as the Cebú coal, giving 5,800 calories.

In Mindanao and its adjacent islets coal is known to exist at many points, but beyond the presence of the seams I have been unable to ascertain anything. I can, therefore, only catalogue them. On the

[1] Jour. Am. Chem. Soc., Vol. XXI, 1899, p. 1116.

small Island of Dinágat, near the northeast cape of Mindanao, there is coal, at Tubajon. On the islet Siargao (near Dinágat) coal occurs at Numancia, on the west side, and at Cabúntug, on the east. Well down on the east coast, in latitude 8° 10′, is point Sancop, which is also a coal locality, as is the river Casauman, in latitude 7°, and Mati, or Matti, in latitude 6° 50′. On the south coast, in latitude 6° 4′, and on the same meridian as Iligan, is the river Craán, or Gran; and here, too, coal is found. Knowledge of all of these localities I owe to Mr. Espina. According to the Guía Oficial, there is coal a few miles north of Iligan, at Naauán, and the same authority gives a locality, Marasingan, which I can not find. A trustworthy Filipino told me that the coal at Naauán was good. Baron von Richthofen speaks of lignite of admirable quality from the Gulf of Sibugai to the northeast of Zamboanga, without specifying the precise locality. Coal is reported by Montero in Balabac.[1]

While it seems reasonable to class all the Visayan coals mentioned above as Eocene, because of their composition and the stratigraphical relations in Cebú and Negros, the same assumption is not justified in Mindanao for lack of knowledge. It would be in no way surprising, however, to find the coals of eastern Mindanao similar to those of Leyte, which is clearly a continuation of the Surigao Peninsula.

GOLD.

There is scarcely a province in the Philippines in which gold has not been obtained by the natives, who are skillful pan miners and clever in dealing with accessible quartz. Gold mining is with them an ancient industry. It is said that Chinese writings of about the third century, A. D., report gold as the chief product of Luzon.[2] Before Magellan's arrival it seems certain that commerce was carried on with China, and that the Filipinos paid for silks and other manufactures in gold, trepang, dyewoods, and edible bird's nests.[3] The unconstrained life and dazzling possibilities of gold digging suit the happy-go-lucky temperament of the Filipino, and, since 10 cents a day is "wages," they have been able to work deposits down to a very low grade. Even the tricks of the trade are not unknown to them, and at the time of my visit to one army post the native miners nearly succeeded in inducing American officers to take an interest in gravel salted with brass filings. Some of the fields seem pretty well exhausted above water level, and it would be rash to assume that there is any really virgin ground among the alluvial deposits or any croppings not familiar to the natives.

The more important known gold fields are three in number, and the

[1] El arch. Fil., etc., su hist., geog., y estad., Madrid, 1886, p. 433.

[2] Dr. O. F. von Möllendorf, formerly German Consul at Manila, is quoted by Mr. F. Karuth as making this statement: U. S. Cons. Rept., 1898, p. 414.

[3] Jagor, Reisen, 1873, p. 10, citing Morga, Sucesos de las is. Fil., 1609.

most northerly of them lies about Mount Datá, in the country of the Igorrotes. Datá is in the Cordillera Central and in latitude 16° 55′. The second and best-known district is that of Camarines Norte, very accessible by sea, and about 115 miles to the E. by S. of Manila. The only other hopeful region is the northeastern portion of Mindanao and the adjacent islets.

The following note on gold in Luzón was compiled for me by Mr. Luis Espina from the records of the Inspección de Minas in Manila, of which he was in charge in September, 1898:

Gold is found in moderate quantities nearly all over the Island of Luzón, but more particularly and under conditions favorable for exploitation in the following townships and districts, proceeding from north to south:

1. Abra Province.
2. Village named Fidelisan, Bontoc Province.
3. Village named Suyuc, Lepanto Province.
4. Village named Tubuc, Lepanto Province.
5. Village named Dugon, Lepanto Province.
6. Village named Acupan, Benguet Province.
7. Village named Tabio, Benguet Province.
8. Village named Capunga, Benguet Province.
9. Village named Itogon, Benguet Province.
10. Village named Gapan, Nueva Écija.
11. Village named Peñaranda, Nueva Écija.
12. Village named Paracale, Ambos Camarines.
13. Village named Mambulao, Ambos Camarines.
14. Village named Labo, Ambos Camarines.
15. Village named Capalongan, Ambos Camarines.
16. Village named Maculabo,[1] Ambos Camarines.

In the Province of Abra gold is found in alluvial deposits, and in the sands of the river of the same name, as grains, and has an average fineness of 750 to 792 thousandths. In the Province of Lepanto gold occurs in three different ways—in veins, in alluvial deposits, and in river sands. Its fineness is from 0.792 to 0.833, and it is somewhat light colored because of a considerable silver content. It is usually accompanied by ores of silver, copper, iron, and lead. In the provinces of Bontoc and Benguet the deposits are in all respects analogous to those of Lepanto. In the Province of Nueva Écija the gold is exceedingly pure, brilliant in color, and 0.958 fine. It is found as rounded particles in alluvium and sometimes in small crystals.

The Igorrotes, who inhabit Abra, Bontoc, Lepanto, and Benguet, are extraordinarily reticent about their gold mining. Nearly two hundred years ago Morga wrote that the "Ygolotes" would not permit the Spaniards access to the mines.[2] Even Semper, who stood on intimate terms with the Filipinos, was not allowed to visit any gold mines in the Cordillera Central. An Englishman of long residence in northern Luzón, who had handled much Igorrote gold commercially, informed me that no outsiders of any race were permitted to visit the quartz mines or even to prospect for quartz, though such are sometimes allowed to wash gravels in the streams of the Agno and the

[1] Islet 10 miles from Mambulao.

[2] Sucesos de las islas Filipinas, Mexico, 1609, p. 134. This rare work is in the library of Harvard College.

Abra river basins. This concession, I take it, is a sign that the Igorrotes consider such gravels pretty well exhausted. As will be seen in the account to be given of the copper deposits, the Igorrotes are gifted with mechanical skill and are not afraid of solid rock. It is to be inferred that their quartz mining, though rude, is tolerably effective, and perhaps approaches Mexican work. The great topographical accentuation of their country favors tunnel drainage and must enable them, in many cases, to dispense with pumping or bailing. Beyond the information already given, I have been able to ascertain nothing of interest concerning this northern district, which, as has been noted elsewhere, lies in a region of crystalline schists and older massive rocks. I am aware of no indication that neo-volcanic rocks are so associated with the quartz veins as to lead to the hypothesis that the gold deposits are related to these eruptions. Indeed, throughout the archipelago the phenomena point to an age at least as great as the Mesozoic for the greater part of the gold, while analogy with other gold fields suggests that the Tertiary period of volcanism must have brought about a partial renewal of the conditions necessary and sufficient to lead to gold deposition. The corresponding phenomena, however, are yet to be observed.

The gold district of Camarines Norte is also in the gneissic rocks. Here quartz veins are found carrying, besides gold, iron pyrite, copper pyrite, galena, and zinc blende, sometimes also accompanied by lead chromate. At Labo, Centeno[1] notes that native copper is occasionally, yet rarely, observed in the veins, and Morga observes that the gold is alloyed with copper. The general direction of the veins in this region, according to Centeno, is north and south, except those of Gumihan and of Mount Lugás, which strike northwest. They are approximately vertical, and their width is from 1 to 5 inches, though at some points they are much wider, reaching 3 or 4 hands (palmas), but in such cases they become poorer.

Mr. von Drasche made an excursion from Mambulao to a locality called Dagupan, which had recently been opened up, and imparts the following information:

> The road from Mambulao leads southwesterly over black clay slates. These clay slates, of uncertain age, are intersected by numerous intensely corroded cellular quartz stringers, in which the gold occurs. The water courses carry numerous auriferous pebbles, and sand, which is washed for gold. At the time of my visit a great number of small shafts were also being driven, some 15 fathoms (Klafter) deep, especially at points where quartz stringers were visible at the surface. The very primitive methods of concentration naturally involve the loss of a great part of the gold, but the profits seemed to me good, for there were more than 700 men and women at work.[2]

[1] Memoria geológico-minera, 1876, p. 47.

[2] Fragmente, 1878, p. 63. I do not find Dagupan near Mambulao. There is gold at Tumbaga, a little west of south from Mambulao.

Of course there are numerous placer mines in this region, but of these there is nothing special to tell. Beach sands are also washed. Reports indicate that gold is found in the wall rocks as well as in the veins, but I suspect that this is for the most part an erroneous conclusion. In such a country the saprolite, or rotten rock in place, is often auriferous, even when the tiniest quartz stringers can not be found, and this is to be traced to the solution or replacement of small auriferous quartz stringers, the gold after the removal of the quartz remaining in the saprolite. Mr. von Drasche's statement that the stringers are corroded and cellular shows that such solvent action is going on, and miners should at least beware of assuming that there is gold in the solid rock, excepting at contact with veins.

Mr. Thomas Browne, a miner, informed me that, at Paracale, the rock is granitic and the nearly vertical veins strike N. about 40° E. He stated that there are veins as much as 20 feet in width ; and a chute in one is alleged to have given assays as high as 38 ounces to the ton. Such assays, of course, mean very little, for it is seldom that a gold mine offers no rich specimens.

The descriptions of Camarines Norte remind me greatly of the gold fields of the southern Appalachians, where also tiny veins and auriferous saprolite play a relatively large part. I can see nothing to indicate that Camarines will ever be very important as a gold-producing region. Certainly it is no "poor man's country," nor has it yet proved profitable to enterprises with capital. The industrial history of this district is one of decadence. It must have been of this region that Hernando Riquel wrote in 1574 in his "very true and certain account of what has recently been known concerning the new islands of the West." He says that in Luzón "there are many mines of gold in many parts which have been seen by Spaniards, and all say that the natives work it as they work silver mines in New Spain. And the metal has a continuous vein like the silver ore. Trials have been made, and the mineral presents itself so plentifully, that I do not write about it, lest they should suspect me of exaggeration [how convincing is such fine self-control!]; but it is sufficient to say that I swear, as a Christian, that there is more gold in this island than there is iron in Biscay."[1]

Tradition, indeed, indicates that the placers were originally very rich; and this there is no reason to doubt. According to Morga the natives worked them with more energy before the Spanish conquest than after it. Spaniards coming from Mexico early settled in Camarines Norte, and brought with them Mexican methods of treating the ore, which are still practiced there. In 1643 the Crown levied a royalty of a fifth, which was later reduced to a tenth. In Morga's time (1609) the reduced royalty yielded $10,000 annually, and Gemelli Carreri learned from the Governor at Manila that the product was $200,000,

[1] Broad sheet printed at Seville in 1574. Taken from App. 4 to H. E. J. Stanley's translation of Morga's Sucesos de las islas Filipinas, Mexico, 1609, London, for the Hakluyt Soc., 1868.

which is a reasonable figure, since such a royalty was sure to be evaded in large measure. Spaniards began to establish works on a larger scale about 1700, and ever since that time there has been a long procession of enterprises following one another to disaster and oblivion. The nearest approach to success seems to have been attained by Francisco Estorgo, in the middle of the last century. He, lucky man, after losing one fortune at Mambulao, made another at Paracale, and wisely went home to Spain. In 1876 Centeno reported that the production was 30 ounces a month, bringing about $10 per ounce, so that the annual gross receipts of the entire mining population were $3,600. It is to be hoped that expenses were small, and it is no wonder that Jagor found the people almost naked and extremely poor.[1]

For pulverizing the ore the natives use a species of trip hammer made by attaching a heavy stone, serving as a head, to a sapling. A second stone answers for an anvil. After placing the quartz on the anvil, the workman drives down the head, the elasticity of the sapling raising it again for a fresh blow. The crushed quartz is ground in an arrastre, concentrated in a batea, and washed clean in a cocoanut shell. In this last operation a soapy vegetable sap (gogo) is added, I fancy in order to prevent gold from floating.

In Panay, Mr. Abella gives a number of localities at which gravels have been washed for gold, seemingly without notable success. The best of them appears to be at Astorga, a suburb of Dumárao. This town is in the Province of Capiz and its latitude is 11° 16′. No product is stated. In the Province of Iloilo gold is known at San Enrique and Barótoc Viejo. In Cebú there are old workings, but all of them were abandoned in 1886. Some of them had been opened on pyritous veinlets in diorite. In the Island of Sámar there is gold at Pambujan.

The Island of Panaón lies immediately south of Leyte. On its eastern coast is a settlement called Pinutan, and a short distance to the southeast of the town is a mine which was examined by William Ashburner: Several veins of quartz outcrop on the coast, and extend in a westerly direction into the mountain. These veins are parallel; they strike east and dip south. The wall rock is "greenstone-porphyry." There is some wall rock in the vein, and the sulphurets are chiefly pyrite, accompanied by galena and zinc blende. One vein, about 6 feet wide, has been worked to a considerable extent, some 871 tons having been treated up to 1883. The yield was $6 or $7 per ton.[2] Concessions for gold mining have been granted at Tigbauan, just south of Pinutan, and, according to the Compendio de Geografia, there was a productive mine at Inolinan. This name is borne by a point in the southwestern part of the Island of Panaón, but no settlement called Inolinan is marked on the map. The deposits of this island are evidently near together and doubtless in the same formation.

[1] Cf. Centeno, Mem. geológ.-min., p. 47; and Jagor, Reisen, pp. 141, 150.
[2] Manuscript report.

The mystery of the unknown still hangs about the Island of Mindanao, and there is an impression in many minds that it is an Eldorado. More is known of it than is generally supposed, and what is known justifies no extravagant anticipations. The auriferous regions are two; one of them lies immediately south of the Bay of Macajalar, on the north coast, in the province or district of Misamis; the other comprises the eastern coast range of the island, in Surigao Province, but is only known to contain gold in promising quantities near the northern end of that range. Of the two districts, that in Misamis is the more famous.

The Misamis gold field has been reported upon by Sainz de Baranda, Centeno, Minard, and Abella. The last-named geologist studied this region more thoroughly than the others, and is the chief authority on the subject.

The auriferous deposits include veins, placers, and river sands; the veins, however, have been worked only to a slight extent and were abandoned long before Mr. Abella's visit. Very little gold comes from the river beds. The placers lie near the rivers, but at some distance above them, and it is evident from the descriptions that the recent uplift of the coast has engorged the rivers to some extent.

Four rivers emptying into the Bay of Macajalar are flanked by placers. The most important is the Iponan, and the gravels are scattered along it for a distance of 12 miles. On the Rio Cagayán (not to be confounded with the great river of northern Luzón), or rather on a tributary, the Bitog, there are gravels for about 2 miles. There is a single placer on the Bigaan and two on the Cutman. The one locality where gold-bearing quartz in place is found is also close to the Cutman, less than 3 miles from the town of Agusan. These rivers are known to be accompanied by placers farther south than the latitude of Iligan—say 8° 10′—but that part of the country was in the hands of hostile Mohammedans and was inaccessible to Mr. Abella. The Moros worked them, however, doubtless by the same methods as the Christian Indians of the coast. Along the Iponan the gravels are found at an elevation above the river which usually does not exceed 66 feet, or 20 meters. They are not continuous, but occur in patches, the conditions showing that intermediate areas have been removed by erosion. They rest on marls or conglomerates, supposed to be Tertiary; and the miners distinguish three layers—black, grass-root soil; red, plastic clay; and the pay streak (dugcálon). The last consists of sand, quartz, pebbles of porphyry, and pebbles of magnetite. The pay streak runs from half a meter to 3 meters in thickness, and seems to average about 1.6 meters, or, say, 5¼ feet. Mr. Abella was at much pains to determine the amount of gold per cubic meter in the Iponan placers, and found it about 3.5 grams. The average fineness of the gold is 0.658, and the pay gravel would, therefore, run 1 pennyweight 3 grains per cubic yard in fine gold.

