must be of later age than the great mass of granite of the Archean area.

The Archean is cut by basic dikes of two ages. The earlier ones were rendered schistose, and the production of this secondary structure was accompanied by a total obliteration of the primary igneous texture and the production of a large amount of mica and hornblende. All the dikes were probably injected at the time of the volcanic activity when the volcanics of the higher series were ejected, but no proof of their connection can be produced. They were, however, injected before the folding of the area took place, as shown by their having been rendered schistose by it.

A single dike belonging to the later series was studied. It is massive, and therefore was irrupted after the folding which produced the schistosity in the earlier series of dikes. It belongs probably to a Keweenawan or post-Keweenawan period of eruption.

[1]For a discussion of the orogenic movements which affected the Crystal Falls district, the reader is referred to p. 158 et seq.

CHAPTER IV.
THE LOWER HURONIAN SERIES.

This series is represented in the Crystal Falls district by the following formations, given in order from the base upward: The Randville dolomite, the Mansfield slate, and the Hemlock formation. At the beginning of the deposition of the Lower Huronian series the entire district was covered by the pre-Cambrian sea, with the possible exception of a small island in the Archean area.

SECTION I.—THE RANDVILLE DOLOMITE.

The best exposures of this dolomite are found near the center of the district east of the western ellipse and in the extreme southeastern part of the district in the Felch Mountain range. Both areas are described by Smyth, to whom we owe the name, and the reader is referred to his description on p. 406 and p. 431 for the detail characterization of the formation. It will suffice for our purpose to state that it is a medium-grained crystalline dolomite.

The few outcrops which I shall mention are important as showing the relations of the formation to the underlying rock, but are, petrographicaily considered, rather exceptional phases of the formation. Hence my description will be brief.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

The area in which the Randville dolomite immediately underlies the drift is a continuous zone adjacent to and surrounding the Archean core. The belt varies slightly in width along the sides of the ellipse. At the ends it is two or three times the width at the sides. This is due to the lower dip of the beds at the ends. Exposures are found in the area studied by me only on the northeast and southwest flanks of the granite core.

The west branch of the Fence River follows the limestone area for a short distance in the northeastern part of the district, skirting the Archean granite. On the whole, however, the Randville dolomite has had no marked effect on the topography or the drainage.

PETROGRAPHICAL CHARACTERS.

Ill general the Randville dolomite consists petrographically of a fine-grained dolomite, with some quartz. This grades down through a calcareous quartzite by increase of quartz into a true quartzite. The nearer the granite, the more quartzitic is the formation. At the southeast corner of sec. 2, T. 45 N., R. 32 W., on the west bank of the west branch of the Fence River, is a very good exposure of the quartzite. Its derivation from the underlying granite is here shown. The rock is a very fine-grained, almost novaculitic, quartzite. It shows current bedding in some places, though no true bedding was observed. Immediately below this quartzite is a very schistose rock, in which one can readily distinguish macroscopically rounded to lenticular quartz areas, with masses of sericite flakes between them. The contact between the quartzite and the schistose rock seems very sharp when viewed from a short distance, but is found to be indefinite when closely examined. A close search was made along a contact for pebbles from the granite, but such were not found. However, small rounded pieces of vein quartz, most probably derived from the granite, were observed. The schistose rock in its turn grades down into a grayish granite, which is also more or less schistose. We have here evidently a transition from the granite, through the intermediate schistose recomposed granite, to the true sedimentary rock above. The meaning of this transition is considered below.

Under the microscope the cause of the schistosity of the rock intermediate between the granite and the quartzite is plain. Quartz and sericite, with some feldspar, are alone present in it. The quartz is grayish and granulated, and mashed out into oval areas representing original quartz grains. Various fragments constituting the areas are, however, angular and more or less equidimensional, and when not so never have a definite orientation of their longer axes. Between these large areas, but not between the individual small fragments constituting the areas, sericite is abundant. When the sericite is not predominant, the flakes lie in a fine mass of quartz grains, each of which agrees in long direction with the mica plates and large oval quartz areas. The sericite flakes are both included in this quartz, and also lie between the grains. In one instance fragments of the original feldspar were found in the midst of such an area. These quartz-sericite areas are unquestionably of secondary origin, and the minerals have developed in connection with pressure. They were probably produced from feldspar which existed in the original granite.

Whether this schistose rock was formed from a weathered but not transported granite, from an arkose or feldspathic sandstone, or from the solid granite, it is impossible to say. A similar sericite-schist which developed from recomposed granites has been described by Van Hise as occurring at several localities in the Marquette district.[1] In these cases at places the fragmental characters are still sufficiently clear to admit of the statement that the rocks are sedimentary. In the Crystal Falls rock mashing has destroyed all original characters. The rock occupies an intermediate position between a metamorphosed sedimentary and a metamorphosed eruptive, and grades on the one hand into the sedimentary and on the other into the eruptive. This makes it impossible to say whether it belongs exclusively to the one or to the other, or in part to both. Similar relations in other parts of Michigan were explained by Rominger[2] as cases of progressive metamorphism of sediments, the granite being supposed to be the extreme stage of alteration of the sedimentary rock. Later the finding of basal conglomerates at or near these localities has shown conclusively that this explanation is incorrect, and it has been abandoned by Rominger.

The quartzite, which immediately overlies the rock of doubtful character, is composed of angular grains of quartz, between which are plates of sericite which have an imperfect parallelism, thus giving a certain degree of schistosity to the quartzite, possibly enough in places to warrant its being called a quartz-schist. The rock shows no conclusive microscopical evidence of a sedimentary origin, but differs from the cherts, with which it might be confused, in the size of the grains and in the presence of sericite. This rock was originally probably chiefly composed of quartz sand, with some feldspathic material from the disintegrated granite. Coincident with the pressure which produced the striking schistosity in the underlying rock, this sand was also mashed, resulting in the production of sericite and quartz from the feldspar and in the crushing of the quartz grains, thus completely destroying the rounded clastic grains and obliterating all the sedimentary character of the rock, except the macroscopic structure of current bedding.

[1]Mon. U. S. Geol. Survey Vol. XXVIII, 1897, p. 226.

[2]The Marquette Iron district, by Carl Rominger: Geol. of Michigan, Vol. IV, Part I, 1878-1880, pp. 15-52.

On the west side of the granite ellipse, at N. 1750, W. 1550, sec. 12, T. 44 N., R. 32 W., about 100 yards from the granite, to the north, and lower down on the slope of the same hill on which the granite is found, is found a carbonaceous quartzite or quartzose dolomite. The strike is N. 25°-35° W. The surface only is seen, so that the dip could not be taken. Microscopical examination shows the rock at the eastern side of the exposure to be made up of quartz grains held together by a fine-grained carbonate cement. This grades up to the west by increase of calcite and corresponding diminution of quartz to a quartzose dolomite.

At N. 500, W. 1550, sec, 1, T. 44 N., R 32 W., one-fourth mile distant from the granite, is seen another outcrop of a very dense quartzose dolomite, appearing macroscopically almost like a vitreous quartzite, but really with just enough quartz grains in it to enable the qualifying term “quartzose” to be appropriately used. The brown ferruginous crust on the weathered surfaces point to a percentage of iron in the magnesium-calcium carbonate. The pure limestones are to be sought slightly farther away from the Archean shore, where the conditions were more favorable for the production of a pure nonclastic sediment.

RELATIONS TO UNDERLYING AND OVERLYING FORMATIONS.

At only the one place cited above has a contact between the granite and the Randville dolomite been found. It is probable that unconformable relations exist, even though no basal conglomerate has been discovered as evidence of wave action on the Archean coast.

Relations between the Randville dolomite and the overlying formations have not been observed in the part of the district studied by me.

THICKNESS.

Reliable data for estimating the thickness of the Randville dolomite have only been obtained in that area surveyed by Smyth. (See p. 433.) According to his estimate, the formation possesses a maximum thickness of 1,500 feet

SECTION II.—THE MANSFIELD SLATE.

The formation of the Lower Huronian, which is next higher than the Randville dolomite, is composed of sedimentary beds, in which a slate predominates.

This formation is found in its most typical development in a narrow valley through which the Michigamme River flows, and in which the village of Mansfield and a mine of the same name are situated. The valley and the slates are well known in the Crystal Falls district on account of their economic importance. For this reason the name “Mansfield slate” is here applied to this formation.

DISTRIBUTIONS, EXPOSURES, AND TOPOGRAPHY.

The part of the valley occupied by the Mansfield slates begins at the northern section line of secs. 17 and 18, T. 43 N., R. 31 W., and extends due south for 3 miles to the southern section line of sec. 29 of the same township. The slate belt is widest at the north, being over one-fourth mile wide on the westren side of section 17. To the south it gradually diminishes in width, until it finally disappears in sec. 29. The strike of the sedimentary rocks is almost due north-south, except in a few places where the rocks have been gently flexed and the strike

varies a few degrees. The dip is high to the west, ranging from 65° to 80°.