The placers of the other river basins just mentioned differ inconsiderably from those of Iponan. The gold from the Cagayán is a little finer, that from the Bigaan and the Cutman a little baser. The thickness of the pay streaks is within the same limits.

The river washings amount to nothing in the way of product. It is well to note that those engaged in it make from 12½ to 25 cents a day.

Quartz stringers carrying gold are found at Pigholugan Hill, on the right bank of the Cutman, between the gulches called Cabagcahan and Pigholugan. The rock is metamorphic argillo-siliceous slate, striking NNE. The stringers vary in thickness from 1.6 to 8 inches, and are nearly vertical, striking E. They contain wire gold as well as metal in scales, and a little arsenopyrite. There are ancient, abandoned, caved-in workings on this deposit.

It is a remarkable fact, pointed out by Mr. Minard, that the Misamis gravels contain platinum as well as gold, a statement confirmed by Mr. Espina, but not referred to by Mr. Abella. Mr. Minard also found in the placers flakes of lead, which he supposed to be native. In all probability, however, it is Spanish, much ammunition having been expended at various times in this region.

In working the placers the natives concentrate by a species of puddling and handle the concentrates with the batea and the cocoanut shell, which in the Philippines seems to take the place of the horn spoon in Mexico. Placers are worked only in the rainy season. I do not find in Mr. Abella's memoir any estimate of the output. Mr. Centeno puts it at about $27,000 per annum.

According to the Compendio de Geografía, the eastern range of Mindanao is auriferous from its northern extremity as far south as Caraga, latitude 7° 12′, but chiefly in the neighborhood of Surigao, Mainit, Taganaan, Placer (all within 20 miles of the northern cape), Lianga (latitude 8° 33′), and Suribao (latitude 8° 25′). Centeno gives some further details. In the townships of Taganaan the localities are Bagon-Duangan and Danao. In Placer Township the gold is found at Tinabingan. The most important district, he says, is in the mountains of Canimon, Binutong, and Canmahat, "a day's journey" (10 miles?) from the town of Surigao. Here there are veins, in talcose, serpentinoid slate, up to 3½ inches in width. Some are quartzose and others carry carbonates. In these, especially the latter, occurs gold with iron and copper pyrite, galena, and zinc blende. The rich veins, he says, strike east and west, while other poorer or barren veins take other directions. The veins are pockety and very little work has been done on them.

William Ashburner, a California mining expert of note, visited Surigao in 1883. He examined some washings on the Consuran River, where the Biga empties into it, 8 miles south of the town of Surigao. Here he found gold which was angular and, in one case, filiform. He met no quartz, and thought the gold must come from decomposed eruptive rock. In discussing Camarines Norte I have referred to the fact that quartz may be removed by solution, or converted into silicates. Ashburner was informed that $20,000 had been taken out during the previous year. The placer is worked in the same way as are the placers on the Iponan. He also examined a slate belt at the head of the Consuran, which contained irregular gold-bearing pockety stringers of quartz and spar. This must be near the locality called Canimon by Centeno, and is perhaps identical with it. It evidently resembles Pigholugan in Misamis. Ashburner visited Placer to see a deposit forming a ridge between two small streams and rising to a height of 150 or 200 feet. Here he found fragments of auriferous quartz, which were being worked, but no vein. Neither in this region nor in the Island of Panaón was Ashburner able to find anything which he could recommend to his clients. Indeed, all the reports from Mindanao made by responsible engineers indicate very mediocre deposits, a large part of which is already exhausted.

In addition to the gold deposits described above in the Philippines, there are certain localities not known to be of any commercial value, but which are of interest because they tend to throw light on the distribution of the formations whence the gold is derived, presumably older massive and schistose rocks. Gold is found at Pamplona,[1] in the extreme north of Luzón, latitude 18° 25′, and is probably derived from the northern portion of the Cordillera del Norte. Another locality is Balincaguin,[2] in Zambales Province, latitude 16° 7′. A gold mine has been opened on the Island of Polillo, near the town of that name,[3] latitude 14° 50′. This island is on the east coast, and belongs to the Province of La Infanta. Lahuy[4] and Catanduanes[5] are islands lying to the eastward of Camarines Sur, and are both reported to be auriferous, as is the township of Caramuan, on the peninsula adjoining them. To the south of Catanduanes is the Island of Rapurapu,[6] which contains both coal and gold. Sibuyan Island[7] is north of Panay, and gold has been found there. At Lubang, on the island of that name, which belongs to Mindoro Province, Dana found gold-quartz veins and chalcopyrite.[8]

It has been alleged that Mindoro itself is auriferous, but this statement, I think, refers to the province rather than to the island; at least the only locality I have been able to hear of in this province, besides Lubang, is at Mospog,[9] on the Island of Marinduque, to the northeast of the Island of Mindoro. The natives wash gold from the sands of Masbate.[10] There is gold in northern Bohol, at Getafe,[11] and on Diná-

[1] Guía Oficial, 1898, p. 125.
[2] Ibid.
[3] Map of Luzon, d'Almonte, 1883.
[4] Guía Oficial, 1898, p. 125.
[5] Espina, op. cit., p. 171.
[6] Centeno, Mem. geológ.-min., 1879, p. 46.
[7] Ibid., and Sainz de Baranda, loc. cit.
[8] U. S. Expl. Exp., Vol. X, 1849, p. 539.
[9] Map of Luzón, d'Almonte, 1883.
[10] Compendio de geografía, 1892, pp. 23, 72.
[11] Guía Oficial, 1898, p. 125.

gat,[1] an island just north of the northern extremity of Mindanao. In Negros, as I learned from Governor Larena, alluvial gold is found in two rivers. One of them is the Nabulao, in the western portion of the island, and the other is the Zamboanguita, at the southern extremity. In Joló also gold is known to exist; at least, so I was assured while there.

COPPER.

The only copper deposits which are known to be important are in the Province of Lepanto, near Mount Datá (latitude 16° 57′), and these are also the only ones concerning which any detailed information is available. They have been reported upon by Antonio Hernandez,[2] who visited them in 1850, and by José Maria Santos,[3] who examined them in 1861. They have been worked by that strange tribe of natives, the Igorrotes, probably before the Spanish discovery of the archipelago, and ever since. For a time they were also exploited by the Cantabro-Filipina Company of Mancayan, under the direction of Santos, whose death would appear to have crippled the enterprise.[4] Preliminary work commenced in 1856,[5] but production did not begin till 1864. From that year to 1874, 1,116 metrical tons (at 1,000 kilos) was produced,[6] but when von Drasche visited the place, in the winter of 1875–76, no work was going on. I have not heard that the company has ever resumed. A difficulty, and seemingly the chief one, is the inaccessible position of the mines on the divide between the headwaters of the Agno and the Abra.[7] When narrow-gauge railways pass up these valleys the question of transportation will be solved.

The chief deposits are at Mancayan, but in the same region there are veins also at Suyuc, Bumucun, and Agbao. These latter carry ores differing somewhat in composition from those of Mancayan, and, in the opinion of Santos, could be mixed with those of the greater deposit to advantage. Mancayan lies about 5 miles west of Datá, and the other localities can most easily be placed with reference to it.

As Santos describes Mancayan,[8] the veins would seem to be associated with a mass of quartz-porphyry, either caught up in an eruption of a neo-volcanic rock or bounded by parallel fissures through which lava has been extruded. It may be somewhat difficult to regard this view as final, but it seems more acceptable than Mr. von Drasche's assertion that the veins lie a lens of quartz embedded in trachyte.

The following notes are taken from Santos and for the most part are

[1] Compendio de geografía, 1892, pp. 23, 72; and Sainz de Baranda, Cons. geogn., etc., 1841.

[2] Revista minera, Madrid, Vol. II, 1851, pp. 112–118.

[3] Informe sobre las minas de cobre. . . . en Lepanto, Manila, 1862.

[4] Centeno, Memoria geológico-minera de las is. Fil., 1876, p. 44.

[5] Santos, Informe, p. 20.

[6] Centeno, op. cit., p. 45.

[7] The altitude does not seem to have been determined. I was told in Manila that it is about 5,000 feet.

[8] Op. cit, pp. 25 et passim.

literally translated. The Mancayan deposit appears in a deep ravine called Fabio or Magambang, on the south side of Mount Aban, one of the western spurs of the great Datá. At this locality there is a quartzose mass in a vertical position, not more than 80 or 100 meters in thickness, which strikes northwest and is exposed at the southeast by a great cut, partly due to the mining operations of the natives. Toward the northwest it is partially concealed and at a distance of 400 meters disappears under argillaceous porphyry,[1] which is more recent. The siliceous mass is of similar character throughout its extent; it is sometimes compact, sometimes crystalline, often porous, and always charged with iron pyrite. It contains decomposed feldspar in irregular veins or porphyritically disposed. The croppings are of columnar form. The whole mass is fissured or jointed in different directions, though the principal ore-bearing fissures strike WNW. On the strike of the quartzose mass, some 14 meters to the northwest, there are, as it were, small islands of quartz-porphyry in the argillaceous rock, which latter is there of small thickness. From these conditions it is to be inferred, according to Santos, that the quartzose mass under discussion, inclosing the ore deposits, is a body of quartz-porphyry completely metamorphosed by the advent of the argillaceous porphyry and subsequently by the process of ore deposition. Be the origin of the compact quartz what it may, it is at all events older than the argillaceous porphyry. This, by its own intrusive force and by the contraction attending its consolidation, produced the fissures or cracks, not only cleaving the quartz but continuing into its own mass; and these openings were filled with ore subsequently to the complete consolidation of the rock. Mr. Santos was led to this conclusion from inspection of a drift on a vein which, after passing out of the quartzose mass, followed the contact between it and the porphyry and at last struck into that rock, the strike of the vein making changes of direction to correspond with the course indicated. In the more important workings it is apparent that the ore occupies not only the larger fissures, which strike WNW., but also veins which have a different direction, the two systems forming a network or reticulated vein. At the time of Mr. Santos's visit three parallel veins were exposed, dipping at 70° to the NNE. They had a mean width of 1 foot. He inferred from the croppings and the old workings of the Igorrotes that there must be not fewer than six veins. As ores Santos recorded tetrahedrite, both antimonial and arsenical, chalcopyrite, chalcosite, peacock ore, the black oxide, and other oxidized or carbonated species, as well as iron pyrite. The chief ore is tetrahedrite. The gangue he calls white clay. Comb or ribbon structure is common and the proportion of the various cupriferous minerals is very variable.

[1] I understand Santos to mean by this term a quartzless, partially decomposed lava, which he, as well as von Drasche, regarded as trachyte.

Santos[1] made an effort to avoid the tendency to select rich specimens in sampling, and gives the following as the mean composition of the different ore breasts of the native workings:

Mean composition of the ore breasts of the native Mancayan copper workings.

	Per cent.		Per cent.
Copper	16.64	Iron	1.84
Silica	47.06	Loss	0.25
Sulphur	24.44	Total	100.00
Antimony	5.12		
Arsenic	4.65		

After a preliminary sorting, which takes place in the mines, about 40 per cent of the ore carries over 10 per cent of copper, and more than half the ore contains above 6 per cent of metal.

Mr. Carl Zerrener[2] described enargite and covellite from specimens of Mancayan ores in 1869, and Mr. A. Weisbach in 1874,[3] from similar specimens, established the species luzonite, which he regarded as dimorphous with enargite. Mr. August Frenzel also has described the luzonite and other ores from Mancayan, as well as the matte.[4]

Mr. von Drasche visited Mancayan and made the following note:[5]

Mancayan was formerly the site of extensive copper-mining operations, which are now discontinued. The ore was known to and worked by the Igorrotes before the coming of the Spaniards. I am indebted to the friendly communicativeness of two Spaniards who were working over old dumps for some information about the occurrence of the ores, and I also went through some of the tunnels. The copper ores occur in a quartz lens embedded in sanidine-trachyte, the lens having, on the whole, an E.-W. elongation. In this ore [apparently misprint for quartz] the ores occur in parallel veins, which likewise strike east and west, so that the tunnels, which run north and south, cut all the veins. The veins are said to be locally as much as 7 meters wide, and have a steep dip. The distance separating these very regular veins is reported as generally very small. The ores are chiefly luzonite, enargite, and covellite, the first often in fine crystals. I also observed barite, calcspar, copper pyrite, malachite, stalactites of copper sulphate, arsenious acid, and a saponite-like mineral stained blue with copper salts.

Suyuc lies 3 or more miles by road southeast of Mancayan. Here the porphyry, instead of being argillaceous, becomes feldspathic and, according to Santos, is trachyte. Sometimes it is so granular as to be easily confounded with syenite. The copper ores contain peacock, chalcosite, and black oxide, but consist chiefly of mingled copper pyrite and iron pyrite. They occur in veins and are associated with a white, opaque, feldspathic mass full of veinlets of quartz and iron oxides. The Igorrotes have worked these deposits, but not extensively.

Three miles eastward of this deposit lies Bumucun. Here there is a vein at the bottom of a stream containing chalcopyrite, quartz, and fluorspar with smaller quantities of derivative copper ores. The vein

[1] Informe, p. 38.
[2] Berg- und hüttenmännische Zeitung, 1869, pp. 105, 113.
[3] Min. Mittheil., suppl. to K.-k. geol. Reichsanstalt, 1874, p. 257.
[4] Min. Mittheil., 1877, pp. 203–204.
[5] Fragmente, 1878, p. 36.

is 8 or 10 inches in width, strikes E., and dips N. almost vertically. The natives were able to go down only some 30 feet on account of water. This ore and that of Suyuc would, in Santos's opinion, be valuable at Mancayan, because they contain no antimony, little arsenic, and plenty of iron.

Agbao is a mile and a half south of Suyuc. It has three small veins within 3 feet, separated only by clay. They aggregate only 6 inches in width, strike NE., and dip SE., at 45°. The ore is tetrahedrite.

The copper mining and smelting of the Igorrotes is a very curious and interesting matter. This tribe is in most respects semibarbarous. They are heathens and live in squalor. Semper visited them and furnishes a really disgusting description. He also points out, however, that industrially they stand on an astonishingly high level, and show most remarkable skill in the working of metals as well as in their extraction. They have turned out not merely implements of small dimensions, but copper kettles no less than 3½ feet in diameter. From 1840 to 1855, according to Santos, as much as 20 tons of copper utensils and ingots were exported annually by the Igorrotes. They made pots, tobacco pipes, and ornaments. It was this trade which drew the attention of the Spaniards to the region. It was the opinion of Santos that the Igorrotes have Chinese or Japanese blood, and it is commonly believed that they are descended from Chinese invaders who brought the art of smelting with them. Their appearance and their customs are considered as indicating such an origin.

Their mining and metallurgy were first investigated by Hernandez, later and more fully by Santos. It is almost humiliating to find how well up in technology these dirty savages are, but perhaps the great discoveries in copper smelting have been common property ever since the age of bronze.

The following account is almost literally translated from Santos's memoir:

The ore-bearing territory is divided among the neighboring villages in proportion to the number of inhabitants, and any attempt to shift the claim limits leads to bloodshed. The property of each village is again divided among certain families, in consequence of which the district looks like a honeycomb. Winning in is accomplished by firing—[1] that is, by kindling a fire at suitable spots against the breasts, so that the tension of the aqueous vapor developed in the ore may split off flakes, this operation being assisted by the use of iron tools. The first sorting takes place in the mines, the rejected portion being left on the floor and so raising it that at subsequent firings the flame of the billets licks the face and much of the roof. The character of the rock and the imperfect nature of the process led to many cases of caving, some

[1] In 1869 I witnessed firing in the Rammelsberg mine at Goslar. It was there practiced only on Sundays. It is doubtless one of the oldest technical processes known to man.

of large extent. The ores won were classified into rich stuff and quartzose ore. The former went directly to the furnace, while the latter was subjected to a long and thorough roasting, during which, after a part of the sulphur, antimony, and arsenic had been volatilized, a sort of sweating of iron and copper sulphides took place. These substances united in globules of matte, which adhered to the exterior of the quartz fragments and, in great part, could then be separated from the gangue.

The furnaces consisted of circular depressions in a clay floor, and were 15 cm. in depth, with a diameter of 30 cm. A nozzle of fire clay, standing at an angle of 30° above the hole, united two bamboo pipes which were fitted into the lower ends of two cylinders made of pine logs, containing pistons packed with grass, which moved alternately up and down, furnishing blast.[1] When the furnace was ready they charged it with 18 or 20 kilos of rich or roasted ore, which, according to repeated assays, contains 20 per cent of copper, taking the remarkable scientific precaution to place the ore at the nozzle and the fuel against the wall of the furnace, this wall consisting of uncemented stones piled to a height of half a meter. After the fire was lighted and the blower put in operation, thick white and orange-colored fumes were thrown off, these being due to the partial volatilization of the arsenic, antimony, and sulphur, until at the end of an hour only sulphur dioxide was given off; and the temperature had reached the highest possible point. The blast was then stopped and the product removed. This consisted of slag (or rather of lumps of ore which on account of the quartz gangue were reduced to a porous mass through the eliquation of the metallic sulphides, and were not scorified because of lack of bases and of a sufficiently high temperature) and a very impure matte, weighing 4 or 5 kilos, with a content of 50 to 60 per cent copper. This matte, with that produced at other similar runs, was roasted in a strong fire for twelve to fifteen hours, with the result that a great part of the three volatile substances mentioned above was dissipated.

In the same furnace they set on edge the cakes of roasted matte, being careful in this operation also to place the charcoal against the wall, and, after blowing half an hour, obtained, first, slag consisting of a silicate of iron with indications of arsenic; second, a matte with 70 to 75 per cent of metal, which they took off in very thin crusts by means of sprinkling the exposed surface with water; third, black copper, more or less in quantity according to the degree of desulphurization of the material smelted, but always impure. The mattes obtained in this second operation were again roasted, with the precaution that the wood was interposed between the crusts to avoid fritting before the fire had driven off the objectionable components.

[1] This is a well-known Chinese blast engine, such as I have seen at the tin-smelting works in Bangka. It was in use in China long before bellows were abandoned in European works.

To avoid loss through oxidation in casting copper, either black or refined, they covered the furnace with a helmet-shaped fire-clay crucible, thus making it easier to lade the metal into molds of the same clay.

The black copper obtained at the second heat, and the matte from it also, but only after previous roasting, were submitted to a third smelting in the same furnace, this being reduced in size by the stone wall and by the addition of the crucible mentioned above. This heat produced an iron-silicate slag, and a black copper, which, after casting in clay molds, was forthwith disposed of commercially. This black copper contained 94 per cent copper and was rendered impure by yellow carbide of the metal and the oxide, formed superficially during slow cooling despite the precautions taken to avoid it by whipping the exposed surface with green boughs.

If the copper is to be employed to manufacture pots, pipes, or other household utensils and ornaments which these natives make with so much patience and skill, they apply a refining process differing from the preceding in only one feature: the amount of charcoal is diminished and the quantity of air increased, as the end of the heat is approached, for the purpose of oxidizing the carbide of copper.

Repeated assays have proved that, even when they treated ores with a mean content of 20 per cent, they got only 8 or 10 of black copper at the third heat.

Concerning the remaining copper deposits in the Philippines, scarcely anything is known except the localities in which they are to be found. In Mr. Abella's summary of mineral resources, in the Guía Oficial, he states that there is copper at Antamoc and at Casalugan in Benguet, but gives no details. In 1823 copper-mining concessions were applied for to work two deposits in a mountain called Taloo, near Antimonan, in Tayabas Province.[1] It is, perhaps, a legitimate inference that these localities are in the small area of crystalline schists there noted by Mr. von Drasche. At the same time application was made for claims 3½ miles south of Mambulao, at Iba, and on the Gulf of Guinobatan, 5 miles south-southwest of Mambulao. These places are in the Province of Camarines Norte and in the schist area. Jagor states that there was a shaft at the Iba locality said to be 84 feet deep. Two copper localities are marked on Mr. d'Almonte's map in Camarines Sur, east of the town of Caramuan, or Caramoan, near the shore of the channel which separates Catanduanes from Luzón. Roth refers to the copper of Caramuan as an indication that the mountains at this point are composed of crystalline schist. Jagor saw specimens of native copper coming from a locality north of Patag Cove.[2] This corresponds to one of the mines laid down on Mr. d'Almonte's map.

In the Island of Masbate, at Milagros, near Assit, native copper was

[1] Centeno, Memoria geológico-minera, 1876, p. 45. Several of these miscellaneous notes are from the same source.

[2] Jagor. Reisen, 1873, pp. 145, 347.

discovered in 1847. Centeno saw fine specimens. This mine was worked for a time, but the ore gave out or was lost. Masbate also contains gold, and the occurrence of these metals suggests a crystalline schist area in this little-known island. On the Island of Capul, between Sámar and Luzón, Centeno also notes copper pyrites.

In Panay Mr. Abella met with no deposit of copper, but saw stains at Mount Carauisan, latitude 10° 50′, Province of Antique. He thinks this corresponds to a report by the provincial governor in 1842 of the discovery of an extensive deposit a league from the town of Sibalom. From the natives of the region he could ascertain nothing about this ore. At Barbaza, in latitude 11° 12′, in the same province, Mr. Abella met a native who owned a specimen of native copper the source of which he refused to disclose, though stating that it was not very far away.[1]

In the Island of Marinduque, at Torrijos, the Guía Oficial states that copper occurs, without further information. At Lubang, on the island of the same name to the northwest of Mindoro, Dana found copper pyrite, probably only as an accompaniment of the gold.[2]

That copper pyrite is met with in the Surigao Peninsula of northern Mindanao among the gold fields is known. According to the geography of the Jesuit fathers, there is a workable deposit of good quality at the hamlet of Taganaan, 3 leagues from the town of Surigao. A merchant resident in Palawan informed me that there is copper in Balábac.

ARGENTIFEROUS LEAD.

Galena is found in Camarines Norte in the area of the crystalline schists accompanying other sulphurets and gold. Concessions have been granted for lead mining at a mountain called Tingá, near Paracale, and at a hamlet named Imbong-imbong, in the township of Mambulao, but these ores were worked only for the gold. Centeno reports the Tingá occurrence as very rich, but the veins as only from 3 to 10 centimeters in width.[3] Paracale and Mambulao have a reputation among mineralogists as a source of lead chromate and vauquelinite. Jagor visited two localities, but found the specimens practically exhausted. One is near Paracale, in a gneiss hill ten minutes' walk from the village of Malaguit. The other is a mile and a half north by east from Mambulao, in the plumbiferous mountain Dinianan, which is composed of hornblende-schist. Roth states that the chromate is found in quartz veins and is accompanied by vauquelinite, like the occurrence in the Ural Mountains.[4] Caramuan, in Camarines Sur, is credited with lead ore in the Guía Oficial. It is probably associated with the copper deposits in that district.

[1] Isla de Panay, p. 197.
[2] U. S. Expl. Exp., Vol. X, 1849, p. 539.
[3] Memoria geológico-minera, 1876, p. 53; Guía Oficial, 1898, p. 127.
[4] Jagor, Reisen, 1873, pp. 144–145, 345.

In the Island of Marinduque, Province of Mindoro, at Torrijos, there is a lead deposit regarded by Mr. Espina as important.[1] The assays are said to give, for average ore, 56.55 per cent lead, 0.0096 per cent silver, and 0.0006 per cent gold. No further information is available.

Cebú contains lead ores upon which Mr. Abella has reported thus:[2]

The most important metalliferous deposits, and indeed the only ones which deserve the name, yet discovered in the island are those of gold- and silver-bearing galena. They lie toward the center of the island, at Panoypoy, township of Consolación, and at Acsubing and Budlaan, in the township of Talamban, the first two being those which gave rise to the claims of the company known as *La Cebuana*. The deposits all consist of bunches, veins, and stringers of pyritous galena, which form an irregular network in the rock complex of the eastern area of the interior of the island. They lack system or regular direction, and form therefore a true *Stockwerk*.

Centeno found the ore extremely rich in silver and gold, but mining seems to have been abandoned.

In Mindanao Mr. Espina saw specimens of lead ores, but was unable to ascertain whence they came.

IRON.

Something like a belt of magnetite deposits exists among the mountains lying to the east of the great plain of Luzón. The northern portion of this belt is 12 or 15 miles to the eastward of San Miguel de Mayumo, on the headwaters of the stream which passes through that place. In this neighborhood the positions of four mines are indicated on Mr. d'Almonte's map. A few miles east of south from this group lies a second, about 10 miles northeast of Angat. Here also four mines are shown, and this district has the reputation of possessing the most valuable iron ores in the archipelago. At a similar distance to the northeast of Bosoboso another iron mine has been worked. Ten miles north of east from Mórong there is still another iron mine, in the Province of Laguna de Bai. All of these deposits are in the foothills of the range which forms the western boundary of the Province of La Infanta and at nearly equal distances from the crest. The belt is 44 miles in length, and evidently stands in genetic relations to the range. According to assays made in the laboratories of the Inspección General de Minas, the Angat ores carry from 60 to 70 per cent of iron. The impurities do not seem to have been determined. I find in so serious a paper as Centeno's Memoria the statement that these ores contain 75 to 80 per cent of iron; but magnetite, though the richest of iron ores, can not contain more than 72 per cent of iron, as should be well known. Of the nature of the deposits I have been able to obtain no descriptions, except that the ore is abundant.

In Camarines Norte there is a mine of magnetic iron some 6 miles

[1] Espina, Bosquejo, 1898, p. 165. [2] Isla de Cebú, 1886, p. 146.

south of Paracale on the Malaguit River. The Guía Oficial also mentions a deposit in the township of Mambulao at Calambayungan.

The Filipinos work the ores of Angat and of San Miguel de Mayumo. Unfortunately I did not succeed in seeing the process or in getting any satisfactory description of it. There is no doubt, however, that it is a bloomery process. The steel produced is chiefly made into plowshares, which are so good that they bring a much higher price than those of European manufacture. The process is probably nearly identical with that still in use in Borneo; but, if not, it would be most interesting to know what are the differences. I therefore make no apology for introducing here Mr. Posewitz's description, in which he follows C. H. L. M. Schwaner, who witnessed it:[1]

The cylindrical blast furnace has a height of 3 feet 4 inches and a circumference of 10 feet. The shaft has the form of a parallelopiped (8 by 6 inches) and becomes wider toward the top, having a pyramidal form. The smelting hearth is 25 inches long, 19 inches wide, and 9 inches high.

The material of which the furnace is constructed is a yellow clay, which is obtained from the banks of the rivers.

This material, having been kneaded and purified, is pressed in a cylindrical bark[2] mold having the dimensions of the furnace. It is allowed to dry for a month or more. The mold is then removed and the furnace bound round with Spanish cane (rattan), in order to give it greater strength and to provide against bursting. The dry-air process is completed by a small fire.

The smelting only lasts one day. The floor of the hearth is first covered with powdered charcoal to a depth of 2 inches, in the middle of which a hole is made, which serves to collect the iron. The tapping hole is closed by clay. A semicircular hole is left to let out the slag. The blast apparatus consists of a hollow tree stem, 5 feet 5 inches long and 3 inches in circumference [diameter?], open at the top and closed at the bottom. Directly above the floor there are 3 openings on the same level and close to one another. These openings are intended for the insertion of 3 bamboo tubes, 29 inches in length, through which the blast has access to the tuyers and to the furnace. The tuyers are made of baked clay. They are 11 inches in length, and narrow considerably in the part opening into the furnace. In the bellows there is a valve, which is made air-tight by feather down. It is worked by hand.

Burning charcoal is thrown from above into the furnace, and a gentle blast produced sufficient to cause the charcoal layer to glow. The furnace is then filled to two-thirds of its height with wood charcoal. The ores are first submitted to a roasting action by piling them up in layers between wood, igniting the pile, and allowing it to burn one day. The ore is then broken into pieces of the size of a nut, mixed with charcoal in the proportion of 1 to 10, and thrown into the furnace. Usually two hours and a half suffice to sink the ore, after which more ore and coal are added.

The slag is run off at intervals of twenty minutes, the tuyers being removed and the blast stopped for five minutes while the slag is running off. A drawback to this method is that a large part of the iron goes into the slag.

As soon as all the fuel is burned the tuyers are taken out and the stopping of the hole in the hearth removed. The iron, which is in the form of a viscid, molten

[1] Posewitz, Borneo, 1892, p. 433. In A. Marche, Luçon et Palaouan, Paris, 1887, p. 85, I find brief notes on the process at Angat, which seem to indicate that the process there employed is substantially the same as in Borneo.

[2] The English translation has cork, by error, for bark.

mass, is then drawn out of the furnace by means of wooden tongs, placed on a finely broken slag, and beaten with wooden hammers until it becomes smooth.

Such a mass, weighing 45 pounds, represents a day's work for four men, and costs 2 florins. It contains much slag, however, and, having been divided into ten parts has to be several times remelted and beaten with hammers until it is pure enough for smithy work.

While iron smelting has almost entirely ceased, this is not the case with the smithy work. Weapon smiths still exist who manufacture excellent blades. Especially worthy of mention are the works of the great industrial place, Negara, in south Borneo, of which the "Negara blades" have a widespread reputation.

The natives prefer their own iron to the European, as experience teaches that the keenness and durability of these weapons are superior to those of European manufacture.

MISCELLANEOUS.

Petroleum has been discovered within a few years in the islands of Panay, Cebú, and Leyte, but is not as yet known elsewhere. In Panay it is found at Janiuay in the Province of Iloilo and is accompanied by natural gas. I have not heard that it is exploited. In Cebú oil is found on the west coast, at Asturias, Toledo, and Alegria. The well at Toledo (10° 17′) has been exploited to some extent,[1] and there is a concession for oil and one for coal at the same locality in this township. An oil concession has also been granted at Alegria. In Leyte oil occurs in the township of San Isidro, and has been taken up. This is probably the locality marked as a petroleum mine on Mr. d'Almonte's map on the west coast, in latitude 11° 15′, though this is closer to Villaba than to San Isidro del Campo. Mr. Espina states that petroleum from near Villaba is highly charged with paraffin.

Sulphur has been extracted under concession only at Bilirán, but the volcanoes and solfataras of the islands offer endless opportunities for "clandestine exploitation" all the way from Mount Apo, in Mindanao, to the volcano of Cagua,[2] near the northern extremity of Luzon. Jagor[3] gives a pleasant account of sulphur extraction a little south of Buráuen, in Leyte.

There have been various reports of the discovery of quicksilver in the Philippines; e. g., in Panay, Mindanao, and in the Province of Albay. All seem to be founded on accidental losses of exotic metal.

Excellent marble is found on the Island of Romblón, to the north of Panay. It is used in Manila for fonts and the like. In Cebú also there is a concession for marble at Tuburan (10° 43′). Marbles for building are quarried at Montalbán and at Binangonan (the nummulite locality) in Manila Province.

Kaolin is found at Los Baños, Laguna Province, and fictile clays at numberless points.

Stibnite from Bataan Province was seen by Centeno,[4] but there is no evidence that any valuable deposit occurs. So, too, zinc blende is known to exist, but only as a valueless sulphuret in gold-quartz veins.

[1] Guía Oficial, 1898, p. 128. [2] Ibid., p. 127. [3] Reisen, 1873, p. 221. [4] Mem. geol-min., 1876, p. 53.

LIST OF BOOKS AND PAPERS ON PHILIPPINE GEOLOGY.

In the following list titles have been given somewhat fully, to facilitate reference, particularly at a distance from great libraries. In the preparation of this report all of the papers here listed, except one, have been consulted at first hand or in complete reprints, and I know of no other works of any value on the subject except two or three mine reports. In the text a number of works are referred to which deal with Malaysian geology, but not with that of the Philippines. Of these only Hochstetter, Posewitz, and Martin are catalogued here. The volume of Posewitz on Borneo makes an excellent introduction to Malaysian geology.