The influence of the Mansfield slate belt upon the topography is strikingly shown by the depression in which the slates are found, and which contains the Michigamme River. The slates are surrounded on all sides by igneous rocks which form fairly high hills, those to the west being composed of rocks of volcanic origin, those to the north, east, and south being intrusive, and later than either the sedimentaries or the volcanics. The Michigamme River flows south through sec. 1, T. 43 N., R. 32 W., and meets the east and west ridge of intrusives in the northeastern part of sec. 12 of the same township and range. It cuts through this at an oblique angle, changing its course to the southeast: In sec. 7, T. 43 N., R. 31 W., it leaves the intrusives and penetrates a short distance into the volcanic rocks, their contact not being able to cause a change in the course of the river, owing to the slight difference in resisting power between the intrusives and the volcanics. Still flowing to the southeast, it finds at the Michigamme dam, on the section line between secs. 7 and 18, near the southeastern and northeastern corners, respectively, the contact between the three kinds of rock, the sedimentaries, the volcanics, and the intrusives. Where the water leaves the eruptive and enters the sedimentary area the more easily erodible nature of the rocks of the latter is well shown by the falls which have been formed, the volcanics constituting the barrier over which the water plunges into a deep basin worn from the slates. Crossing the slates in the same direction, i. e., southeast, the river strikes squarely against the intrusive dolerites and is deflected to the south, following the contact between the two rocks for a short distance, then gradually working to the west into the center of the sedimentary area, the river takes an almost directly southerly course, with only minor bends. In the slates the river has fairly low flat banks on both sides. In the southern portion of the area the valley is narrower, owing to the progressive narrowing of the sedimentary belt. As soon as the river leaves the Mansfield slate belt, it resumes the sinuous course it had before the Mansfield belt is entered, and flows between high banks through the intrusives, out through the sand plains near Lake Mary.

POSSIBLE CONTINUATION OF THE MANSFIELD SLATE.

In sec. 10, T. 44 N., R. 32 W., about 7 miles northwest of the extreme northern end of the Mansfield area of slate, there are one or two exposures of much crumpled interbedded brown and black slates. Their strike is about N. 16°-20° W., but owing to their plicated condition the dip varies from 55° southwest over to 85° northeast. The average dip, however, is presumed to be to the southwest, which is in accord with the general structure of the area.

The slate exposures are surrounded by coarse-grained basic intrusives, dolerites, which outcrop within short distances on all sides. The nearest sedimentary beds are quartzose dolomite ledges which outcrop 1½ miles to the east, in secs. 1 and 12, T. 44 N., R 32 W., rather close to the Archean granite. A section across the Lower Huronian rocks at this point shows the Archean granite overlain by quartzose dolomite, which is in its turn overlain by the slates. The relations which these rocks bear to one another are those which similar ones bear to one another near Michigamme Mountain,[1] and the slates of the two areas are consid red to be of the same age. Since the slates correspond stratigraphically to the slates of the Michigamme Mountain and to those of the Mansfield area, they have been connected on the map with the slates of Michigamme Mountain by a narrow belt included between dotted lines; but this belt is not based on any connecting exposures. These two ledges of slate are taken as the northernmost outcrops of the Mansfield slate formation, although a number of miles north and in direct continuation of them along the strike there was found a single doubtful outcrop of a graywacke, showing neither strike nor dip. Whether it represents a shallower water deposit contemporaneous with the slates it is impossible to say. However, on such slight evidence it was not deemed advisable to continue the slate belt to this point.

PETROGRAPHICAL CHARACTERS.

A petrographical description of the Mansfield slate belt must necessarily be very brief, owing to the small area and to the scarcity of the exposures.

The rocks of the Mansfield slate belt are graywackes, clay slates, phyllites, siderite-slates, cherts, ferruginous cherts, and iron ores, with the various rocks which have been derived from them by metamorphism. They vary from coarse-grained rocks to very fine grained slaty ones. The latter predominate, and for that reason this belt is called a “slate” belt. The color of the rocks varies from an olive green and purplish black to bright red for those which are very ferruginous and more or less altered.

The ordinary detrital rocks may be divided into the coarser and the finer kinds. The first are the graywackes, and the second are the ordinary clay slates and phyllite. There is, however, a gradation from the one to the other.

[1]See Part II, Chapter IV, Sec. IV, by H. L. Smyth.

GRAYWACKE.

The graywackes consist largely of grains of quartz, and feldspar of unquestionably detrital origin. Associated with these is a large amount of mica, chlorite, and actinolite, with invariably more or less rutile. This last is in minute grains as well as in crystals. Many of the crystals show fine knee twins, triplets, and more rarely, heart-shaped twins. Tourmaline is sometimes present. The ferro-magnesian minerals develop chiefly from the alteration of the feldspar, and from the finer detritus which is presumed to have existed between the grains. As a consequence, the secondary minerals lie between

the original grains. Many of the quartz grains are enlarged, and here the secondary minerals are included in the new areas of the enlarged grains. In numerous cases the new quartz occupies about as much space as the original grains themselves. This shows very clearly the porous character of the original sandstone. All original grains of the rocks show signs of extensive mashing. Some specimens contain a large amount of tourmaline in long slender crystals, which penetrate both the feldspar and the quartz grains. The presence of tourmaline is especially interesting as indicating that these sedimentaries may have been subjected to a certain amount of fumarole action. According to the proportion in which the various minerals have developed, we obtain sericite-, actinolite-, or chlorite-schists produced from the graywackes.

CLAY SLATE AND PHYLLITE.

The clay slates are dull and lusterless and are black, olive green, or red in color. They are usually impregnated with more or less iron pyrites in large macroscopical crystals. One can distinguish in them quartz, white mica, a few needles of actinolite, rutile, hematite, with a small proportion of a dark ferruginous and carbonaceous interstitial material.

The amount of iron which these clay slates contain varies considerably. In some, hematite is present in such quantity as to cause the slates to be appropriately called hematitic slates. Such, for instance, is the one forming the foot well of the Mansfield ore body. The iron oxide gives to the slates a very bright red color where they are weathered. These weathered hematitic slates are very commonly known in the district as red slates, or as “paint rock” or “soapstone,” though rocks of very different character are also at times designated by these names.

The phyllites have a silky luster and a bluish-black color. They are composed essentially of white mica quartz, some feldspar, innumerable minute crystals of rutile and dark ferruginous specks. These seem to differ from the rocks called here clay slates only in that they are more completely crystalline, the interstitial material of the slates having disappeared.

ORIGIN OF CLAY SLATE AND PHYLLITE.

The origin of the clay slates of the Mansfield formation is probably to be looked for in the disintegration and decay of the Archean granite, and the subsequent metamorphism of the resulting clay. For between the granites and the slates no other rock masses are known to have existed from which the clay could have been derived. The phyllites are presumed to have resulted from the metamorphism of the clay slates.

PRESENT COMPOSITION NECESSARILY DIFFERENT FROM THAT OF ROCK FROM WHICH DERIVED.

It is a well-recognized principle of rock weathering that in the alteration of rocks near the surface of the earth there is a relatively rapid diminution in the quantity of the more soluble constituents. Hence a clay shows a lower percentage of alkalies and alkaline earths than is found in the parent rock, with an increase in the percentage especially of alumina and water. This relation is made clear by Adams in a statement of the comparison of the composition of certain slates and granites:[1] “On comparing the analyses of a series of granites with those of a series of slates, as, for instance, those given in Roth’s ‘Gesteins Analyzen,’ the latter are seen to be on an average considerably higher in alumina and much lower in alkalies, while at the same time they are lower in silica, which has been separated both as sand and in combination with the alkalies which have gone into solution, and in most cases contain more magnesia than lime instead of more lime than magnesia, as is usual in granites.” Adams concludes further, after a comparison of the alkalies in the slates and granites, that “The slates thus contain on an average about two-thirds of the amount of alkali present in the average granite.”[2] An examination of series of analyses of granites shows that while the percentages of soda and potassa vary considerably, now the one being predominant, now the other, oil the whole in the typical granites the potassa is higher than the soda.[3] This is the relation which we would expect in the case of an ideally pure granite in which no anorthoclase replaces the orthoclase. As a consequence of the easier solubility of the soda, this relation between the two alkalies, soda and potassa, is maintained, and is often made more striking in the clay slates. An average of 31 analyses of clay slates taken from various sources shows two and one-half times as much potassa as soda. In the case of the Mansfield slate this difference has been increased, so that there is ten times as much potassa as soda present.

[1] A further contribution to our knowledge of the Laurentian, by F. D. Adams: Am. Jour. Sci., 3d sep., Vol. L, 1895, p. 65.

[2] Loc. cit., p. 65.

[3] Zirkel states that in the weathering of granites the soda is much more readily removed than is the potassa: Lehrbuch der Petrographie, Vol. II, 1894, p. 32.

ANALYSIS OF MANSFIELD SLATE.

Mr. George Steiger, of the United States Geological Survey, has prepared a complete analysis (No. 1 in the following table) of a typical specimen of the Mansfield clay slate. Analyses Nos. 2 and 3 were prepared by W. Maynard Hutchings,[1] and numbered by him Nos. 2 and 5, respectively.

Analysis of the Mansfield clay slate.

Constituent.	1.	2.	3.
SiO_2	60.28	59.28	53.57
TiO_2	.69	.....	.....
Al_2O_3	22.61	21.85	24.53
Fe_2O_3	2.53	5.80	6.51
FeO	.45		
MnO	Trace.	.....	.....
CaO	.13	.45	.76
BaO	.04	.....	.....
MgO	1.35	1.24	1.81
K_2O	5.73	4.13	4.34
Na_2O	.54	1.18	.97
H_2O at 100°	.60	6.25	7.65
H_2O above 100°	3.62		
P_2O_5	.03	.....	.....
CO_2	None.	.....	.....
C	.97	.....	.....
Total	99.57	100.18	100.12

COMMENTS ON ANALYSIS,

That which is the most striking about the analysis is the relative proportion of the alkaline earths, lime, and magnesia, the latter being present in the greater quantity. As a rule, in all of the igneous rocks (and to the igneous rocks all clay slates owe their ultimate origin), except in the nonfeldspathic ultrabasic ones, the reverse condition exists, namely, the magnesia subordinate in quantity to the lime. The difference in amount of soda and potassa is very striking and should he noticed, in view of certain points to which attention will be called in subsequent pages. The percentage of alumina is higher than is usual in the clay slates. It will be noticed that considerable water is present, but in consideration of the character of the rock this is to be expected. If anything, the value is rather lower than would be expected, indicating a possible loss of water due to the rock having already undergone some dynamic action. The carbon present is considered as offering trustworthy evidence of the presence of organic life at the time of the deposit of the slates, though no more satisfactory evidence of the existence of life has been found.

[1]Notes on the composition of clays, slates, etc., and on some points in their contact metamorphism: Geol. Mag., Vol. I, 1894, p. 38,

COMPARISON OF ANALYSIS OF MANSFIELD CLAY SLATE WITH ANALYSES OF CLAYS.

During the last few years there have appeared in the Geological Magazine, from the pen of Mr. W, Maynard Hutchings, some very elaborate and suggestive articles upon the composition of clays, shales, and slates, and from one of these[1] I have taken two analyses of Carboniferous clays for comparison with the Mansfield clay slate. These two analyses, Nos. 2 and 3, p. 59, are from the very fine grained clays, in which the quartz was not distinguishable with the microscope, and are the analyses showing the highest and lowest percentages of silica. Mr. Hutchings says of his analyses that the samples were dried at 220° F., and that the titanic oxide was not determined but is contained in the silica and alumina. Concerning the clays, he writes:

From these analyses it will be seen that these clays would be capable, chemically considered, of transformation into very typical "clay-slates." Mineralogically they are clay-slates, having already undergone all, or nearly all, the mineral changes requisite to constitute the normal (unaltered) slates. Nothing more is needed but physical changes, such as compacting, arrangement of mica in a plane, increase of size of mica, etc.[2]

The great similarity of these clays with the Mansfield clay slate is very evident. The only material difference which exists between them is in the higher percentage of water contained in the clays. This difference is natural, clays usually containing about twice as much water as do the slates.

[1]Notes on the composition of clays, slates, etc., and on some points in their contact metamorphism, by W, Maynard Hutchings: Geol. Mag., Vol. 1, 1894, p. 38.

[2]Loc. cit., p. 38.

COMPARISON OF ANALYSIS OF MANSFIELD CLAY SLATE WITH ANALYSES OF OTHER CLAY SLATES.

In the following table there are given, for purposes of comparison with the Mansfield clay slate, analyses of typical clay slates, roofing slates from the Cambrian of Vermont and New York.

Analyses of typical clay slates.

Constituent.	1.	2.	3.	4.	5.
SiO_2	60.28	62.37	59.70	67.61	67.89
TiO_2	.69	.74	.79	.56	.49
Al_2O_3	22.61	15.43	16.98	13.20	11.03
Fe_2O_3	2.53	1.34	.52	5.36	1.47
FeO	.45	5.34	4.88	1.20	3.81
MnO	Trace.	.22	.16	.10	.16
CaO	.13	.77	1.27	.11	1.43
BaO	.04	.07	.08	.04	.04
MgO	1.35	3.14	3.23	3.20	4.57
K_2O	5.73	4.20	3.77	4.45	2.82
Na_2O	.54	1.14	1.35	.67	.77
H_2O at 100°	.60	.34	.30	*a* .45	*a* .36
H_2O above 100°	3.62	3.71	3.82	*b* 2.97	*b* 3.21
P_2O_5	.03	.06	.16	.05	.10
CO_2	None.	.87	1.40	None.	1.89
FeS_2	.....	.06	1.18	.03	.04
C	.97	Trace.	.46	.....	.....
Total	99.57	99.80	100.05	100.00	100.08

a H_2O at 110°. *b* H_2O above 110°.

No. 1. Black slate, Sp. 32497, N. 450, W. 1620, sec. 17, T. 43 N., R. 31 W., Michigan. Analyzed by George Steiger.

No. 2. Sea-green slate, Griffith & Nathaniel Quarry, South Poultney, Vermont. W. F. Hillebrand.

No. 3. Black slate, American Black Slate Company, Benson, Vermont. W. F. Hillebrand.

No. 4. Red slate, three-fourths mile south of Hampton Village, New York. W. F. Hillebrand.

No. 5. Green slate, three-fourths mile northwest of Janesville, Washington County, New York. W. F. Hillebrand.

Nos. 2, 3, 4, and 5 taken from Analyses of rocks and analytical methods, 1880–1896, Clark and Hillebrand: Bull. U. S. Geol. Survey, No. 148. Nos. 2 and 3 are, respectively, C and F, p. 277, and Nos. 4 and 5 are A and D, p. 280.

The strong similarity between the composition of these clay slates is at once apparent, and needs no further comment. The only marked difference between the Huronian clay slate and the Cambrian ones is the higher percentage of alumina present in the former.

SIDERITE-SLATE, CHERT, FERRUGINOUS CHERT, AND IRON ORES.

The two most interesting kinds of rock from the Mansfield slate belt are those known as the siderite- or

sideritic slates and the cherts or ferruginous cherts, according to the quantity of iron carbonate and iron oxide present. These alternate with each other, and are found also interstratified with the fragmental slates, and thus there can be no question as to their sedimentary character. The siderite-slates are of a light to dark gray color. They are well laminated, and in some places cleave rather readily along the laminæ, though at other places they break with an almost conchoidal fracture. The weathered siderite slates are covered by a crust of reddish-brown hydrated iron sesquioxide.

Microscopically the siderite slates are composed of siderite, or of siderite and exceedingly fine grained cherty silica. Roundish rhombohedra of siderite compose the purer sideritic portions. If one passes from the pure to the less pure slates, the siderite gradually diminishes in quantity, the silica grains increase correspondingly, and the rock grades into the chert which, in bands, is commonly associated with iron carbonate in the Lake Superior region. As the carbonate alters to the oxide or hydrated oxide ferruginous cherts are produced. The cherts are white to red, depending on the amount of iron oxide present. The manner in which the siderite alters to limonite and hematite, and the various steps of the process have been so well described and beautifully illustrated in Monograph XXVIII, that the reader is referred to that volume for further information. None of the brilliant red jasper or jaspilite, such as that found in the Marquette district, is associated with the Mansfield slates. Iron ores of economic importance, however, are found associated with these slates, and are described in detail farther on. None of the sideritic slates, ferruginous cherts, or ores, although interbedded with the fragmental slates, show any evidence of fragmental origin so far as the individual grains of the minerals composing them are concerned.

RELATIONS OF SIDERITE-SLATE, FERRUGINOUS CHERT, AND ORE BODIES TO CLAY SLATES.

Owing to the scarcity of the outcrops of the sedimentaries in the Mansfield Valley, it is practically impossible to decipher the relations of the individual beds. Neither the study of the surface exposures nor the exposures in the mine workings have given definite results. That the beds represent interbedded strata is well understood, but the sequence of the strata is indeterminable. It is of especial interest to determine; so far as possible, the relations of the ferruginous rocks, in order that the possible iron-ore deposits associated with them may be found. A cross section through the Mansfield mine from east to west shows the following relations: The foot-wall of black hematitic slate is overlain by 25 to 30 feet of ferruginous chert and iron ore. This stratum is succeeded by “red slate,” so called by the miners, which is probably weathered greenstone impregnated with iron. This is followed by a conglomerate, and this by amygdaloidal greenstone, of the overlying volcanic formation. The ore body extends north and south, agreeing thus with the strike of the slates. All drifts end on the north in mixed ore, and on the south in mixed ore, with “quartz-rock” and “lime-rock” of the miners in some places. From these facts we may justly conclude that the ore-bearing ferruginous cherts exist in beds in the slates or as lenticular masses which agree in dip and strike with the surrounding slates. This conclusion is confirmed by test pits along the strike of the exposed beds, which have disclosed similar ferruginous cherts at various places for a distance of half a mile to the north.

RELATIONS OF MANSFIELD SLATE TO ADJACENT FORMATIONS.

RELATIONS TO INTRUSIVES.