It should be noted that when a Spanish writer uses a double surname the latter is his mother's maiden name. The matronymic is not always employed; for instance, Centeno sometimes adds "y García" to his patronymic, but more often omits it. If in citations only one name is used, it must be the first and not the second.

1574. RIQUEL, HERNANDO. Very true and certain account of that which has newly been known of the new islands of the West, and of the discovery which they mention of China, which was written by H. R. secretary of the governor of them. Seville, Barrera, 1574. Broad sheet.

In English trans. of Morga, Sucesos, app. 4, p. 389.

1609. MORGA, ANTONIO DE. Sucesos de las islas Filipinas, Mexico, en casa de Geronymo Bahi, Ano 1609. Por Cornelio Adriano Cesar. 4°, 10 p. l. and 172 leaves.

This rare book may be seen in the library of Harvard College.

1698. GASPAR DE SAN AVGVSTIN. Conquistas de las islas Philipinas [sic]; la temporal por las armas del Señor Don Phelipe [sic] segundo el prudente y la espiritval, por los religiosos del orden de nuestro padre San Augustin; fvndacion, y progressos de sv provincia del santissimo nombre de Jesus. Parte primera. Madrid, Mvrga, 1698. Fol., 544 pages; index and preliminary matter not paged.

1792. JUAN DE LA CONCEPCIÓN. Historia general de Philipinas [sic]. Sampaloc, Moriano, 1792. Sm. 4°, 14 v.

Great eruption of Taal in 1754 described, v. 13, pp. 345–350.

1803. MARTINEZ DE ZÚÑIGA, JOAQUÍN. Historia de las islas Philipinas. Sampaloc, Argüelles, 1803. 8°, iv, 687 pp.

1814. MARTINEZ DE ZÚÑIGA, JOAQUIN. Historical view of the Philippine Islands; trans. from Spanish original of 1803 by John Maver. London, 1814. 8°, 2 vols.

1817. HORSBURGH, JAMES. The India directory, or directions for sailing to and from the East Indies. 2d ed. London, 1817.

Philippines, p. 328, where the volcanoes of the Babuyanes are mentioned.

1825. BUCH, LEOPOLD VON. Physicalische Beschreibung der Canarischen Inseln. Berlin, Academie, 1825. 4°.

Philippine volcanoes, pp. 375–378.

There is a French translation, Paris, Levrault, 1836, 8°, in which the passage relating to the Philippine Islands begins p. 437.

1829. CHAMISSO, A. VON. Bemerkungen und Ansichten auf der Entdeckungsreise von O. v. Kotzebue. 1829.

Philippines, v. 3, p. 92.

1829. HOFMANN, ERNST. Geognostische Beobachtungen aufgestellt auf einer Reise um die Welt in den Jahren 1823 bis 1826 unter dem Befehl . . . von Kotzebue.

In Archiv für Mineralogie, Geognosie, Bergbau, und Hüttenkunde, von C. J. B. Karsten, Berlin, 1829, 8°, v. 1, pp. 243–315.

Philippines, pp. 312–315, in which Taal and other volcanic masses are described.

1832. BERGHAUS, HEINRICH. Geo-hydrographisches Memoir zur Erklärung und Erläuterung der reducirten Karte von den Philippinen und den Sulu-Inseln (No. 13 von Berghaus' Atlas von Asia). Gotha, Perthes, 1832. 4°, 114 pp.

1835. MEYEN, F. J. F. Reise um die Erde . . . auf dem . . . Schiffe *Prinzess Louise* in den Jahren 1830–1832. Berlin, Sander, 1835. 4°.

Philippines, 2d part, p. 237.

1841. SAINZ DE BARANDA. Constitución geognóstica de las islas Filipinas.

In Anales de Minas, Madrid, 1841, 8°, v. 2, pp. 197–212.

Volumes 1 to 4 of this journal are in the library of the Museum of Comparative Zoology, Cambridge, Mass., and no more were published. They contain no other papers by this author.

1843. DELAMARCHE. On Taal Volcano in 1842.

In Comptes Rendus . . . Académie des Sciences, Paris, 1843, 4°, v. 16, p. 756.

Substantially the same account by Delamarche is printed in Bulletin de la Société de géographie de Paris, v. 19, 1843, p. 79.

1844. CHEVALIER, E. Voyage autour du Monde, exécuté pendant les années 1836 et 1837 sur la corvette "*La Bonite.*" Géologie et Minéralogie. Paris, 1844. 8°.

Chapter IX, pp. 231–256, deals with the geology of Mariveles, Manila, and Laguna de Bai.

1845. ITIER, JULES. Fragment d'un journal de voyage aux îles Philippines.
In Bulletin Société de géographie, Paris, 1845, 8°, s. 3, v. 5, pp. 365–389.

1846. ———. Extrait d'une description de l'archipel des îles Solo.
In Bulletin de la Société de géographie, Paris, Bertrand, 1846, 8°, s. 3, v. 5, pp. 311–319.

1849. DANA, J. D. U. S. Exploring Expedition during the years 1838–1842, under the command of Charles Wilkes, U. S. N. 4°. v. 10, Geology. Philadelphia, Sherman, 1849.
Philippines, pp. 539–548.

1850. BUZETA, MANUEL, and BRAVO, FELIPE. Diccionario geográfico, estadístico, historico de las islas Filipinas. Madrid, Peña, 1850. 8°, 2 v. (Half-title gives date of 1851).

1851. HERNANDEZ, ANTONIO. Report on copper in the district of Lepanto [Spanish].
In Revista minera, Madrid, v. 2, 1851, 8°, pp. 112–118.
This is much less detailed than Santos's paper of 1862 on the same subject.

1855. HUERTA, F. DE. Estado geográfico, topográfico, estadístico de . . . las islas Filipinas. Manila, 1855.
Geological notes passim.

1855. LA GIRONIÈRE, P. DE. Aventures d'un gentilhomme breton aux îles Philippines, avec un aperçu sur la géologie, etc. Paris, Lacroix-Comon, 1855. 8°.
Contains only loosely stated reports of no value. His communications to Perry are no better.

1858. HUMBOLDT, A. VON. Kosmos. Stuttgart, Cotta, 1858. 8°, 4 v.
Philippines, v. 4, pp. 404–409.

1859. HOCHSTETTER, F. VON. Schreiben an A. von Humboldt.
In K.-k. Akademie der Wissenschaften, Sitzungsberichte. Wien, 1859, 8°, v. 36, pp. 121–141.
This is a report on the volcanoes visited during his cruise in the *Novara*. Luzón, pp. 130–138.

1860. PERRY, ALEXIS. Documents sur les tremblements de terre et les phénomènes volcaniques dans l'archipel des Philippines. 4th part. Extrait des Annales de la Société d'émulation des Vosges, v. 10, 3d part, 1860, 8°, 110 pp., 1 map.

1861. SEMPER, CARL. Reise durch die nordöstlichen Provincen der Insel Luzón.
In Zeitschrift für allgemeine Erdkunde, neue Folge, vol. 10, Berlin, Reimer, 1861, 8°, pp. 249–266.
On this journey Semper collected important Miocene fossils near Minanga.

1862. RICHTHOFEN, F. VON. Vorkommen der Nummulitenformation in den Philippinen.
In Zeitschrift der Deutschen geologischen Gesellschaft, Berlin, Hertz, 1862, 8°, v. 14, pp. 357–360.

1862. SANTOS, JOSÉ MARÍA. Informe sobre las minas de cobre de las rancherías de Mancayan, Suyuk, Bumucun y Agbao en el Distrito de Lepanto, ilas de Luzón de las Filipinas. Manila, Press of the College of Santo Tomás, 1862. 8°, 72 pp.

1862. SEMPER, CARL. Reise durch die nördlichen Provinzen der Insel Luzón.
In Zeitschrift für allgemeine Erdkunde, neue Folge, v. 13, Berlin, Reimer, 1862, 8°, pp. 80–96.
This paper deals with northwestern Luzón and the raised atoll of Benguet.

1866. HOCHSTETTER, F. VON. Reise der österreichischen Fregatte *Novara* um die Erde, geologischer Theil. Wien, Government, 1866. 4°, v. 2.
This volume contains nothing about the Philippine Islands, but gives author's divisions of the Tertiary, p. 149.

1868. MORGA, ANTONIO DE. The Philippine Islands . . . . Translated from the Spanish . . . by H. E. J. Stanley. London, Hakluyt Society, 1868. 8°, xxx, 413 pp.
This is a translation of Sucesos de las Islas Filipinas. It contains some appendices of value.

1869. SEMPER, CARL. Die Philippinen und ihre Bewohner; sechs Skizzen. Würzburg, Stuber'sche Buchhandlung, 1869. 8°, 143 pp., 1 map.
These interesting lectures deal with volcanoes and coral reefs, besides other matters. In the appended notes is included the author's paper on the coral reefs of the Pelew Islands, from Zeitsch. f. wiss. Zool., v. 13, pp. 563–569.

1869. ZERRENER, CARL. Nachricht über eine Anzahl aus verschiedenen Gegenden der Erde bei mir eingegangener interessanter Mineralien.
In Berg- und Hüttenmännische Zeitung, Leipzig, Felix, 1869, 4°, pp. 105–106.
In this paper copper ores from Mancayan are described.

1873. JAGOR, F. Reisen in den Philippinen. Berlin, Wiedmannsche Buchhandlung, 1873. 8°, xvi, 381 pp., 1 map.
This very important work contains among the appendices the papers of Roth and Virchow catalogued separately. An English translation exists, but is said to be bad and to omit the appendices. There is also a Spanish translation, which I have not seen.

1873. ROTH, JUSTUS. Ueber die geologische Beschaffenheit der Philippinen.
In JAGOR, F., Reisen, 1873, pp. 333–354.
This paper includes most of the essential facts known at the time it was written, and contains Roth's discussion of Jagor's lithological collection, with some paleontological notes by E. von Martens.

1873. VIRCHOW, RUDOLF. Ueber alte und neue Schädel von den Philippinen.
In JAGOR, F., Reisen, 1873, pp. 355–377.
This paper discusses particularly the Negritos. Virchow has since published other papers on the Philippine races, which, however, are scarcely geological. See Zeitschrift für Ethnologie, v. 15, 1883, p. 465; Sitzungsberichte der K. preussischen Akad. der Wiss., Berlin, 1897, p. 279; ibid., 1899, p. 14, etc.

1874. DARWIN, CHARLES. Structure and distribution of coral reefs. 3d ed., New York, Appleton, 1889. 8°.
Philippines, p. 180, where Cuming's observations are recorded, and map.

1874. MINARD, ——. Sur les gisements d'or de Philippines.
In, Bulletin Société géologique de France, Paris, the Soc., 1874, s. 3, v. 2, pp. 403–406.

1876. MENDEZ DE VIGO. Historia geográfica, geológica y estadística, de Filipinas. Manila, 1876. 8°, 2 v., maps.
Geological notes passim.

1876. CENTENO Y GARCÍA, JOSÉ. Ministerio de Ultramar. Memoria geológico-minera de las islas Filipinas. Madrid, Tello, 1876, 8°, viii, 64 pp., 1 map.
This appeared separately and also in Boletín de la Comisión del Mapa Geológico de España, v. 3, 1876.

1876. DRASCHE, RICHARD VON. Ausflüge in die Vulcangebiete der Umgegend von Manila.
In Verhandlungen der K.-k. geologischen Reichsanstalt, 1876, 8°, pp. 89–93.

1876. ———. Mittheilungen aus den Philippinen.
In Verhandlungen der K.-k. geologischen Reichsanstalt, 1876, 8°, pp. 193–198.

1876. ———. Aus dem Süden von Luzón.
In Verhandlungen der K.-k. geologischen Reichsanstalt, 1876, 8°, pp. 251–255.

1876. ———. Einige Worte über den geologischen Bau von Süd-Luzón.
In Mineralogische Mittheilungen gesammelt von Gustav Tschermak, Wien, Hölder, 1876, 8°, v. for 1876, pp. 157–166.
This volume of Mineralogische Mittheilungen appeared also as supplement to K.-k. geologische Reichsanstalt, Jahrbuch, v. 26, 1876.

1876. WALLACE, A. R. Geographical distribution of animals. New York, Appleton, 1876. 8°, 2 v.

Philippines, v. 1, pp. 345 and 359.

1877. FRENZEL, AUGUST. Mineralogisches aus dem ostindischen Archipel.

In Mineralogische Mittheilungen gesammelt von Gustav Tschermak, Wien, Hölder, 1877, 8°, v. for 1877, pp. 297–308.

Philippines, 302–304.

This volume of Mineralogische Mittheilungen appeared also as supplement to K.-k. geologische Reichsanstalt, Jahrbuch, v. 27, 1877.

1878. DRASCHE, R. VON. Fragmente zu einer Geologie der Insel Luzón (Philippinen), mit einem Anhange über die Foraminiferen der tertiären Thone von Luzón, von Felix Karrer. Vienna, Gerold's Sohn, 1878. 4°, 5 pl. (incl. 2 maps).

This book appears to include all the material of Von Drasche's earlier papers.

1878. MEYER, A. B. Earthquakes in the Philippines in 1876.

In Nature, London and New York, Macmillan, 1878, 4°, v. 18, p. 265.

Data from "Ateneo municipal." Mount Tabacon should probably be Mayón, but that mountain seems to have had no eruption in 1876.

1879. ABELLA Y CASARIEGO, ENRIQUE. Memoria acerca de los criaderos auríferos del segundo distrito del departamento de Mindanao, Misamis. Seguido de varios itinerarios geológicos referentes á la misma comarca. (Del Boletín de la Comisión del mapa geológico.) Madrid, Tello, 1879. 8°, 49 pp., 5 pl.

This is much the best authority on the gold field of Misamis, and contains suggestive remarks on the general geology of the region.

1879. ARANA, C. DE. Derrotero del archipiélago Filipino. Madrid, Government, 1879.

This is the official Spanish "sailing directions" for the Philippines; useful especially with reference to coral reefs. It contains erroneous determination of Mount Malaspina (Canlaón), viz, 1,390 meters.

1879. DRASCHE, RICHARD VON. Ueber paläozoische Schichten auf Kamtschatka und Luzón.

In Neues Jahrbuch für Mineralogie, etc., 1879, pp. 265–269.

The purpose of this paper is to suggest, on lithological grounds, that his Agno beds are Paleozoic.

1881. ———. Datos para un estudio geológico de la Isla de Luzón (Filipinas).

In Boletín de la Comisión del Mapa geológico de España, v. 8, 1881, pp. 269–342.

This is a translation of the Fragmente, 1878, and is in part very untrustworthy.

1881. OEBBEKE, K. Beiträge zur Petrographie der Philippinen and der Palau-Inseln.
In Neues Jahrbuch für Mineralogie, etc., Beilage-Band I, Stuttgart, Koch, 1881, 8°, pp. 451–501.
This is an extremely important contribution to the lithology of the Philippine Islands. The material was Semper's collection and the work was done in Rosenbusch's laboratory.

1883. CENTENO, JOSÉ. Memoria sobre los temblores de tierra ocurridos en julio de 1880 en la isla de Luzón. Madrid, Tello, 1883. 8°, 91 pp.
This paper appeared both separately and in Boletín de la Comisión del Mapa geológico de España, v. 10, 1883. It is entirely devoted to earthquakes and their causation.

1883. MEYER, HANS. Height of Datá, 2,245 m.
In Petermann's Mittheilungen aus Justus Perthes' geographischer Anstalt, Gotha, Perthes, 1883, 4°, v. 29, p. 194.
Quoting Globus, 1883, no. 11 et seq., to which I have not access.