The Mansfield slates are surrounded on three sides—east, north, and south—by coarse-grained basic eruptive rocks. The fact that they are so surrounded by these rocks, which cut them off in the direction of their strike, points to the later origin of these eruptives. Moreover, the quartzitic character of some of the sedimentaries shows that they could not have been derived from the eruptives which stratigraphically underlie them, for in these no quartz is found. The quartzitic character would thus seem also to indicate that the slates are older than the intrusives. Wherever the igneous rocks and slates are in contact or in close association, the latter have been metamorphosed, and adinoles, spilosites, and desmosites have been formed which are similar to those described as occurring in other areas along the contact zone of basic intrusives. Although no single instance of a dike penetrating the slates has been found, it can hardly be doubted from the relations which have been outlined that the slates are older than the intrusive dolerites.

RELATIONS TO VOLCANICS.

The sedimentaries are overlain by volcanics, both lava flows and tufaceous deposits. In these tuffs, at the northeast corner of sec. 7, T. 43 N., R. 31 W., angular black-slate fragments have been found similar in every respect to the slates of the Mansfield belt. From this it is clear that at least some of the volcanics are younger than part of the slate formation. In section 29 similar relations obtain, the only difference being that the masses of slate and graywacke are inclosed in rather larger fragments in a volcanic conglomerate, and still retain very closely their normal strike. In the conglomerates near the Mansfield mine are found chert fragments and in some places fragments of iron oxide. These latter were evidently not included as oxide, but as fragments of cherty carbonate. Like the great mass forming the ore body, the fragments have since their deposition been altered, forming iron-oxide bodies of small size. Further discussion of the relations between the volcanics and slates will be found under the heading “Hemlock formation.”

STRUCTURE OF THE MANSFIELD AREA.

It has already been seen that the Mansfield rocks strike north and south and have a high westerly dip. The two possible explanations of this structure which are compatible with the facts in other portions of the area are (1) that they form a westward dipping monocline, and (2) that they are the western limb of an anticline.

THICKNESS.

As the sedimentaries forming the Mansfield belt now dip west at a very high angle, and as there is no evidence of duplication of strata due to folding, I feel comparatively safe in giving an estimate of their thickness. The belt is widest at the north end, and there has a breadth of about 1,950 feet. The average dip of the beds is 80°, and this gives a maximum thickness of 1,900 feet. Toward the south the belt rapidly narrows, until it is cut out by the intruding dolerites. A thickness of 1,500 feet is probably not far from the average.

To the east of the Mansfield slates is a belt, varying in width up to about 1,200 feet, in which are found large masses of metamorphosed slates, surrounded by intrusive dolerite. In this belt the slate masses still show a general north-south strike, with slight variations to the east or west, and a westward dip. One might, perhaps, consider this a slate area which has been completely saturated with intrusives. If it should be so considered, this thickness should be added to the estimated thickness of the slates as above given, but as intrusives predominate in it, the slate being, as it were, merely incidental, I have preferred not to include it in the belt with the slate.

ORE DEPOSITS.

Although a great deal of exploring for iron ore has been done in the Mansfield slates, only one large body of ore has thus far been discovered, in which is the Mansfield mine. This mine is situated on the west bank of the Michigamme River, in secs. 17 and 20, T. 43 N., R. 31 W. The mine was apparently prospering when, on the night of September 28, 1893, a cave-in occurred, letting in the waters of the Michigamme River and drowning 28 miners.

For two hours after the caving occurred, the bed of the river below the mine was bare, the water flowing into the mine workings. The accompanying figure, fig. 6, prepared by J. Parke Channing, October 8, 1893, shows the relative position of the shaft and the river, and the concentric cracks caused by the caving of the mine. (Plan copied from address of president: Proc. Lake Superior Inst. Min. Eng., Vol. III, 1895, plate opposite p. 42.) The timber shaft is near the center of these cracks.

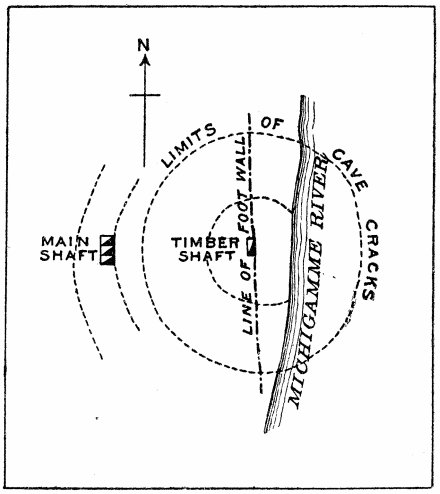


FIG. 6.—Concentric cracks formed by the caving in of the Mansfield mine.

After the caving the mine remained idle until recently. At the present writing the DeSoto Mining Company has obtained control of the mine and, I understand, have freed it from water.

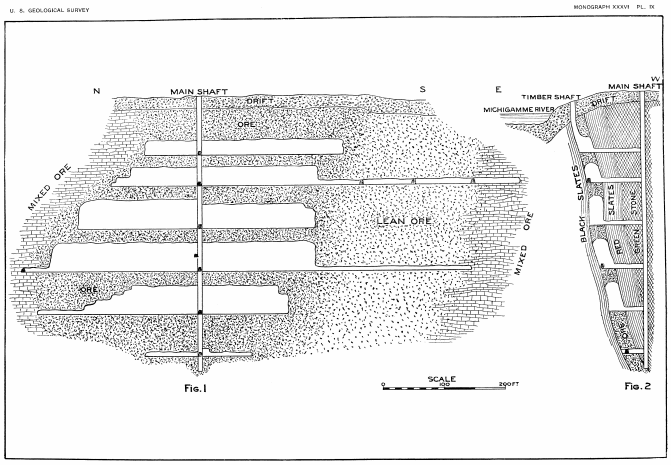
In May they began the task of diverting the channel of the river to a point several hundred feet south of the old course. They have dredged out a cut 2,050 feet in length by 100 feet wide and 18 feet deep. At the upper end of the new channel a cofferdam containing 14,000 cubic yards of earth has been constructed, and where the waters join the old outlet several hundred feet below the mine another embankment has been constructed across the course of the old bed that has 8,000 cubic yards of earth. This task was a very expensive one, and it has been well completed, the old channel being perfectly dry.

The turning of the river's course brings out with startling distinctness the criminal negligence or carelessness of those who were working the mine at the time of the accident. The upper tier of timbers in the mine are plainly seen, as also the ground that had been cut out to receive the set that was being gotten into place when the waters broke through. This shows the miners had worked up to within 12 feet of the water of the river. A great crack in the formation shows where the water first gained entrance. The ore made up the bed of the stream—was a portion of the bed in fact—and the walls of the mine were nearly vertical. The ore deposit had a width of about 20 feet. The water pressure must have been considerable, and the blasting of the ore (as it is hard, and explosives are needed to loosen it) shattered the thin protection over the miners, permitting the water to find ready and unimpeded entrance into the mine. An engineer could not have been employed and the wildest sort of guessing must have been done by those who had the work in charge. No sane man would have permitted the opening of the deposit so near the river's bottom.[1]

Owing to the long abandonment of the mine, the direct sources of information have been closed. For a description of the, ore body I am compelled to rely on such data as are available from existing notes and plats. I am especially indebted to a manuscript description of the mine by J. Parke Channing, and to Mr. C. T. Roberts, of Crystal Falls, for plats of the mine. The sketch of the mine here introduced, Pl. IX, is compiled from an original drawing of J. Parke Channing,

reproduced on the plate cited, and from data obtained from other sources.

[1]Report of Commissioner of Mineral Statistics of Michigan, George A. Newett, for 1896, p. 84.



SKETCH OF THE MANSFIELD MINE AS IT WAS BEFORE IT CAVED IN, IN 1893.
Fig. 1. Longitudinal section. Fig. 2. Cross section.

[Plate IX. Sketch of the Mansfield mine as it was before it caved in, in 1893]

GENERAL DESCRIPTION OF MANSFIELD MINE DEPOSIT.

The Mansfield mine has an ore body varying from 16 to 32 feet in width. It is in almost vertical position; it has well-defined foot and hanging walls composed of impervious rock; it has a somewhat indefinite longitudinal extent. The ore is Bessemer and occurs in an iron-bearing formation, which corresponds in every particular to those of the other iron-bearing districts of the Lake Superior region. The ore was first found in a test pit which passed through 9 feet of drift. The main working shaft was then located about 100 feet west of this point. It was put down to a depth of 460 feet before ore was struck. From this shaft crosscuts were driven east at average intervals of 70 feet, and the ore body was met at a distance varying from 74 feet at the first level to 10 feet at the sixth level. The crosscuts, in every case after leaving the greenstone, pass through so-called red slate, at the maximum about 25 feet thick, before ore is reached, this rock constituting the hanging wall. From these data the dip of the ore body may be calculated to be about 80° W., agreeing well with the observed dip of the slates, which outcrop over the area. The thickness of the ore, as shown by the cross sections, averages about 25 feet. The extreme variation in thickness ranges from two sets, or 16 feet, to four sets, or 32 feet. The strike of the slates is north and south, and the trend of the ore body agrees with this. This brings its southern end under the original course of the Michigamme River as the stream bends slightly to the west, south of the shaft. An examination of the longitudinal (north-south) section through the ore body does not determine whether or not it has a pitch. The southern boundary is nearly vertical from top to bottom, while the northern boundary lengthens about 140 feet between the first and the fifth levels.