1884. ABELLA Y CASARIEGO, ENRIQUE. Terremotos de Nueva Vizcaya (Filipinas) en 1881, informe acerca de ellos, seguida de unos apuntos físicos y geológicos tomados en el viaje de Manila á dicha provincia. Madrid, Tello, 1884. 8°, 131 pp., 1 pl. (map).
The apuntos, etc., form in fact a separate paper, quoted as such in this report. They appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 10, 1883.

1885. ———. El Mayón, ó volcán de Albay (Filipinas). Madrid, Tello, 1885. 8°, 23 pp., 2 pl.
This appeared separately and also in Boletín de la Comisión del Mapa geológico de España v. 11, 1884.

1885. ———. Emanaciones volcánicas subordinadas al Malínao (Filipinas). Madrid, Tello, 1885. 8°, 14 pp., 3 pl.
This appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 11, 1884.

1885. ———. El monte Maquilin (Filipinas) y sus actuales emanaciones volcánicas. Madrid, Tello, 1885. 8°, 28 pp., 2 pl.
This appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 11, 1884.

1885. ———. La isla de Bilirán (Filipinas) y sus azufrales. Madrid, Tello, 1885. 8°, 15 pp., 1 pl. (map).
This appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 11, 1884.

1885. CENTENO, JOSÉ. Estudio geológico del volcán Taal. Madrid, Tello, 1885. 8°, 53 pp., 4 pl.
This is much the most complete paper on the subject. It appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 12, 1885.

1885. CENTENO, JOSÉ. Noticia acerca de los manantiales termo-minerales de Bambang y de las salinas de monte Blanco. Madrid, Tello. 1885, 8°, 14 pp.

This appeared both separately and in Boletín de la Comisión del Mapa geológico de España, v. 12, 1885.

1885. JORDANA Y MORERA, RAMÓN. Bosquejo geográfico é históriconatural del archipiélago Filipino. Madrid, 1885. Fol.

Geology, pp. 115–159.

1885. MONTANO, JOSEPH. Rapport à M. le ministre de l'instruction publique sur une mission aux îles Philippines et en Malaisie (1879–1881). [Paris, Hachette, 1885.] 34 pl., 2 maps.

This work is chiefly ethnological.

1885. RENARD, A. F. Le volcan Camiguín, aux îles Philippines.

In Bulletin de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique, Bruxelles, Hayez, 1885, 8°, s. 3, v. 10, pp. 733–751.

1885. WEBSTER, H. A. Philippine Islands.

In Encyclopedia Britannica, 9th ed., Edinburgh, Black, 1885, 4°, v. 18, pp. 748–753.

Philippine geology, pp. 748–750.

1886. PLANT, FRANK S. Notes on the Philippines, with two maps.

In Journal of Manchester Geographical Society, Manchester, the Soc., 1886, 8°, v. 2, pp. 19–49.

1886. ABELLA Y CASARIEGO, ENRIQUE. Rápida descripción física, geológica y minera de la Isla de Cebú (archipiélago Filipino). Madrid, Tello, 1886. 8°, 187 pp., 6 pl., incl. map geologically colored and geological sections.

This appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 13, 1886.

1886. MONTERO Y VIDAL, JOSÉ. El archipiélago Filipino y las islas Marianas, Carolinas y Palaos, su historia, geografía y estadística. Madrid, Tello, 1886. 8°, xv, 511 pp., 2 maps.

1886. RENARD, A. F. Notice sur quelques roches des îles Cebú et Malanipa (Philippines).

In Bulletin de l'Académie royale des sciences, des lettres et des beaux-arts de Belgique, Bruxelles, Hayez, 1886, 8°, s. 3, v. 11, pp. 95–105.

1886. TENISON-WOODS, J. E. The geology of Malasia, southern China, etc.

In Nature, London and New York, Macmillan, 1886, 4°, v. 33, pp. 231–232.

1887. MARCHE, ALFRED. Luçon et Palaouan, six années de voyage aux Philippines. Paris, Hachette, 1887. 8°, 398 pp., 2 maps.

1888. SUESS, E. Das Antlitz der Erde. Vienna, Tempsky, 1888. 8°, 2 v.

Philippines, v. 2, pp. 213–217. Treats especially of alignment of volcanoes and contains good notes on the literature.

1889. GUILLEMARD, F. H. H. The cruise of the *Marchesa* to Kamschatka and New Guinea, with notices of Formosa, Liu-Kiu, and various islands of the Malay archipelago. 2d ed., London, Murray, 1889. 8°, 455 pp. and maps.

Notes on Cagayán de Joló, p. 175.

1889. POSEWITZ, THEODOR. Borneo; Entdeckungsreisen und Untersuchungen. Gegenwärtiger Stand der geologischen Kenntnisse. Verbreitung der nutzbaren Mineralien. Berlin, Friedländer, 1889. 8°.

1889. RECLUS, ÉLISÉE. Nouvelle géographie universelle, la terre et les hommes. Paris, Hachette, 1889. 8°, v. 14.

Philippines, pp. 515–580.

1889. RENARD, A. F. Report on the rock specimens collected on oceanic islands during the voyage of H. M. S. *Challenger* during the years 1873–1876. 4°, 180 pp.

In Report of the scientific results of the exploring voyage of H. M. S. *Challenger*, 1873–1876, London, Government, 1889, 4°, v. 2, part 4.

Philippines, pp. 160–175; nearly or quite a translation of Renard's two papers in Bull. Acad. de Belgique.

1890. ABELLA Y CASARIEGO, ENRIQUE. Descripción física, geológica y minera en bosquejo de la isla de Panay. Manila, Chofré, 1890. 8°, 203 pp., 5 l., and 5 pl. (incl. 2 maps of the island colored geologically).

1890. CENTENO and others. Memoria descriptiva de los manantiales minero-medicinales de la isla de Luzón estudiados por la comisión compuesta de los Señores José Centeno, Anacleto del Rosario y Sales, y José de Vera y Gomez. Madrid, Tello, 1890. 8°, 117 pp.

This appeared separately and also in Boletín de la Comisión del Mapa geológico de España, v. 16, 1889.

1890. MEYER, HANS. Eine Weltreise. Leipzig und Wien, Bibliographisches Institut. 1890. 8°.

Philippines, pp. 253–287, determined height of Datá.

1892. BARANERA, FRANCISCO X. Compendio de geografía de las islas Filipinas, Marianas, Joló y Carolinas. 3d ed. Manila, Bren, 1892. 12°, 192 pp., 3 maps.

An extremely useful little book, though not free from errors. Among other matters it contains an index of the principal towns and geographic features of the islands, pp. 121–162.

1892. POSEWITZ, THEODOR. Borneo; its geology and mineral resources, translated from the German by Frederick H. Hatch. London, Stanford, 1892. 8°, xxxii, 495 pp., 4 maps.

This work does not deal with the Philippine Islands, but is important for suggestive analogies. It contains a list of several hundred papers on Borneo.

1892. WALLACE, A. R. Island life. London, Macmillan, 1892. 8°.

Philippines, pp. 387–390.

1893. ABELLA Y CASARIEGO, ENRIQUE. Terremotos experimentados en la isla de Luzón durante los meses de marzo y abril de 1892, especialmente desastrosos en Pangasinán, Unión y Benguet. Manila, Chofré, 1893. 8°, 110 pp., 1 diagram and map.

The map is on a larger scale than any other known to me of the same region. The memoir is largely geological.

1893. ABELLA and others. Estudio descriptivo de algunos manantiales minerales de Filipinas, ejecutado por la comisión formada por Don Enrique Abella y Casariego, inspector general de minas, Don José de Vera y Gómez, médico, y Don Anacleto del Rosario y Sales, farmacéutico, precedido de un prólogo escrito por el Excmo. Sr. D. Angel de Avilés, director general de Administración Civil. Manila, Chofré, 1893. 8°, 150 pp.

The half-title is: Manantiales minerales de Filipinas; 2°, estudio descriptivo. This paper is largely geological.

1893. MARTINEZ DE ZÚÑIGA, JOAQUÍN. Estadismo de las islas Filipinas, ó mis viajes por este país. Publica esta obra por primera vez extensamente anotada W. E. Retana. Madrid, 1893. 8°, 2 v.; v. 1, 549+XXXVIII pp.; v. 2, 118+629* pp.

Among the appendices is a valuable bibliography of Spanish works, 384 titles, and an index of geographical points, pp. 352–420. The report on the three eruptions of 1641 is reproduced in v. 2, p. 334.

1893. AGUILAR, J. N. Colonización de Filipinas. Madrid, Alonso, 1893. 8°, 414 pp.

Geology and mineral resources, pp. 345–409, seemingly without any original matter.

1895–1896. ELERA, CASTO DE. Catálogo sistemático de toda la fauna de Filipinas, etc. Manila, Colegio de Santo Tomás, 1895–96. 8°, 3 v.

The introduction contains geological opinions.

1896. MARTIN, K. Ueber tertiäre Fossilien von den Philippinen. *In* Sammlungen des geologischen Reichs-Museums in Leiden, 1st s., Leiden, Brill, 1888–1899, 8°, v. 5, pp. 52–69, 2 cuts.

This paper is translated as a complement to this report.

1897. LANZAS, PEDRO TORRES. Relación descriptiva de los mapas, planos, etc., de Filipinas existentes en el archivo general de Indias. Madrid, 1897. 12°, 55 pp.

In Archivo del bibliófilo filipino, W. E. Retana, Madrid, Rios, 1897, v. 3, pp. 445-497.

Maps chronologically arranged from 1565 to 1847.

1898. CORONAS, JOSÉ. La erupción del volcán Mayón en los días 25 y 26 de junio de 1897. Manila, Observatorio, 1898. fol., 55 pp., 1 leaf, 2 pl., 2 maps.

Father Coronas gives a succinct account of the earlier known eruptions. For geological information he refers to Abella's paper.

1898. BECKER, GEORGE F. Memorandum on the mineral resources of the Philippine Islands.

In U. S. Geological Survey, 19th annual report, part vi continued, pp. 687-693.

This paper was prepared as a report to Admiral Dewey, at his request. It was reprinted in A Treaty of Peace between the United States and Spain, 55th Congress, 3d session, document 61, part 1, Washington, Government, 1899, pp. 514-518; reprinted again in The Philippine Islands, report by Mr. Lodge from Senate Committee on the Philippines, 56th Congress, 1st session, document 171, Washington, Government, 1900, pp. 19-24.

1898. ESPINA Y CAPO, LUIS. Ligero bosquejo acerca de los principales yacimientos metalíferos de Filipinos. Manila, MS., 1898. fol., 191 l., folding tables and maps.

Report prepared at my request by official in charge of Inspección de Minas from material in that office.

1898. GOBIERNO GENERAL DE FILIPINAS. Guía oficial de las Islas Filipinas para 1898, publicada por la secretaría del Gobierno General. Manila, 1898. 8°, 1144 pp. and appendices.

Contains papers by heads of departments on the meteorology, resources, history, and government of the islands and much miscellaneous information. Abella is said to have written the section on Reino Mineral, pp. 124-131.

1898. HILDER, F. F. The Philippine Islands.

In National Geographic Magazine, Washington, D. C., 1898, v. 9, pp. 257-301.

1898. KARUTH, FRANK. A new centre of gold production. London, 1894.

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1898. WORCESTER, DEAN C., and BOURNS, FRANK S. Contributions to Philippine ornithology.

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1899. BECKER, GEORGE F. Brief memorandum on the geology of the Philippine Islands.

In U. S. Geological Survey, 20th annual report, 1898–99, 8°, part 2, pp. 3–7.

Prepared as a report to Gen. E. S. Otis, military governor.

1899. HERRMANN, RAFAEL. Besuch im Golddistrict von Camarines Norte (Luzón).

In Globus, Braunschweig, Vieweg, 1899, 4°, v. 73, pp. 10–12.

1899. KOTÔ, B. On the geologic structure of the Malayan archipelago.

In the Journal of the College of Science, Imperial University of Tōkyō, Japan, v. 11, part 2, published by the University, Tōkyō, Japan, 1899, 4°, pp. 83–120, 1 map.

1899. STIERE, J. B. Volcanoes and earthquakes in the Philippines.

In Scientific American, New York, 1898, fol., p. 395.

MINING CONCESSIONS.

Mining concessions in force in the Philippine Islands on August 17, 1897.

Name of mine.	Mineral exploited.	Locality.	Township.	Province or district.	Number of claims.	Area in square meters.	Grantees.
Ntra Sra del Carmen	Gold	Pinutan	Liloan	Leyte	1	60,000	Aldecoa & Co
La Amistad	do	Tigbanan	do	do	2	120,000	
Bilbaina	do	do	do	do	2	120,000	
Excess on the three preceding	do				(a)	20,056	
Esperanza	do	Tumbaga	Mambulao	Ambos Camarines	2	120,000	The Philippines Mineral Syndicate, Limited.
La Concepción	do	Imbong-imbong	do	do	2	120,000	
Trinidad	do	Dinaanan	Paracale	do	2	120,000	
Luisa	do	Colapnit	do	do	2	120,000	
Rosalía	do	Tinga	do	do	2	120,000	
Noria	do	La Noria	Mambulao	do	1	60,000	
Sta. Gertrudis	do	Calupcup	do	do	1	60,000	
Animas del Purgatorio	do	Longos	Paracale	do	2	120,000	
San Antonio	do	Dinaanan	do	do	2	120,000	
María	do	Tumbaga	Mambulao	do	2	120,000	
Francisco	do	do	do	do	2	120,000	
San Juan	do	Salulong	Paracale	do	(b) 2	81,000	
San Enrique	do	Gumamela	do	do	2	120,000	
San Pablo	do	Oguis	do	do	2	120,000	Bonancita M. Co.
San Antonio	do	Dinaanan	Mambulao	do	1	60,000	Eugenio Espedido.
El Secreto	do	Togús	Paracale	do	2	120,000	Bonancita M. Co.
Mi Porvenir	do	Mariconia	do	do	2	120,000	
Santa Marta	do	Manaug	do	do	2	120,000	
La Muy Rica	do	Carbongajar	do	do	2	120,000	
Nueva Galicia	do	Gumobacan-Bata	Mambulao	do	2	120,000	The Philippines Mineral Syndicate, Limited.
Aurora	do	Gumobacan-Matandá	do	do	2	120,000	
San Ramón	do	Gumaos	do	do	2	120,000	

San Rafael	do	Togús	Paracale	do	2	120,000	Nicolas Carranceja.
Registro No. 1	do	Rio de Paracale	do	do	1	60,000	
Registro No. 2	do	do	do	do	1	60,000	
Registro No. 3	do	do	do	do	1	60,000	
Registro No. 4	do	do	do	do	1	60,000	García, Beltran & Co. Mining Company.
Registro No. 5	do	do	do	do	1	60,000	
Cusa	do	Colorán	do	do	2	120,000	
Pep	do	Togús	do	do	2	120,000	
Quim	do	do	do	do	2	120,000	
Santa Bárbara	do	Bejuquillo	do	do	2	120,000	Eugenio Espedido.
Felicidad	do	Dinaquitan	Mambulao	do	2	120,000	The Philippines Mineral Syndicate, Limited.
San Mauricio	do	Calupcup	do	do	2	120,000	
Doña Guillerma	do	Tagontón	do	do	1	60,000	La Bonancita Mining Co.
Doña María	do	Longos	Paracale	do	2	120,000	
Margarita (investigation)	do	Pansol	do	do	c 2	120,000	
Excess to south of San Antonio	do	Salulong	do	do	(a)	18,200	The Philippines Mineral Syndicate, Limited.
Excess to north of San Antonio	do	Longos	do	do	(a)	45,000	
Excess of San Juan	do	Baluarte	do	do	(a)	10,256.25	
Santa Barbara	do	Manaug	do	do	2	120,000	La Bonancita Mining Co.
Don Carlos	do	Tagontón	do	do	1	60,000	
Leo Taxil	do	Casalogan	do	do	2	120,000	Ramón Caberudo.
San Vicente	do	Máquima	do	do	2	120,000	La Bonancita Mining Co.
Padre José	do	Lipata	do	do	2	120,000	
Nueva California, first	do	Casalogan	do	do	4	240,000	
Nueva California, second	do	Guiaman	do	do	4	240,000	
Nueva California, third	do	Casalogan	do	do	4	240,000	
Nueva California, fourth	do	Magsimato	do	do	4	240,000	Martin Buck and Joaquín Casanovas.
Nueva California, fifth	do	Cabisnuan y Colorán	do	do	4	240,000	
Germania	do	Capulugan	do	do	4	240,000	
Magallanes	do	Bonotan, Malagangao, Capinangan and Tinapahan.	do	do	24	1,440,000	
La Candelaria	do	Calangag, Pinaglambirán, Tiniguiban, Quinabagacayan.	do	do	33	1,980,000	Vicente Atienza.

a Excess. b Incomplete. c Investigation.