In the northern end of the mine—that is, in line with the strike of the sedimentaries—the ore body terminates, in a more or less irregular way, in so-called mixed ore. This mixed ore continues to the north for over half a mile, as shown by the numerous test pits which have been bottomed in it. To the south of the mine shaft the ore body proper extends for 200 feet. It then changes its character, becoming a lean non-Bessemer ore. A long drift (335 feet) at the second level was run through this ore, and after leaving it penetrated a mixed ore, the so-called lime rock (siderite?) and quartz rock (chert?) of the miners. Three crosscuts along this drift show the ore body to vary from 20 to 30 feet in thickness, with the same foot and hanging wall as for the remainder of the mine. The same condition exists also lower down, as shown by a drift from the fourth level, 260 feet south. The figures on Pl. IX, giving longitudinal and cross sections of the mine, show clearly the dimensions of the ore body.

RELATIONS TO SURROUNDING BEDS.

The foot wall of the ore is a black slate, described as being rich in hematite and bearing large crystals of iron pyrite. No crosscuts have been driven for any distance into the foot wall, so that it is impossible to say what thickness of the hematitic black slate there may be before the greenish pyritiferous slate begins. In places a gray “soapstone” takes the place of the black slate as the foot wall.

The dump obtained by sinking the shaft in the material overlying the ore shows large masses of conglomerate, the pebbles of which are rounded and predominantly of volcanic rocks, with pebbles of chert and slate from the iron formation and slates below. These fragments are well rounded. The microscope also shows quartz grains with secondary enlargements, so that there can be no doubt that the rock is a true conglomerate. Similar conglomerates, except that the sedimentary fragments are wanting, have been noticed farther north along the west side of the river. Just west of the bridge at Mansfield, near the mine, there is also a small exposure of conglomerate, which shows an alternation of coarse and fine sediments, with a strike nearly north and south, and a dip of 80° W. To the west, above this conglomerate, and not more than 15 to 20 feet distant, are found the lavas of the Hemlock volcanics. According to the mine captain, the succession west from the ore body in the hanging wall is 20 to 25 feet of paint rock, or, as it is usually called, red slate, then conglomerate, then greenstone. It is difficult to diagnose the paint rock, as no specimens are to be had, but it is highly probable that it is a ferruginous and extremely altered lava sheet. Similar rocks are commonly found thus altered in association with the ores in the Penokee-Gogebic and Marquette districts. Lending weight to this conclusion is the fact that in some places an amygdaloidal greenstone has been exposed in test pits immediately above the iron-bearing formation.

COMPOSITION OF ORE.

The Mansfield mine up to the present time has raised only Bessemer ore, and is the only mine in the Crystal Falls district which has supplied any considerable quantity of ore of this character. An average of a number of analyses gives the following composition for the Bessemer ore: Metallic iron, 64.80; phosphorus, 0.037; silica, 3.70.[1] According to Dr. N. P. Hulst,[2] those ore deposits in the Menominee range which have poorly defined walls carry a minimum of phosphorus. This body, however, shows that the same conditions do not exist at the Mansfield mine, since, while it has both sharply defined foot and hanging walls, it contains but a low per cent of phosphorus. From an examination of the analyses from which the above average was obtained I find that the percentage of phosphorus shows a marked increase in the lower levels of the mines over that of the higher, and there is also a slight corresponding decrease in the content of metallic iron. Increase of phosphorus with depth is also found in the adjoining Menominee range, as noted by Messrs. E. F. Brown,[3] of the Pewabic mine, and Per Larsson,[4] of the Aragon. It is impossible to state whether or not this distribution is due to the action of percolating water, as suggested by Hulst,[5] Larsson,[6] and other Michigan mining engineers. Only a large number of good analyses from carefully selected ores and associated rocks and a detailed study of conditions of occurrence could lead to any accurate determination of the reason for such distribution, and a discussion of these reasons is by no means warranted by the few and imperfect analyses of the Mansfield ores, which I have been able to obtain. The ore body changes in composition to the south of the shaft, as shown by the drifts in this direction. The ore in this part of the mine contains more phosphorus, alumina, and calcium, and less iron. This low-grade lean ore then passes over into the banded chert and ore mixed with the lime and quartz rock mentioned above.

MICROSCOPICAL CHARACTER OF THE ORES AND ASSOCIATED CHERT BANDS.

The ore varies from a soft limonitic hematite to a moderately hard hematite. It is for the most part opaque under the microscope, but in places shows bright-red to brownish-red color in transmitted light. In incident light the ore for the most part shows a dull-brown or reddish color, though in places it has a bright metallic reflection. In places in the ore are spots, in which is a large quantity of chert mixed with iron oxide. As such ferruginous-chert areas increase in quantity the ore grades into the ferruginous chert and chert which is found associated with it in hands and lenticular areas.

[1]An average of 62 per cent metallic iron and .030 per cent phosphorus is reported in Report of Commissioner of Mineral Statistics of Michigan (G. A. Newett) for 1896, p. 85.

[2]The geology of that portion of the Menominee range east of the Menominee River; by N. P. Hulst: Proc. Lake Superior Inst. Min. Eng., Vol. 1, 1893, p. 28.

[3]Distribution of phosphorus and system of sampling at the Pewabic mine, Iron Mountain, by E. F. Brown: Proc. Lake Superior Inst. Min. Eng., Vol. III, 1895, p. 49.

[4]Op. cit., p. 52.

[5]Op. cit., p. 28.

[6]Op. cit., p. 53.

ORIGIN OF THE ORE DEPOSITS.

The mode of occurrence and general characters of the ore body having been described, we are now prepared to determine the cause of concentration of the iron at this particular point and the source. From the description it was seen that the appearance of the body of ore was that of a bedded deposit. The microscopical examination shows, however, that the ore presents no evidences of clastic origin. An examination of the cherts and rocks of the area which are interbedded with the ore, and also a study of the southern contact of the ore body, shows that the ore is a chemical deposit, or the result of a replacement process, by which the original rock was largely removed, and its place taken by the present ore. It has been shown (p. 62) that the siderite bands pass into hematitic and limonitic chert bands. It has been seen that in the southern end of the mine the lean ore merges into a mass of ore bedded with chert and mixed with a rock called by the miners lime and quartz rock. I interpret this rock to be banded siderite and chert, possibly with some quartzite bands, all of which are found outcropping at the surface. The siderite evidently has been changed into iron oxide and the silica replaced by iron oxide, the banding of the original rock not having been destroyed thereby. Irving[1] considered siderite to be the source of similar ore and associated chert and jasper. Van Hise[2] has fully explained the process of the concentration of the ores of the Penokee-Gogebic and Marquette districts, and has applied the explanation to the other districts in the Lake Superior region. I shall not do more, therefore, than to add that the investigations in this area have shown the probable correctness of this explanation.

[1]Origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving: Am. Jour. Sci., 3d series, Vol. XXXII, 1886, pp. 255-272.

[2]The iron ore of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XLIII, 1892, pp. 116-132.

Iron ores of the Penokee-Gogebic series of Michigan and Wisconsin, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XXXVII, 1889, pp. 32-48.

The Penokee iron-bearing series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise, Tenth Ann. Rept. U. S. Geol. Survey, Part I, 1890, pp. 341-507.

The Penokee-Gogebic 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. 245-290.

The Marquette iron-bearing district of Michigan, 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. 400-405.

It is very interesting from an historical standpoint to note that as far back as 1868 Credner had made the suggestion, with reference especially to the Marquette

district, that the ores were derived from an original iron carbonate. The following quotation will show his idea of the processes of development of the ore:[1]

Sphaerosiderit wurde aus kohlensäurereiclien Gewässen abgesetzt, durch eine theilweise Oxydation desselben entstand Magneteisenstein, durch weitere Aufnabme von Sauerstoff das Gemenge von Magneteisenstein mid Rotheisenstein und endlich reiner Rotheisenstein.; aus diesem sporadisch durch Zutritt von Wasser Brauneisenstein.

Credner's suggestion seems to have been lightly considered by other workers in that area. In 1886 Irving[2] suggested the theory of replacement of an original ferruginous carbonate to explain the Penokee-Gogebic iron ores. This theory has since then been elaborated by Van Hise, and shown to have a wider application to the other Lake Superior ore districts. He has also traced the iron to its source in the rocks removed by denudation, and shows why it occurs in the positions in which the ore bodies are at present found to occur. Moreover, Van Hise has also explained the process of development in detail, and, what is perhaps far more important, the reason certain ores develop and not others. In its essentials, however, the process is the same as that suggested by Credner in the lines quoted above, though in them no suggestion of the replacement to which is due the enrichment of the ore bodies is made.

Much of the iron of the Mansfield ore is presumed to have resulted directly from the alteration of the ferruginous carbonate in place, but a large amount was brought in from above by infiltrating waters. The ferruginous matter, which was taken into solution during the denudation of the area, has been carried down by percolating waters and deposited at places favorable for its accumulation. The beds are now on edge, offering the most favorable condition to percolation. The conclusion is obvious that these deposits were formed after the beds were tilted, and the iron derived from the upward extension of the rocks, which has been removed by erosion.