Mining concessions in force in the Philippine Islands on August 17, 1897—Continued.

Name of mine.	Mineral exploited.	Locality.	Township.	Province or district.	Number of claims.	Area in square meters.	Grantees.
San Félix	Gold	Cabúgao	Paracale	Ambos Camarines	2	120,000	Emilio Sprüngli.
San Ricardo	do	May Nanca	do	do	2	120,000	
El Ángel	do	Delinquenta	do	do	2	120,000	Juan Fernandez and S. Luis.
El Patriarca	do	Monte Maynanca	do	do	2	120,000	
San Alfredo	do	Calupcup	Mambulao	do	1	60,000	
Santiago	do	do	do	do	1	60,000	
Caridad	do	Dinaquitan	do	do	1	60,000	The Philippines Mineral Syndicate, Limited.
San Sebastián	do	Calupcup	do	do	2	120,000	
San Federico	do	do	do	do	2	120,000	
San Ciriaco	do	do	do	do	1	60,000	
Robinson group	do	Catigahan	do	do	57	3,420,000	William Urquhart.
Santa Balbina	do	Bulalácao	do	do	2	120,000	
San Nicolás	do	do	do	do	2	120,000	Calatino Flores.
La Concepción	do	do	do	do	2	120,000	
San Rafael	do	Tigbí	do	do	2	120,000	Aguedo Macandog.
La Aurora	do	Puló ni Antón	Gapan	Nueva Écija	2	120,000	Auturo Carlos Fleming.
Santa Calalina	do	do	do	do	2	120,000	
Pilar	do	Palidan	Mancayan	Lepanto	2	120,000	
Santa Rita	do	Cayaan	do	do	2	120,000	
San Luis	do	Dugoon	do	do	2	120,000	Rafael Yanguas.
San Antonio	do	Gatugat	do	do	2	120,000	
San Alberto	do	Rio Pacat	do	do	2	120,000	
Adela y Micaela	do	Arroyo Arup	do	do	2	120,000	
Pilar y Mercedes	do	Cali	do	do	2	120,000	José Mills y Baralls.
María Asunción y San Lorenzo	do	Balaan	do	do	2	120,000	
San Eugenio y Eduarda	do	Rio Abra	Cervantes	do	2	120,000	
San Fernando y San Isidro	do	Gubasan	Mancayan	do	2	120,000	Federico Lopez Pascual.
Encarnación	do	Deplás	Sagada	Bontoc	2	120,000	Saturnino Villaverde.

Capunga	do	Lusong	Tublay	Benguet	2	120,000	
Tabio	do	La Trinidad	do	do	1	60,000	Pablo Emilio Herrmann.
Acupan	do	Acupan	Itogon	do	1	60,000	
Nameless, known as Santa Bárbara	Copper	Arroyo Magambang	Mancayan	Lepanto	*a*2	83,848.62	Cántabro Filipina Co., now Venancio Balbás.
Cántabro Filipina, known as Santa Lucía.	do	do	do	do	*a*2	83,848.62	
De Hison	Iron	Sapang Bacal	Angat	Bulucán	*a*1	111,798.16	Hison's heirs.
Santa Lutgarda	do	Pinugayan	do	do	1	150,000	Anchuelo's heirs.
Constancia	do	do	do	do	2	300,000	Francisca Talag.
De Concha	do	Sapang Bacal	San Miguel de Mayumo.	do	*a*2	125,772.93	Conche's heirs.
San Pio V	do	do	do	do	2	300,000	Pablo Carlos.
Sapang Muntí	do	Mantamuro	Angat	do	1	150,000	Francisco Sanchez.
Santa Rosalía	Sulphur	Monti Caibirán	Caibirán	Leyte	2	120,000	Prudencio Ruiz.
San Antonio	do	Cajúcao	Naval	do	1	60,000	
San José	Coal	Nabangig	Cataingan	Masbate	4	600,000	José Muños.
Santa Cruz	do	do	do	do	4	600,000	José Muños de Bustillo.
Magallanes	do	Bairán	Danao	Cebú	2	300,000	
Nueva Langreo	do	Manganas-anas	do	do	2	300,000	
Cebuana	do	Silangon	do	do	2	300,000	New Langreo Mining Co
Portiella	do	Bairan	do	do	2	300,000	
La Mestiza	do	Tugonón	do	do	1	150,000	
Ángeles	do	Licos	Compostela	do	12	1,800,000	Ramón Montañés.
San Julián	do	Silí	Danao	do	8	1,200,000	New Langreo Mining Co.
Santa María	do	Panian	Semerara	Mindoro	2	300,000	Antonio de Tribar.
Carolina	do	Siay	Bulalácao	do	4	600,000	
San Armando	do	Napisian	do	do	4	600,000	
San Rafael	do	Siay	do	do	4	600,000	
San Claudio	do	Napisian	do	do	4	600,000	
San Joaquin	do	Siay	do	do	4	600,000	Rafael Cascarosa y Martinez.
San Ramón	do	do	do	do	4	600,000	
San Clemente	do	Napisian	do	do	4	600,000	
Prudencia	do	do	do	do	4	600,000	
San Enrique	do	Tag-angilan	Compostela	Cebú	4	600,000	Ramón Montañés.
Rafael Reyes	do	Lupá	do	do	2	300,000	

a Old.

Mining concessions in force in the Philippine Islands on August 17, 1897—Continued.

Name of mine.	Mineral exploited.	Locality.	Township.	Province or district.	Number of claims.	Area in square meters.	Grantees.
Balerma	Coal	Pututan	Bacón	Sorsogón	1	150,000	
Urgera	do	Bencalon	do	do	1	150,000	Villanueva & Co.
Ganalda	do	Liguan	do	do	1	150,000	
San Francisco	do	do	do	do	4	600,000	Emilio Muñoz.
Perseverancia	do	Malabog	do	do	1	150,000	Villanueva & Co.
Sodupe	do	Napisay	do	do	2	300,000	
Bilbao	do	Calanaga	do	do	4	600,000	
Lucus y Josefa	do	Caticatigahan	do	do	1	150,000	Jacinto Gil y Gorroño.
Chifladura	do	do	do	do	1	150,000	
Presentación	do	Saburi	do	do	2	300,000	
Olaveaga	do	Aguis	do	do	2	300,000	
Carlota	do	Camansi	Danao	Cebú	1	150,000	Nueva Langreo Co.
Alfonso XIII	do	Actini	Toledo	do	4	600,000	
María Cristina	do	Tidiong	do	do	4	600,000	
Progreso	do	Canlumampao	do	do	2	300,000	Cornelio Roberto Blair Pickford.
Reina Regente	Petroleum	do	do	do	2	300,000	
Langob	Guano	Taguaya	Catmon	do	2	300,000	Ramón Montañés.
Santo Domingo Quarry	Marble	Sablayan	Montalban	Manila	2	300,000	Marcelo Dominguez.
Santa Matilde Quarry	do	May-Putí	Binangonan	Mórong	2	300,000	Ángel Tapia y Aragonés.
Santa Rosa Quarry	do	Mag-Manga	do	do	2	300,000	Fausto Tabotabo.
Do	do	Panahicon	Tuburan	Cebú	2	300,000	
Alfa Quarry	Kaolin	Lupang-Putí	Los Baños	Laguna	2	300,000	
Beta Quarry	do	do	do	do	2	300,000	José Martín y Martinez.
Delta Quarry	do	do	do	do	2	300,000	
Epsilon Quarry	do	do	do	do	2	300,000	

List of mines staked out after the above date, the titles of which are conceded and which only await registration in the general office of the treasury (hacienda).

Name of mine.	Mineral exploited.	Locality.	Township.	Province or district.	Number of claims.	Area in square meters.	Grantees.
San Rafael	Gold	Tigbí	Mambulao	Ambos Camarines	2	120,000	Aguedo Macandog.
Santa Balbina	do	Bulalácao	do	do	2	120,000	}
La Concepción	do	Ibaba ng̃ Bulalacao	do	do	2	120,000	}Catalino Flores.
San Nicolás	do	Gajugaju	do	do	2	120,000	}
Ángeles	Coal	Tugnon	Compostela	Cebú	8	1,200,000	Ramón Montañés.
Alfonso XIII	Petroleum	Su-uy	San Isidro	Leyte	1	150,000	}Smith, Bell & Co.
Alegría	do	Talayong	Alegría	Cebú	1	150,000	}
La Esperanza	Gold	Cansuran	Surigao	Surigao	52	3,120,000	Williams Urquhart.
María y Leopolda	do	Tinabigan	Placer	do	2	120,000	}
Mundaca	do	Centuan	do	do	2	120,000	}
Andres y Agustina	do	Isla Campiña	do	do	1	60,000	}José Cortés Dominguez.
Viscaya	do	Uacatan	do	do	2	120,000	}
Castilla	do	Tinopan	do	do	2	120,000	}

PROVINCIAL INDEX.

The following index is intended to enable the reader to collate the statements contained in the foregoing paper by provinces or districts, each locality mentioned there being represented here by a page reference opposite the province to which it belongs. In order to facilitate geographical acquaintance with the archipelago, the index gives also the name of the capital town of each province or district and the latitude thereof, so that if a reader who is unfamiliar with the islands desires to know where to look for any province, the data here presented will give him the information.

The provincial divisions of the Philippines were of two classes, provinces being administered by civil governors and districts by "politico-military" governors who were army officers. The distinction is now unimportant excepting that, in reading, confusion may arise unless the system is understood.

The list of provincial divisions is that given in the Compendio de Geografía of the Jesuit Fathers, 1892, and is that found on most maps. More recently some changes were made by the Spanish Government, of which two should be known to the reader. They are the division of Albay into the two provinces of Albay and Sorsogón, the latter being the more southerly, and the union of Camarines Norte and Camarines Sur into the single province of Ambos Camarines. As the purpose of this index is to assist in the use of the maps of d'Almonte, Abella, and the Jesuits, it would be inexpedient here to adopt the recent changes in administration, which will soon be replaced by some system of American origin.

Luzón and adjacent islands.

Province.	Capital.	Latitude of capital.		Page references.
		°	′	
Albay	Albay	13	8	497, 531, 533, 540, 557, 561, 569, 570, 583.
Bataan	Balanga	14	42	514, 516, 518, 522.
Batangas	Batangas	13	45	515, 524, 534, 539, 563, 564.
Bulacán	Bulacán	14	48	498, 570, 591.
Cayagán	Tuguegarao	17	37	540, 569, 583.
Camarines N	Dáet	14	5	498, 503, 570, 577, 578, 589, 590, 591.
Camarines S	Nueva Cáceres	13	37	503, 504, 517, 521, 533, 557, 589, 590.
Ilocos N	Laoag	18	13	
Ilocos S	Vigan	17	34	501.
Isabela	Ilagan	17	8	502, 552, 559.
Laguna	Santa Cruz	14	17	495, 511, 521, 533, 534, 563, 591, 593.
Manila	Manila	14	36	496, 498, 499, 500, 521, 539, 562, 570, 593.
Mindoro	Calapan	13	24	497, 498, 504, 531, 539, 557, 571, 583, 590.
Nueva Écija	San Isidro	15	18	498, 501, 577.
Nueva Vizcaya	Bayombong	16	27	501.
Pampanga	Bacolor	15		515, 517, 521, 539.
Pangasinán	Lingayén	16	4	498, 521, 524.
Tayabas	Tayabas	14	1	503, 524, 557, 569, 570, 589.
Unión	San Fernando	16	38	501, 502, 527, 539, 558, 569.
Zambales	Iba	15	21	498, 499, 500, 583.

District.	Capital.	Latitude of capital.		Page references.
		°	′	
Abra	Bangued	17	37	500, 569, 577.
Batanes	Santo Domingo de Basco	21	7	540.
Benguet	Trinidad	16	30	501, 502, 558, 559, 562, 577, 589.
Bontoc	Bontoc	17	13	501, 518, 521, 522, 577.
Cavite	Cavite	14	29	539.
Corregidor	San José	14	23	514, 516, 518, 539.
Infanta	Binangonan de Lampong	14	48	498, 503, 509, 570, 583.
Lepanto	Cervantes	17	1	501, 521, 522, 540, 577, 584.
Mórong	Mórong	14	31	493, 500, 517, 521, 522, 551, 559, 562, 570, 591.
Príncipe	Baler	15	47	
Tárlac	Tárlac	15	30	499, 521, 522, 560.

Central Islands, or Visayas.

District.	Capital.	Latitude of capital.		Page references.
		°	′	
Antique	San José de Buenavista	10	44	498, 504, 505, 512, 518, 521, 522, 590.
Bohol	Tagbilaran	9	38	497, 521, 530, 563, 565, 583.
Burias	San Pascual	13	8	497.
Calamianes	Cuyo	10	52	496, 504, 563, 566.
Cápiz	Cápiz	11	35	571, 580, 583.
Cebú	Cebú	10	18	497, 498, 505, 506, 507, 512, 514, 521, 523, 530, 551, 552, 560, 561, 564, 565, 566, 572, 580, 591, 593.
Concepción	Concepción	11	13	505.
Iloilo	Iloilo	10	42	557, 560, 566, 571, 580, 593.
Leyte	Tacloban	11	15	497, 498, 504, 507, 515, 523, 530, 557, 575, 580, 593.
Masbate	Masbate	12	24	497, 546, 557, 566, 571, 583, 589.
Negros Occidental	Bacólod	10	42	505, 514, 522, 556, 560, 564, 572.
Negros Oriental	Damaguete	9	20	497, 512, 513, 514, 523, 529, 564, 572, 584.
Romblón	Romblón	12	34	497, 593.
Sámar	Catbalogan	11	48	496, 498, 504, 530, 557, 559, 571, 580, 590.

Mindanao, Joló, and Palawan.

District.	Capital.	Latitude of capital.		Page references.
		°	′	
Balábac	Balábac	7	59	497, 566, 590.
Basilan	Isabela de Basilan	6	45	511, 564.
Cottabato	Cottabato	7	15	495, 528, 576.
Dávao	Dávao	7	2	508, 523, 526, 527, 576.
Joló	Joló	6	5	497, 523, 526, 559, 562, 564, 566, 584.
Misamis	Cagayán de Misamis	8	30	498, 507, 508, 513, 523, 528, 530, 547, 558, 559, 576, 581.
Paragua	Puerto-Princesa	9	45	509, 530, 540, 561, 563, 565, 566.
Surigao	Surigao	9	48	494, 498, 507, 508, 523, 547, 557, 576, 581, 584, 590.
Zamboanga	Zamboanga	6	57	508, 523, 551, 557, 560, 563, 565, 576.

CONCERNING TERTIARY FOSSILS IN THE PHILIPPINES.

By K. MARTIN.[1]

The occurrence of Tertiary deposits in the Philippines has long been known. As early as 1861 F. von Richthofen[2] reported on nummulites which he had discovered in limestones in place, close to the village of Binangonan, on Bay Lake, not far from Manila. R. von Drasche[3] represented these Eocene limestones, which also appear at various other points north of Binangonan, on his geological sketch map of southern Luzón; and von Richthofen furthermore expressed his opinion that the well-developed series of strata in the mountains of Zamboanga, on the southwest coast of Mindanao, likewise belong to the nummulite formation.