[1]Die vorsilurisclien Gebilde der "Oberen Halbinsel von Michigan" in Nord-Amerika, by H. Credner: Zeitschr. deutsch. geol. Gesell., Vol. XXI, 1869, p. 547.

[2]On the origin of the ferruginous schists and iron ores of the Lake Superior region, by R. D. Irving: Am. Jour. Sci., Vol, XXXII, 1886, p. 263.

CONDITIONS FAVORABLE FOR ORE CONCENTRATION.

The conditions favorable for the accumulation of ore deposits have been ascertained by Van Hise from studies in the other iron-bearing districts of the Lake Superior region. He summarizes these results as follows:[1]

[1] The iron ore is confined to certain definite horizons, known as the iron-bearing formations. . . . [*a*] All ore bodies have been found to be distributed very irregularly in these iron-bearing formations. This is due to the fact that they are secondary concentrations produced by downward percolating waters, and the ore bodies therefore occur at the places where water is concentrated, in accordance with the laws of the underground circulation of waters. [*b*] These places are just above an impervious formation, at the contact of the Upper Huronian and Lower Huronian and where the rocks are shattered. [*c*] The impervious basement formation may be a surface volcanic, a subsequent intrusive, an argillaceous stratum, or any other impermeable formation. [*d*] These impervious basements are most effective when they are in the form of pitching troughs, thus concentrating the waters from the sides along a well-defined channel. These pitching troughs may be formed by a single one of the above rocks or by a combination of two or more of them. The horizon marked by the unconformity between the Upper and Lower Huronian is a great natural zone of percolating waters. Here oftentimes the basement formation of the Upper Huronian is itself a lean ore, having derived its material from the Lower Huronian, but in this case a secondary concentration has occurred in order to produce the present ore bodies. [*e*] Finally, as a result of folding, the iron-bearing formations have been shattered, thus producing natural water-courses. More frequently than not, more than one of these classes of phenomena are found together where the great ore bodies occur, and in many cases all are combined. The original source of the iron ores has been ascertained to be in many cases a lean carbonate of iron, often with a good deal of carbonate of calcium and magnesium, formed as an ocean deposit.

Van Hise adds to the above statement that generally the ore bodies, as a result of their methods of concentration, somewhere reach the rock surface.

The Mansfield ore body has well-defined foot and hanging walls of normally impervious rock. The iron-bearing formation is much fractured. We thus have certain of the conditions favorable to the concentration of an ore body. Whether a trough is completed by a slight cross fold in the formation, or possibly by an intersecting dolerite dike, has not been determined.

[1]Fourteenth Ann. Rept. U. S. Geol. Survey, Part 1, 1893; pp. 107-108.

EXPLORATION.

Exploration has developed no other deposits along the Mansfield slate belt.[1] If other deposits exist, it is highly probable that they extend to the rock surface—that is, are covered by the drift mantle alone.

The intervals between possible ore bodies along the strike of the slates are probably occupied by mixed chert and ore or ferruginous chert. Explorations should extend from the impervious slate below the iron-bearing formation to the impervious rock above the iron-bearing formation. In order to explore the belt thoroughly, rows of pits cross-sectioning the formation ought to be made at intervals not greater than 100 feet, and even with such intervals an important deposit might be missed, for it frequently happens that at the surface of the rock an ore deposit is smaller than it is at a moderate depth.

SECTION III.—THE HEMLOCK FORMATION.

This formation, the most interesting petrographically in the Crystal Falls district, consists almost exclusively of typical volcanic rocks, both basic and acid, with crystalline schists derived from them. Sedimentary

rocks play a very unimportant role. With one exception they have been formed directly from the volcanics, and occur interbedded with them. Cutting through the volcanics are intrusive rocks, which likewise include both basic and acid kinds. Chemically the intrusive and extrusive rocks show very close relationships. The name Hemlock has been given to this volcanic formation because the river of that name flows through it for a number of miles, and in places affords excellent exposures.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning in sec. 36, T. 46 N., R. 32 W., the place where the Hemlock formation enters the part of the district studied by me, the formation has a width of one-half of a mile. From this place the formation has a northwestern course for about 5 miles, gradually widening. It then bends to the west, and after a short distance to the south, which course it follows for about 9 miles. In township 45 N., Rs. 32 and 33 W., the belt has a maximum width of 5 miles. At the end of the southern course the formation bends to the southeast, and continues with this general trend for about 16 miles into T. 42 N., R. 31 W., where my field study of it ended. At the north the belt runs into the eastern half of the district described by Smyth, and swings south, which course is followed for some 15 miles. The entire belt thus forms an oval surrounding the sedimentaries, except in the southeastern part of the district. Another area of Hemlock volcanics is found in T. 43, Rs. 32 and 33, just north of Crystal Falls. This area is about one-half a mile wide just north of the city of Crystal Falls, but rapidly widens as it is followed to the west until at the western limits of the area it is about 3½ miles wide. A third small isolated area is found in secs. 17, 18, 19, and 20, T. 42 N, R. 32 W., and sec. 24, T. 42 N., R. 33 W., about 4 miles south of Crystal Falls.

[1]Since the above was written I have been informed that Mr. George J. Maas, of Negaunee, has, with a diamond drill, located a body of bessemer ore 30 feet thick on lot 6, sec. 20, T. 43 N., R. 31 W., 1 mile south of the Mansfield mine.

The topography of the Hemlock formation is exceedingly rough where-ever erosion has succeeded in cutting through the drift mantle. This occurs only adjacent to some of the streams. The rough topography at these places is due to differential erosion working upon rocks approximately on edge, and of varying hardness. The valleys usually indicate the location of beds of tuff and the higher grounds are almost universally occupied by dense rocks forming the lava flows, or of the coarse-grained massive intrusive rocks. In a few places, however, the thoroughly consolidated and indurated tuffs form high hills. In traversing the Hemlock formation one makes an abrupt ascent, followed by a sharp descent into a narrow swamp, then another ascent, and so on. Exposures appear for the most part in small areas along the edges of the swamps and scattered over the faces of the hills. These are fairly numerous, but so small and disconnected as to prevent the tracing out of the individual flows, although this might be possible if the traverses were made at very short intervals and the area mapped in great detail.

THICKNESS.

As has been seen, the belt of eruptives varies in width from one-half of a mile to nearly five miles. The dip of the rocks is about 75° W. The enormous thickness of 25,500 feet which these data would give is probably illusory.

In the case of the assumption of the thickness of a series of lava flows and tuffs, it is important that the initial dip, which these deposits must have, be considered. This dip varies greatly, depending on the slope of the cone, which in its turn, is dependent on the viscosity of the lava and the presence of varying quantities of fragmental products. If we assume these pre-Cambrian volcanic products to have had an initial dip of 15°, I believe we are within limits for products consisting, as these do, of what was probably moderately viscous basalt and vast masses of fragmental material. This estimate is based on the assumption that the volcanics here represented were deposited for the most part upon the westward slope of a volcano, or a series of volcanoes. This initial dip of 15° is then to be deducted from the present dip, 75°, of the flows. Taking this into consideration, we get a thickness of 23,000 feet for the volcanics.

It is highly probable that the rocks have been subjected to close folding, and for this reason also the apparent thickness would be much greater than the true thickness. The schistose character of some of the rocks shows clearly that they have been severely mashed, and this mashing was probably produced in connection with folding. It is probable that this possible maximum thickness should be very materially reduced, possibly to one-half or one-third of the amount. However, even the maximum above calculated is probably paralleled by the vast masses of volcanic material accumulated in certain volcanic areas, such as those of Hawaii or Iceland. Geikie writes:[1]

> The bottom of these Iceland Tertiary basalts is everywhere concealed under the sea. Yet their visible portion shows them to be probably more than 3,000 meters in thickness.
>
> An especial interest belongs to this Icelandic plateau because volcanic action is still vigorous upon it at the present day.

RELATIONS TO ADJACENT FORMATIONS.

In the northern part of the Crystal Falls district the volcanics overlie the quartzose dolomite formation known as the Randville dolomite. In the central part of the district, through which the Deer River runs, as shown in section *G-H*, Pl. VI, outcrops are so scarce that it has been found impossible to trace the boundaries of the formations with any degree of accuracy. Consequently this part of the district is mapped as Pleistocene.

[1]The Tertiary basalt-plateaux of northwestern Europe, by Sir A. Geikie; Quart. Jour. Geol. Soc. London, Vol. LII, 1896, p. 395.

From the few outcrops of slate, probably equivalent to the Mansfield slate, which have been found in the Deer River area, it has been thought highly probable that this slate in an extremely plicated condition may underlie the volcanics of this area, and it is so represented in section *G-H*, Plate VI. As evidence of this, in T. 43 N., R. 31 W. the volcanics overlie the Mansfield slate unconformably.

In places test pits have disclosed an amygdaloidal lava flow immediately overlying the Mansfield slates. At one place, at the northeast corner of sec. 7, T. 43 N., R. 31 W., angular fragments of the underlying black slate have been found in the tufaceous deposits of the Hemlock volcanics. Farther south, along the contact just west of the Mansfield mine, a conglomerate is exposed, which contains fragments of slate, lava, and rounded grains of quartz with secondary enlargements. The rock is evidently water deposited. There is also obtained from the workings of the mine a conglomerate, taken from just above the ore, which consists of lava fragments and pieces of chert and ore, as mentioned on pp. 64, 68. From these occurrences it is clear that some of the sedimentaries are unquestionably older than some of the volcanics, and yet the conglomerates bearing the fragments of ore and slate contain also fragments of lava, showing the existence of some of the volcanics before the deposition of this conglomerate. The only explanation of all of the facts which has occurred to me is as follows: After the ore-bearing Mansfield slate was deposited, an erosion interval occurred. Then followed a volcanic outbreak. It is highly probable that this outburst began far north of the Mansfield mine, coincident with the upheaval which resulted in the erosion of the Mansfield slate. The volcanic ejectamenta were mixed with the sedimentary fragments and all together were rounded and bedded, forming in places conglomerates. In places along the shore lava flows descended, some reaching into the sea and covering the sedimentaries along the shore where no conglomerate had been formed. At other places deposits of scoriae, etc., including fragments of slates from the sedimentaries through which the volcano burst, were made, and thus deposits of tuff are found overlying the sedimentaries. The various deposits, though really separated by a slight physical break, are practically conformable with the series below, all having a north-south strike and a high westward dip.

The formations which underlie the volcanics in the northern and southern parts of the district are of different character. This difference may be explained by supposing the volcanoes broke out in the northern part, while the Mansfield slate was still being deposited in the south. Gradually, however, the volcanic activity spread toward the south, probably following a fissure along the pre-Cambrian shore, and igneous materials buried the Mansfield slate. Hence, while on the whole these volcanics are younger than the Mansfield slates, some of the lower of them are contemporaneous with some of the upper Mansfield beds. The volcanics invariably overlie the Randville dolomite, and are unquestionably of later age than that formation.

The Hemlock volcanics are overlain throughout their extent by the Upper Huronian series of graywackes and slates. Near the contact line with the volcanics wherever the Huronian outcrops, or has been exposed by exploration, it has been found to be characterized by a line of magnetic attraction. By means of magnetic observations the line of contact has been traced, where owing to lack of exposures it would have been otherwise impossible to connect the isolated outcrops.

RELATIONS TO INTRUSIVES.

High ridges composed of dolerite are found extending in a general northwest and southeast direction through the volcanics. That these masses were forced up through the Hemlock formation is indicated by the folding which they cause in certain places. Such rocks are unquestionably younger than the volcanic series. There may be seen also on the map, in T. 44 N., R. 32 W., a number of isolated knobs. These are also doleritic, and are presumed to be, like the larger ridges, intrusive in the volcanics.

The dolerites have in their turn been cut by acid dikes. These are coarse micropegmatitic granites. Similar acid dikes have been found cutting the surrounding volcanics. This set of acid dikes may be looked upon as the youngest intrusive igneous rocks occurring in the Hemlock volcanic formation.

Cutting the volcanics are also basic dikes varying from fine to moderately coarse grain. It is well known that during a volcanic epoch the outpoured lavas and clastic volcanic deposits are penetrated by dikes coming from the same magma. Whether or not these dikes are of this origin, and are hence contemporaneous with the later volcanics, or are of later age, and correspond to the coarse dolerites, it is impossible to determine with certainty. They are presumed, however, to form an integral part of the Hemlock volcanics, as no connection between the dikes and the unquestionably intrusive dolerites could be traced in the field.

VOLCANIC ORIGIN.

In spite of numerous occurrences of ancient volcanics which have recently become known, the late Professor Dana makes the following statement:[1]

> It is not yet certain that a volcano ever existed on the continent of North America before the Cretaceous period; for the published facts relating to supposed or alleged *volcanic* eruptions in the course of the Paleozoic ages are as well explained on the supposition of outflows from fissures and tufa ejections under submarine conditions; and none of the accounts present evidence of the former existence of a volcanic cone, that is, of an elevation pericentric in structure made of igneous ejections.

The presence in the Hemlock formation of a quantity of pyroclastics, great in proportion to the solid lavas, and the absence of any great sheets of lava, so important a product of great fissure eruptions, seem to point to the derivation of the Hemlock rocks from a volcano or volcanoes situated near the border of the contemporaneous Huronian sea, rather than from a simple fissure. While some of the eruptives may have been submarine, the occurrence of large quantities of clearly subaerial deposits shows that the eruptives were largely on the land. Thus it appears that neither a fissure flow nor a submarine volcano will wholly explain the Hemlock formation. However, it is highly probable that this volcanic outburst, which piled masses of volcanic material upon the land, was accompanied, as have been all or nearly all the great outbursts of recent times, by submarine lava flows and tuff ejections. No such clear evidence of the presence of a Paleozoic or pre-Paleozoic volcano on the North American continent has been adduced as that given by the English geologists for certain volcanoes in the British Isles. But while the presence of a central cone with pericentric arrangement in the Hemlock district is not conclusively proven, the presumption in favor of such a cone or cones having existed is certainly strong.

[1]Manual of Geology, by J. D. Dana: 4th ed., 1895, p. 938.

An attempt was made to locate the vent or vents from which the material was derived, but no evidence could be found, unless we consider the vents to have been where the accumulations were the greatest. The coarse-grained rocks which were first supposed to represent the plugs of ancient volcanoes, on careful and detailed examination appear to be later intrusives, or else are indeterminate.

CLASSIFICATION.

The general character and distribution of the Hemlock formation having been given, we may now proceed to a petrographical consideration of the rocks comprising it. This will be given in more detail than for the other rocks of the Michigamme district because this great pre-Cambrian volcanic formation possesses peculiar interest.

The rocks of the Hemlock formation are chiefly of direct igneous origin. Some interleaved sedimentary rocks occur, which, however, with a single exception are composed of fragments of the igneous rocks. For the sake of easy reference, the usual classification into igneous and sedimentary rocks will be used. The massive igneous rocks are subdivided according to chemical composition into acid and basic rocks. The acid rocks include rhyolite-porphyries,[1] aporhyolite-porphyries, and acid pyroclastics. The basic rocks include altered nonporphyritic basalts, porphyritic basalts, and variolite and basic pyroclastics. The sedimentary rocks are divided into the volcanic sedimentaries and the nonvolcanic sedimentaries or normal sedimentaries. The first include tuffs and ash beds—the æolian deposits, and volcanic conglomerates—subaqueous deposits. The normal sedimentaries are represented by slates and limestones. Various schists are locally produced from these numerous kinds of rocks through metasomatic changes and dynamo-metamorphic action. Many of these schists resemble one another very closely, though, as will be seen later, they are derived from both the massive rocks and from the clastics. These have been described in connection with the rocks from which they have been derived.

[1]According to a late ruling of the Director of the United States Geological Survey, based on the recommendation of a committee on nomenclature for geologic folios, “porphyry” is to be used only with a textural significance. Hence “quartz-porphyry,” according to this ruling should no longer be used as a rock name. The rhyolite-porphyries here described are what have been known as normal quartz-porphyries.

The following table will show the arrangement outlined above, which will be followed in the descriptions:

Classification of the rocks of the Hemlock formation.

Igneous	Acid	Lavas	Rhyolite-porphyry	Schistose acid lavas	Crystalline schists.
			Aporhyolite-porphyry		
		Pyroclastics			
	Basic	Lavas	Metabasalt	Nonporphyritic	
				Porphyritic	
				Variolitic	
		Pyroclastics	Eruptive breccia	Eruptive breccia	
				Flow breccia	
Sedimentary	Volcanic sediments	Eolian deposits		Tuffs	
				Ash beds	
		Subaqueous deposits		Conglomerates	
	Normal sediments	Slate			
		Limestone			

ACID VOLCANICS.

The acid volcanics are comparatively unimportant in quantity. They may be conveniently subdivided into the lavas and pyroclastics.

ACID LAVAS.

The acid lavas occur in such small quantity as to make it impossible without very great exaggeration to place them upon the accompanying small-scale general maps, though they have been introduced upon the detail maps wherever the scale permitted. They usually form isolated ridges, and their relations to the surrounding basic volcanics are obscured by lack of exposures. The trend of the individual ridges agrees with the general strike of the banding in the basic tuffs. Moreover, in nearly all cases the isolated exposures which are closest together lie in such relations to one another that when connected the large sheets thus formed follow the strike of the tuff banding, as do the individual ridges, and they are therefore confidently assumed to be the isolated portions of acid flows interbedded with the basic volcanic rocks.

The rock types represented are the two closely related rocks—the rhyolite-porphyry and the aporhyolite-porphyry. Under the rhyolite-porphyries are included the porphyritic acid lavas, which have, so far as can be determined, an original holocrystalline groundmass. Under the aporhyolite-porphyry, following Miss Bascom’s use of *apo*,[1] I include those acid lavas which are now likewise holocrystalline, but which owe this character to

the devitrification of an original glassy base, supposing them in their original vitreous condition to have corresponded to the modern hyalorhyolite-porphyries.