C. Semper collected a great number of fossils in the Philippines, but, while the rocks brought back by this naturalist have been worked up by K. Oebbeke,[4] the fossils have remained undescribed. Nevertheless, it was not unknown to Semper that these latter, at least in part, came from Tertiary strata, for he says: "Against this trachytic core (of the Philippines) lie numerous sedimentary strata at various elevations. They are fossiliferous sandstones and shales, whose mussels and snails are in part still found living in the surrounding seas. They surely, therefore, belong to a very recent period." Further on it is remarked, concerning the highest coral reefs, standing at elevations far above sea level, that "they seem to belong as far back as the Tertiary."[5]

J. Roth,[6] who, in 1873, compiled all the information then available, came to this conclusion: "In the Philippines, on a formation of crystalline schists, lie strata which are in part certainly Tertiary (Eocene), and abundant younger beds, raised banks, and coral reefs which contain mollusca of species still surviving in the Pacific." Shells from a

[1] Sammlungen des geologischen Reichs-Museums in Leiden, Vol. V., 1896, pp. 53–69. Translated by Mr. George F. Becker as a complement to his paper, published herewith, on the Geology of the Philippine Islands.

[2] Ueber das vorkommen von Nummulitenformation auf Japan und den Philippinen: Zeitschr. Deutsch. geol. Gesell., Vol. XIV, 1862, p. 357.

[3] Fragmente zu einer Geologie der Insel Luzón, mit einem Anhange über die Foraminiferen der tertiären Thone von Luzón von Felix Karrer, Wien, 1878.

[4] Beiträge zur Petrographie der Philippinen und der Palau-Inseln: Neues Jahrbuch für Mineral., Geol., Palæont., Beilage-Band I, p. 451.

[5] C. Semper, Die Philippinen und ihre Bewohner, Sechs Skizzen, Würzburg, 1869, p. 17.

[6] Ueber die geologischen Beschaffenheit der Philippinen: In F. Jagor, Reisen in den Philippinen, Berlin, 1873, p. 333.

bank on the west side of the peninsula of Jalajala, in Bay Lake, were determined by von Martens as belonging exclusively to recent species. On the other hand, extinct as well as living species, according to the same naturalist, occur in yellowish-gray clays which lie near Paranas, on the west coast of Sámar. Banks of recent shells, however, were found also both at Paranas and on the south coast of Sámar, near Basey and Nipa-Nipa.[1]

The occurrence of Miocene in the Philippines was first established by Karrer through investigation of Foraminifera which came from the western slope of the Sierra Zambales on the western coast of northern Luzón. There occur "tuffaceous Foraminifera-bearing marls up to altitudes of 400 feet along the sea coast between Palauig and Santa Cruz, and perhaps still farther north."[2] These marls are compared by Karrar with those from Java and elsewhere. He reached the conclusion that the marls in question are younger than certain Javanese beds which at that time had already been assigned to the Miocene, but he calls attention to the fact "that the difference in age need not be considered so great as to necessitate assignment to different divisions of the Tertiary, since they probably represent only older and younger horizons." Accordingly, Karrer correlates the marls of the Sierra Zambales as younger Miocene.[3]

R. von Drasche pursued the comparison between the strata of Luzón and the Javanese Tertiary still further, taking as his basis the division of the strata of Java given by F. von Hochstetter.[4] He says: "The thick tuffs of northern Luzón may be included in group *a* of the Miocene (of von Hochstetter). In this group, too, are to be mentioned the foraminiferous marls of the Sierra Zambales. To group *b* belong the coral reefs of Luzón, which, in Luzón, and no doubt also in Java, may be characterized as Pliocene." It must be explicitly mentioned, however, that the Foraminifera determined by Karrer furnish the only paleontological evidence for these age determinations by von Drasche, so that, except so far as they apply to the marls of the Sierra Zambales, they must be characterized as mere suppositions.

Th. Fuchs investigated ill-preserved remains from the same coralline limestones of Luzón which were considered by von Drasche, according to the statements cited above, as probably Pliocene. According to this authority "the forms could all be referred to living species, and, indeed, without forcing matters at all." Fuchs says: "In fact, there is no objection to regarding them as entirely Recent."[5] In harmony with this statement Semper[6] mentions that in the hills of Aringay, northwest Luzón, he found a coral which is closely related to *Heteropsammia rotundata* Semp.

[1] Roth, loc. cit., pp. 342, 352, 353. [2] R. von Drasche, loc. cit., p. 21. [3] Ibid, p. 84.

[4] Reise der östereichischen Fregatte *Novara* um die Erde, geolog. Theil, Vol. II, 1866, p. 149.

[5] R. von Drasche, loc. cit., p. 42.

[6] Ueber Generationswechsel bei Steinkorallen, etc.: Zeitschr. für wiss. Zoologie, Vol. XXII, 1872, p. 266.

The foregoing gives an account, I believe, of everything which is thus far known of Tertiary fossils in the Philippines. As is apparent, this is to all intents confined to the Nummulites from the neighborhood of Manila, and to the Foraminifera from the Sierra Zambales of northwestern Luzón. Even on that account the fossils which were collected by Semper, and which, after the death of that tireless naturalist, came into the possession of the Leiden museum would excite special interest. They acquire a greater importance from their localities, for a large part of them come from regions which were visited neither by Jagor nor by von Drasche, and which, indeed, have never been geologically investigated at all.

Now, in reviewing Semper's collection, I was at once struck with *Vicarya callosa* Jenk., which is known from Java and is described in detail below; and this induced me to make a closer comparison between the fossils of the Philippines and those of the Indian Archipelago, whereby it at once became apparent that a whole series of species, especially of the Javanese Tertiary, is common to both regions. Thus far, indeed, I have been unable to make a complete study of Semper's collection, and for the time being it has little further interest, because statements as to stratigraphical position are entirely lacking and the equivalent deposits of neighboring regions are still very insufficiently known. After completion of my monograph on the fossils of Java, however, I hope to undertake a more thorough study of the Philippine fossils, and to supplement this preliminary communication.

The species of the Semper collection which have thus far been determined are as follows:

	Occurrence elsewhere.
Terebra Jenkinsi K. Mart. (Foss. von Java, p. 8)	M.
Terebra bandongensis K. Mart. (Foss. von Java, p. 10)	M.
Conus sinensis Sow. (Foss. von Java, p. 13)	P; L.
Conus insculptus Kien. (Foss. von Java, p. 14)	M; L.
Conus palabuanensis K. Mart. (Foss. von Java, p. 16)	J.
Conus Loroisii Kien. (Foss. von Java, p. 21)	M; P; L.
Pleurotoma gendinganensis K. Mart. (Foss von Java, p. 32)	P.
Pleurotoma carinata Gray (Foss. von Java, p. 37)	P; L.
Pleurotoma coronifera K. Mart. (Foss. von Java, p. 38)	E. (?); M.
Pleurotoma neglecta K. Mart. (Foss. von Java, p. 42)	M.
Turricula bataviana K. Mart. (Foss. von Java, p. 78)	P.
Fusus Verbeeki K. Mart. (Foss. von Java, p. 85)	M; P.
Latirus madiunensis K. Mart. (Foss. von Java, p. 88)	P.
Pyrula gigas K. Mart. (Foss. von Java, p. 90)	M.
Tritonidea ventriosa K. Mart. (Foss. von Java, p. 99)	M.
Nassa Verbeeki K. Mart. (Foss. von Java, p. 110)	P.
Murex Verbeeki K. Mart. (Foss. von Java, p. 123)	P.
Murex djarianensis K. Mart. (Foss. von Java, p. 124)	M.
Murex brevispina Lam. (Foss. von Java, p. 126)	M. (?); P; L.
Murex pinnatus Wood. (Foss. von Java, p. 127)	M; L.
Murex microphyllus Lam. (Foss. von Java, p. 127)	M; L.
Murex capucinus Lam. (Foss. von Java, p. 123)	—; L.

	Occurrence elsewhere.
Murex Grooti Jenk. (Foss. von Java, p. 131)	M.
Ranella spinosa Lam. (Sammlg. I, p. 201)	M; L.
Ranella elegans Beck. (Sammlg. III, p. 137)	M; L.
Ranella raninoides K. Mart. (Sammlg. I, p. 203)	M.
Ranella gyrina Linn. (not yet known from Java)	—; L.
Cypraea Smithi K. Mart. (Sammlg. III, 141)	M.
Strombus isabella Lam. (Notes Leyden Mus. III, p. 19)	Q; L.
Rostellaria Javana K. Mart. (Tertsch. Java, p. 50)	M.
Vicarya callosa Jenk. (Tertsch. Java, p. 62)	M.
Potamides Jenkinsi K. Mart. (Sammlg. III, p. 147)	P.
Turritella terebra Lam. (Sammlg. III, p. 171)	Q; L.
Natica mamilla Lam. (Tertsch. Java, p. 81)	M; L.
Arca granosa Linn. (Sammlg. III, p. 242)	P; L.
Cardita decipiens K. Mart. (Tertsch. Java, p. 110)	P.
Venus squamosa Lam. (Sammlg. III, p. 207)	P; L.
Clementia papyracea Gray (Tertsch. Java, p. 99)	M; P; L.
Corbula scaphoides Hinds. (Sammlg. III, p. 196)	M; P; L.
Callianassa Dyki K. Mart. (Sammlg. III, p. 36)	M; Q.

The appended initials indicate the occurrence of the species in the Tertiary of other parts of the Indian Archipelago, as well as among the fauna of the present day. Thus E denotes Eocene; M, Miocene; P, Pliocene; J, later Tertiary in general; Q, Quaternary; L, living species.

The above-mentioned fossils are distributed among the following localities:

I. LUZÓN.

1. Minanga; right bank of the Catalangan.

Fusus Verbeeki Mart.	M; P.	Rostellaria javana Mart	M.
Tritonidea ventriosa Mart.	M.	Vicarya callosa Jenk	M.
Murex brevispina Lam	M. (?); P; L.	Natica mamilla Lam	M; L.
Murex pinnatus Wood	M; L.	Cardita decipiens Mart	P.
Ranella raninoides Mart.	M.	Venus squamosa Lam	P; L.

2. Minanga; right bank of the Ilaroen.

Terebra Jenkinsi Mart	M.	Ranella gyrina Linn.	L.
Terebra bandongensis Mart.	M.	Rostellaria javana Mart	M.
Fusus Verbeeki Mart.	M; P.	Vicarya callosa Jenk	M.
Murex Grooti Jenk	M.	Cardita decipiens Mart	P.

3. Right bank of the Ilaroen; 4 miles above Minanga.

Fusus Verbeeki Mart.	M; P.	Rostellaria javana Mart	M.
Murex brevispina Lam	M. (?); P; L.	Natica mamilla Lam	M; L.
Ranella raninoides Mart.	M.		

4. Left bank of the Ilaroen; 1¼ mlies above Goroen.

Murex djarianensis Mart.	M.	Ranella spinosa Lam	M; L.
Murex brevispina Lam	M. (?); P; L.	Potamides Jenkinsi Mart	P.
Murex microphyllus Lam.	M; L.	Natica mamilla Lam	M; L.
Murex Grooti Jenk	M.	Cardita decipiens Mart	P.

5. Left bank of the Ilaroen; 4 miles above Goroen.

Conus sinensis Sow	P; L.	Fusus Verbeeki Mart	M; P.
Conus palabuanensis Mart	J.	Ranella gyrina Linn	L.

6. Foothills in front of Aringay.

Conus Loroisii Kien	M; P; L.	Nassa Verbeeki Mart	P.
Pleurotoma gendinganensis Mart	P.	Natica mamilla Lam	M; L.

7. Hills close to Aringay.

Pleurotoma carinata Gray .... P; L.

8. Dicamui Brook.

Vicarya callosa Jenk .... M.

9. Satput.

Cypraea Smithi Mart	M.	Rostellaria javana Mart	M.

II. MINDANAO.

1. Left bank of Agúsan River at Tagasáp.

Latirus madiunensis Mart	P.	Ranella gyrina Linn	L.
Murex microphyllus Lam	M; L.	Turritella terebra Lam	Q; L.
Ranella raninoides Mart	M.		

2. Agúsan River between Pagasáp and Libuton.

Turritella terebra Lam	Q; L.	Venus squamosa Lam	P; L.

3. Maasin on the Agúsan.

Conus insculptus Kien	M; L.	Murex Verbeeki Mart	P.
Turricula bataviana Mart	P.	Natica mamilla Lam	M; L.

4. Salac y Maputi River.

Murex Verbeeki Mart	P.	Arca granosa Linn	P; L.
Strombus isabella Lam	Q; L.	Clementia papyracea Gray	M; P; L.
Natica mamilla Lam	M; L.	Corbula scaphoides Hinds	M; P; L.

5. Zamboanga, river bank $2\frac{1}{2}$ miles north of Zamboanga, upper stratum.

Murex capucinus Lam .... L.

III. CEBÚ.

Coal mines at Alpaco.

Vicarya callosa Jenk .... M.

For a considerable number of species the exact localities are unfortunately entirely unknown. These are *Pleurotoma coronifera* Mart., *Pl. neglecta* Mart., *Pyrula gigas* Mart., *Ranella elegans* Beck., and *Callianassa Dyki* Mart.

The most interesting of these fossils are those collected from the bank of the Catalangan River and the Ilaroen. These are two small streams which at Minanga empty into the Ilagan, a right-hand tributary of the Rio Grande de Cagayán, which debouches on the north coast of Luzón. The Catalangan, "a narrow mountain torrent," is the less important and flows from the east. The Ilaroen comes from the south.[1] Unfortunately Semper's notes on his journey in this neighborhood bear the impress of haste. Lack of food and illness prevented exact observations, and consequently his report contains no precise information as to the localities of the Tertiary fossils from the Catalangan and the Ilaroen.

Among these fossils *Vicarya callosa* Jenk. is of the utmost importance, because this characteristic genus, of which only two species are known, may be considered as a good guide-fossil to the tropical Miocene. For *V. callosa* Jenk. has hitherto been found only in the upper Miocene of Java, and *V. Verneuili* d'Arch. occurs only in the Gaj series of western India, which also belongs to the Miocene. According to this indication, there would be Miocene beds in place both on the bank of the Catalangan and on that of the Ilaroen. The other fossils from the same localities are in complete harmony with this supposition. From the right bank of the Catalangan, as appears in the list given, there are in the collection 10 species, of which 6 are extinct, 8 are known in the Miocene (unquestionably), and 4 have hitherto been found only in the Miocene deposits of the Indian Archipelago. From the right bank of the Ilaroen at Minanga 8 species have been determined, among which only 1 is still living, while 6 occur in the Miocene, and 5 of these exclusively in the Miocene. Each of the localities, even taken by itself, thus points unambiguously to the occurrence of the Miocene near Minanga, and it may be considered as beyond question that the strata of the two localities are coeval. On this assumption all the fossils of Minanga may be regarded as a single group. This method of dealing with the subject gives 14 different species, of which 9, or 36 per cent,[2] are extinct, 11 are Miocene, and 7 are exclusively Miocene. Judging from all these facts, the strata at Minanga are to be classed with the upper Miocene bed which exists in Java in the locality denoted by Junghuhn by *O* and at Selatjau on the Tji Longan.

It is also presumable that the remaining fossils which were collected from the bank of the Ilaroen above Minanga and Goroen (Nos. 3 to 5 of the above list) were taken from upper Miocene strata. Further-

[1] Compare the map in Semper's Philippinen, and, further, Semper's journey through the northeast provinces of the Island of Luzón: Zeitschr. für allg. Erdkunde, Neue Folge, Vol. X, 1861, pp. 256–258. In the latter paper one of the streams is called Ilagon or Ilaron, but both on the labels and on Semper's map it appears as Ilaroen, so that I must consider this last form the correct one. [On Mr. d'Almonte's map, Semper's Minanga seems to be represented by Malunú. The stream from the east is called Catalangan, but that from the south is put down as Tarretic. Polynomial streams form an abiding source of confusion throughout the Philippines.—G. F. B.]

[2] This should read 36 per cent still alive or 64 per cent extinct.—G. F. B.

more, there must be such also on the brook Dicamui, since thence also comes a specimen of *Vicarya callosa*. Unfortunately I was unable to determine certainly where this brook is, yet it is presumably identical with the Dicamuni, which flows, according to Oebbeke, "in the land of the Minangas on the west side of the cordillera of northwest Luzón."[1] The same typical fossil of the upper Miocene, *Vicarya callosa*, occurs finally at the coal mines of Alpacó, on the island of Cebú, to the north of Mindanao. These mines lie in the interior of the island, in a southwesterly direction from the town of Cebú and to the northwestward of Naga.

Abella y Casariego, who has drafted a general geological map of Cebú,[2] divides the rocks into a core of eruptives and superimposed strata of the Nummulite formation, post-Pliocene limestone, and finally Recent alluvium. The determination of the post-Pliocene strata depends upon a thorough investigation of the remains found in them, of which twenty-nine could be identified with living species, while no extinct species whatever were found.[3] Paleontological proof is also given for the existence of the Nummulite formation,[4] but it must be regarded as very questionable whether the entire system of strata[5] considered as belonging to it ought to be regarded as Eocene. That at least a part of this system must be excluded is proved by Semper's find; for according to the map of Abella y Casariego the mines of Alpacó, at an elevation of 298 meters, are also in the Eocene, which, as shown above, is incorrect. The strata which contain *Vicarya callosa*, however, seem to be the same which have attracted the attention of the Spanish naturalist and which crop out on the slope of Sibod. In fact, according to Abella, the limestones at this point are covered by a fossiliferous marl which can not be classed with them either on petrographical grounds or by its fossils.[5] Although the conditions are not described with the clearness which would be desirable, it must be considered very probable that, in this region of Cebú, Eocene limestones are overlain by Miocene marls.

In addition to the localities already dealt with, the neighborhood of Aringay in Luzón requires attention first of all. This place lies in the northwestern portion of the island, on the northeast coast of Lingayén Bay, and Semper visited it from the capital of the district of Benguet,[6] which is likewise called Benguet, or, also, La Trinidad. It

[1] Ibid., p. 498. [I have heard of no tribe of Minangas. According to Semper's text and his map, Minanga is in "the land of the Irayas," a well-known tribe in the Province of Isabela. The probabilities are strongly in favor of the hypothesis that Dicamui or Dicamuni is a brook near the Catalangan, and that in the phrase quoted from Oebbeke northeast should be substituted for northwest. In Ilocos I can find no suggestion of similar names, and Semper correctly labels that part of the country "land of the Igorrotes." Minanga is one of the few names entered on Semper's map in northern Luzón.—G. F. B.]

[2] D. Enrique Abella y Casariego. Rapida descripción física, geológica y minera de la Isla de Cebú, Madrid, 1886.

[3] Ibid., p. 125. [4] Ibid., p. 109. [5] Ibid., p. 114.

[6] Reisen durch die nördlichen Provinzen der Insel Luzón: Zeitschr. für allg. Erdkunde, 1862, p. 86.

is in this sense that his descriptive terms "foothills in front of Aringay" (Vorhügel vor A.) and "hills close to Aringay" (nächster Hügel von A.) are to be understood, since they manifestly indicate a reference to the road followed. According to von Drasche, a range of hills, 200 to 300 feet in height, lies between Aringay and the sea, following the narrow strip of alluvium which accompanies the coast. This range is steep on the side toward the sea, and at the point in question is composed of light-yellow earthy tuff. Layers of tuff are also exposed, according to this authority, at many points between Aringay and Benguet,[1] but these tuffs toward the interior, even at Galiano, are "no longer earthy, but quite hard, crystalline and sandstone like." Probably on this account Semper states[2] that sandstones form the entire western slope of the Cordillera from Benguet to Aringay, but he particularly states that this rock, "at all events the upper strata of it, is absolutely devoid of fossils." The *Heteropsammia* already mentioned, which Semper collected, can not, therefore, come from the neighborhood of Galiano, as von Drasche supposed. They can come only from the range of hills parallel with the shore near Aringay, from which also the fossils that I have determined, embedded in a dirty, gray, sandy marl, must also have been derived. This range of hills at Aringay, then, must belong to the later Tertiary, as the fossils enumerated prove, and the conditions suggest that they may be coeval with the strata which are developed as tuffaceous marls along the seacoast between Paláuig and Santa Clara, claimed by Karrer as late Tertiary. The fossils thus far identified, however, are insufficient to determine whether the sediments of Aringay are referable to the Miocene or the Pliocene.

The position of Satpat, on Luzón, from which two Miocene fossils mentioned above were obtained, I have unfortunately been unable to ascertain.

As for Mindanao, it can not be demonstrated from specimens which have been investigated that Miocene strata occur there, for I have but a single species, *Ranella raninoides* Mart., which is known only in the Miocene.[3] On the other hand, it is clear that there are upper Tertiary beds along the Agusan River. If it were permissible to assume that all the fossils of the list given above originated in equivalent beds,

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[1] Fragmente, pp. 29–31.

[2] Ibid., p. 84. [Abella asserts positively that these rocks are sandstones derived from a dioritic area. Terremotos experimetados en la Isla de Luzón durante . . . . 1892, Manila, 1893, p. 33.—G. F. B.]

[3] Marine Miocene is assumed, however, by Casariego in Mindanao, in his Memoria acerca de los criaderos auriferos del segundo distrito de Mindanao: Bol. de Comisión del Mapa geológ. de España, Vol. VI, Madrid, 1879. This paper, which is noticed in Neues Jahrbuch, 1883, I, p. 355, I have unfortunately been unable to consult, and on what grounds the determination of the strata in question as Miocene rests is not inferable from the notice. [Abella, whose mother's maiden name was Casariego, relied chiefly on the petrographical character and geognostic position of these beds in referring them provisionally to the middle Tertiary. In the limestones of the hills surrounding Pigtao, on the Iponan River, he found imperfect fossils, including one which he thought himself justified in referring to the genus *Turbinolia*. Loc. cit., pp. 35, 46.—G. F. B.]

and their state of preservation makes this probable, there would be in all 10 species, 6 of them, or 60 per cent, still living; 4 species occur in the Miocene and the same number in the Pliocene; but of these last three are known only from the Pliocene. These are *Latirus madiunensis* Mart., *Turricula bataviana* Mart., and *Murex verbeeki* Mart. All this argues the occurrence of the Pliocene on the Agusan River, and in harmony with this indication is the exceedingly fresh appearance of the fossils at hand.

The same age finally may be ascribed to the fossils from the river Salac y Maputi in Mindanao; for although of the 6 species determined from this locality no fewer than 5 belong to the present fauna, yet of these latter 4 reach back to the Miocene and Pliocene and a single species, *Murex verbeeki* Mart., is known only in the Pliocene. Of the deposit at Zamboanga nothing definite can be said as yet on the strength of the solitary fossil *Murex capucinus* Lam.

To the age determinations of Philippine fossils it is proper to add that their state of preservation resembles that of the Javanese fossils to a very remarkable extent—to such a degree, indeed, that the specimens from the two regions might easily be confounded. The same statement is true of the tuffs and marls in which they were embedded, and this accords with the fact that the younger massive rocks of the Philippines show an extraordinary likeness to those of the East Indian Archipelago.[1]

Collecting the results of the investigations thus far made, we get the following general scheme for the fossil-bearing strata of the Philippines:

1. Eocene.

To this formation belong the nummulitic limestones from the neighborhood of Manila (Luzón) and of Cebú. The same formation is perhaps developed at Zamboanga (Mindanao).

2. Upper Miocene.

(*a*) Tuffs and sandy marls which are equivalent to the upper Miocene of Java exist in the neighborhood of Minanga, in the valley of the Rio Grande de Cagayán (Luzón). Deposits of the same age are to be found also on the stream Dicamui, the position of which could not be ascertained, and finally at the coal mines of Alpacó (Cebú).

(*b*) Tuffaceous, foraminiferal marls from the western slope of the Sierra Zambales (Luzón), which are younger than the beds enumerated under *a*, and which possibly belong in the Pliocene. Perhaps equivalent to these are the masses of tuff which form the range of hills on the coast at Aringay (Luzón) and which certainly belong to the upper Tertiary.

[1] Roth, Ueber d. geolog. Besch. d. Philippinen, p. 338. Oebbeke, Beiträge, p. 453.

3. Pliocene.

The beds of the Agusan River (Mindanao) are Pliocene. It is probable that as such are also to be counted the hard, light-gray marls of the river Salac y Maputi (Mindanao) and the clay beds of Paranas (Sámar), as well as the older coral reefs of the Philippines, especially those of Benguet,[1] which are assuredly not older than the Pliocene.

4. Quaternary.

Quaternary are the shell banks which stand 15 feet above the level of Laguna de Bay (Luzón), and those on the beach at Paranas, and again on the south coast of Sámar, where, at Nipa-Nipa, these beds reach an elevation of 60 feet above sea level. Here, too, belong the fossil coral reefs, which are intimately connected with the living reefs and are widely distributed in the Philippines.[2] With them belong the recent limestones of Cebú.

Vicarya callosa Jenk., var. nov. semperi.

Vicarya (?) callosa Jenk. Javan fossils: Quart. Jour. Geol. Soc. 1864, Vol. XX, p. 57, Pl. VII, fig. 5. Martin, Tertiärschicht. auf Java, p. 62, Pl. XI, fig. 3.

The turreted shell consists of flattened whorls, which are separated from one another by a distinct but not incised suture, and carry a number of sharply defined spiral beadings. Even on the older part of the shell five such beadings are visible, the last of which runs immediately in front of the after suture of the whorl, and is much stronger than the two beadings which lie immediately in front of it. Then follows a strong ridge, again succeeded by a very slender one on the anterior edge. On the younger parts of the shell sharp knots are situated on the last spiral of the whorls. They number eight to nine, and with the growth of the shell become modified into short, sharp prongs which stand at right angles to the axis of the shell. In front of this row of prongs, which accompanies the suture, only three spiral beadings are observable, of which the first two are the strongest, while the fifth spiral beading of the older turns is covered by the succeeding whorl. The incremental lines are smoothly but deeply bent into the shape of an S, in such a way that the deepest incurvation, corresponding to the incision of the exterior lip, lies between the two strong spiral beadings on the frontal termination of the whorls.

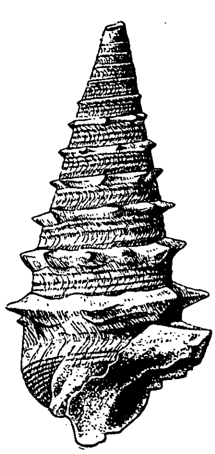

Fig. 103.—*Vicarya callosa* from Minanga.

The terminal whorl carries in front of the suture several more spiral beadings of variable strength. The canal is short and bent backward,

[1] Compare Semper, Zeitschr. für allg. Erdkunde, 1862, p. 84; and Philippinen, p. 18; also von Drasche, Fragmente, p. 31.

[2] For distribution see Semper, Philippinen, p. 18.

the pillar is provided with a distinct fold, the interior lips being swollen and thickened in such a way that the thickening on the left forms a half-moon-shaped swelling which rests on the terminal whorl and is prolonged as a tongue to the right. The exterior lip is not preserved, but, judging from the incremental lines, it has the same shape as in *V. Verneuili* d'Arch. The length of the largest complete individual is 74 mm., and this size, to judge from the material at hand, is rarely or never exceeded.

A slight variation from the foregoing usual development is brought about by the interpolation of a fine additional beading between the two spirals which include between them the incision of the outer lip. In other cases these spirals are inconspicuous at this point, while between the horns two longitudinal beadings are developed.

V. callosa Jenk. from Java is never provided with such prominent beadings as is the fossil here described, and only in very isolated cases is the sculpture of the latter feebly indicated on the former, so that the spiral sculpture of the Philippine fossil affords a good distinction. The Javanese form is also larger and stouter, and its prongs have a different character, while the callosity of the inner lip reaches farther back and here, as a rule, envelops a prong of the previous whorl. Nevertheless, the relationship of the fossil under discussion to the Javanese *V. callosa* Jenk. is so close that I can regard it only as a local variety of the latter.

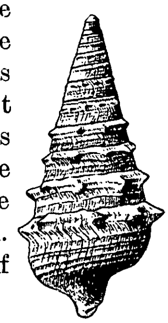

FIG. 104.—*Vicarya callosa* from Dicamui Brook.

From *V. Verneuili* d'Arch. (Descript. d. anim. foss. de l'Inde, p. 298, Pl. XXVIII, fig. 4) it is easy to distinguish the Philippine form, as well as that from Java; for the species from British India, in addition to the principal row of knobs, bears spirals provided with delicate granules. Moreover, knobs along the suture of the younger portion of the shell are not transformed into prongs, as in the Javanese fossils, and still more in those from the Philippines; and finally, the callosity of the inner lip is differently shaped.

No other representatives of *Vicarya* are yet known, for the fossil which Hislop described as *V. fusiformis* Hislop (Foss. shells of Nagpur, Quart. Jour. Geol. Soc., Vol. XVI, p. 177, Pl. VIII, fig. 36) certainly can not be grouped with the species mentioned.

I have before me fourteen individuals and fragments of the Philippine variety of *V. callosa* Jenk., which I wish to call var. *Semperi*.

Fig. 1 comes from Minanga, from the right bank of the Catalangan.

Fig. 2 comes from the brook Dicamui in Luzón.[1]

Finished October, '95.

[1] These figures have been reduced to three-fourths the size of the original, to facilitate copying.—G. F. B.

INDEX.

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[Twenty-first Annual Report, Part III.]

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STATISTICAL PAPERS.

Mineral Resources of the United States, 1882, by Albert Williams, jr. 1883. 8°. xvii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1883 and 1884, by Albert Williams, jr. 1885. 8°. xiv, 1016 pp. Price 60 cents.

Mineral Resources of the United States, 1885. Division of Mining Statistics and Technology. 1886. 8°. vii, 576 pp. Price 40 cents.

Mineral Resources of the United States, 1886, by David T. Day. 1887. 8°. viii, 813 pp. Price 50 cents.

Mineral Resources of the United States, 1887, by David T. Day. 1888. 8°. vii, 832 pp. Price 50 cents.

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Mineral Resources of the United States, 1891, by David T. Day. 1893. 8°. vii, 630 pp. Price 50 cents.

Mineral Resources of the United States, 1892, by David T. Day. 1893. 8°. vii, 850 pp. Price 50 cents.

Mineral Resources of the United States, 1893, by David T. Day. 1894. 8°. viii, 810 pp. Price 50 cents.

On March 2, 1895, the following provision was included in an act of Congress:

"*Provided*, That hereafter the report of the mineral resources of the United States shall be issued as a part of the report of the Director of the Geological Survey."

In compliance with this legislation the following reports have been published:

Mineral Resources of the United States, 1894, David T. Day, Chief of Division. 1895. 8°. xv, 646 pp., 23 pl.; xix, 735 pp., 6 pl. Being Parts III and IV of the Sixteenth Annual Report.

Mineral Resources of the United States, 1895, David T. Day, Chief of Division. 1896. 8°. xxiii, 542 pp., 8 pl. and maps; iii, 543-1058 pp., 9-13 pl. Being Part III (in 2 vols.) of the Seventeenth Annual Report.

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Mineral Resources of the United States, 1897, David T. Day, Chief of Division. 1898. 8°. viii, 651 pp., 11 pl.; viii, 706 pp. Being Part VI (in 2 vols.) of the Nineteenth Annual Report.

Mineral Resources of the United States, 1898, David T. Day, Chief of Division. 1899. 8°. viii, 616 pp.; ix, 804 pp., 1 pl. Being Part VI (in 2 vols.) of the Twentieth Annual Report.

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