[1]Structures, origin, and nomenclature of the acid volcanic rocks of South Mountain, Pennsylvania, by Miss Florence Bascom: Jour. Geol., Vol. 1, 1893, p. 816.

RHYOLITE-PORPHYRY.

The rhyolite-porphyries on fresh fracture are dark grayish-blue to black. From this they grade with advancing alterations through chocolate brown to purplish. The weathered surface varies from white to reddish. The weathering has in one case brought out very well the fluxion banding of the rock. Their texture is very pronouncedly porphyritic. The quartz and feldspar crystals stand out plainly from the groundmass, which is usually dense with a somewhat resinous luster. The porphyritic quartzes average perhaps the size of a small pea, and hence are macroscopically very plainly visible. They frequently stand out on the weathered surface and show their crystal forms, and in other cases we see the angular cavities out of which they have fallen, like the kernel from the nut.

Under the microscope the rocks are seen to be typical rhyolite-porphyries. The phenocrysts are chiefly corroded dihexahedral crystals of quartz. Crystals of plagioclase and orthoclase are less common. These lie in a very fine-grained holocrystalline groundmass, composed largely of feldspar and quartz, with some zircon in small crystals, and here and there magnetite.

These are presumed to be the original constituents of the groundmass. Associated with them are considerable quantities of secondary chlorite, epidote, biotite, muscovite, calcite, and reddish to brown alteration products of the magnetite. Included in the groundmass are here and there oval areas of finely crystalline secondary quartz, probably filling former amygdaloidal cavities.

In thin section the crystal contours of the quartz phenocrysts are more or less rounded, with here and there embayments of the groundmass projecting into them. The crystal form is, however, always clearly marked. In some cases the individuals have been broken before the cooling of the magma, the fragments of an individual, though now separated, being seen to conform to one another. That they have been subjected to pressure is shown by the undulatory extinction and also by the separation of the black cross of uniaxial minerals into hyperbolae. Embayments of groundmass, and liquid inclusions in which a dancing bubble may be seen, are in places rather thickly distributed through the quartz. The liquid inclusions have very commonly an hexagonal form, corresponding to the contours of the inclosing quartz.

These liquid inclusions are certainly in some cases secondary. This character is well shown in some of the crystals, which are broken across, giving along the line of fracture a very wavy extinction. Along this line of fracture the greatest quantity of inclusions are seen, both with and without bubbles. As the distance from a fracture increases, both the undulatory extinction and the number of inclusions diminish. (See fig. *A*, Pl. XIX.) These fractures in the quartzes are but continuations of those which extend in many cases all the way across the section. The fractures have since been healed by secondary quartz. This secondary quartz has also in some cases healed the fractured quartz phenocrysts, and then agrees with them in orientation. The possession of an imperfect rhombohedral parting is very noticeable in a number of quartzes, and especially those which, being on the edge of the section, are very thin. (See fig. *B*, Pl. XIX.) Similar parting in the quartz occurs in various rocks studied in this district.

The phenocrysts of the porphyries are traversed by fractures, some of which are more or less circular, and simulate very imperfectly perlitic cracks. With the exception of those in porphyries in two localities, the quartz phenocrysts are surrounded by zones, largely of quartz, of varying widths, and considerably lighter than the remainder of the groundmass. Much of the quartz of these zones has the same optical orientation as the phenocrysts. In those sections in which the zones are observed they occur around every section of quartz.

The feldspar phenocrysts are orthoclase and plagioclase, the latter apparently predominating. They occur usually in rounded, badly corroded crystals, with indentations filled with groundmass. They are always altered, and have associated with them as secondary products calcite, epidote, muscovite, biotite, and chlorite.

No large original ferro-magnesian phenocrysts appear to have been present in the porphyry. Their former presence is at least not indicated by any aggregates of secondary products. Whatever ferro-magnesian minerals were present must have been scattered through the groundmass, and have been completely altered. The secondary minerals contained in the groundmass are chlorite, calcite, epidote, muscovite, and biotite.

TEXTURE OF THE PORPHYRIES.

The texture of the dense groundmass varies according to the mode of association of the two chief minerals—quartz and feldspar. The commonest variety is the rhyolite-porphyry with microgranitic groundmass (porphyre granulitique of Michel Lévy). A second variety is the rhyolite-porphyry with micropoikilitic groundmass.[1] The microgranitic texture is too well known to warrant a description of it here.

The micropoikilitic texture presents certain characters which render a further description desirable. This peculiar phase of the micropoikilitic texture was briefly described by the writer and illustrated by microphotographs in 1895.[2] Shortly after the separates of this article were distributed, I received from H. Hedström, of the Swedish Geological Survey, an article published in 1894 containing a description of what appears to be very nearly the same texture.[3] If I have understood the description correctly, however, there

seems to be one essential difference. In order to explain clearly this difference, I shall describe the texture in detail.

[1]Eruptive rocks of Electric Peak and Sepulchre Mountain, by J. P. Iddings: Twelfth Ann. Rept. U. S. Geol. Survey, 1891, p. 589. On the use of the terms poikilitic and micropoikilitic in petrography, by G. H. Williams: Jour. Geol., Vol. 1, 1892, pp. 176-179.

[2]Volcanics of the Michigamme district of Michigan, by J. Morgan Clements: Jour. Geol., Vol. Ill, 1895, pp. 814-816, figs. 1 and 2.

[3]Studier öfver Bergarter från Morän vid Visby, by H. Hedström: Geol. Fören i Stockholm Förhandl, Bd. 16, H. 4, 1894, pp. 5-9.

In certain of the rhyolite-porphyries, as already mentioned, the quartz phenocrysts are surrounded by certain zones. These zones in the rocks having a micropoikilitic texture possess exactly the same texture as does the groundmass. The zones are composed of minerals which are of sufficient size to permit readily their determination. Quartz and feldspar are the essential components, with some chlorite, epidote, muscovite, and iron oxide. The first two are the important minerals, and will alone be referred to in the further description. The chief peculiarity of the zone is in the arrangement of the two minerals, and this character is best shown on the accompanying microphotographs. This texture can be seen even in ordinary light. It is brought out better when the field is partly shaded, so as to exhibit the difference in relief of the minerals, and, best of all, between crossed nicols. (See fig. *A*, Pl. XX.) The zones are seen to be made up of reticulating areas of clear quartz, in which lie embedded irregular pieces of feldspar. Where two or more of the quartz stringers or needles unite, one secs broad areas of limpid quartz. The network of quartz is best seen when it exhibits its highest polarization color, as then the feldspar is for the most part dark. The pieces of feldspar in such a quartz area for the most part have irregular orientation, as is shown by their varying extinction, although a number extinguish simultaneously. This quartz net is connected with the quartz phenocrysts, as shown by the continuation of the quartz of the phenocrysts and that of the zone, and the consequent agreement in orientation. The lack of a uniform optical orientation of the feldspar grains is made especially apparent when the quartz is cut perpendicular to the *c* axis, and consequently remains dark under crossed nicols. Under the above circumstances we see certain feldspar grains polarizing in the zone around the quartz, and as the stage revolves other particles lighten as those which polarized in the previous position of the stage become dark. From this description it is evident that the texture is not micropegmatitic according to the generally accepted definition of the term, but corresponds to the micropoikilitic, as described by Iddings and Williams.[1]

A gradation toward a spherulitic texture was noticed in one instance where a number of long quartz stringers were arranged perpendicular to the periphery of the quartz phenocryst. (Fig. *B*, Pl. XX.) The texture of this micropoikilitic mass, it will be observed, is finer than that before described.

The groundmass of the porphyries is formed of irregular roundish areas having exactly the same micropoikilitic texture as the zones surrounding the quartz phenocrysts. An explanation of the origin of the zones should therefore also explain the texture of the groundmass. Certainly in many cases, probably in most cases, the groundmass areas result from tangential sections through one of the micropoikilitic zones surrounding the quartz phenocrysts.

The description given by Hedström[2] of this same structure as observed by him is essentially the same as the above, if I have understood him correctly. The following difference is, however, to be noted. In speaking of the structure where the quartz is surrounded by this micropoikilitic zone, he calls it the granophyric structure. As I have already emphasized above, the feldspars in the network of quartz have varying orientation, and the structure is, strictly speaking, micropoikilitic, and in no sense granophyric (micropegmatitic). Moreover, he describes in addition to the above type one in which are found phenocrysts of quartz lying in a micropoikilitic groundmass with the above reticulating texture, but the phenocrysts abut sharply against the groundmass, instead of being connected with it by means of these zones.

[1]Op. cit., pp. 589 and 179.

[2]Op. cit., p. 8.

The micropoikilitic texture has been held in some cases to be of secondary origin and the result of devitrification. While recognizing that there may be certain unquestionable cases where a micropoikilitic structure results from the devitrification of a glassy groundmass, I can find no evidence in the rocks here described that points to this origin for the micropoikilitic texture under discussion. On the other hand, there is an absence of evidence that indicates its unquestionably primary character. Rather than to regard the quartz as secondary and influenced in its orientation by the phenocrysts, as in the enlargements of quartz grains, it seems natural to suppose that when the lava was extruded after the crystallization of the phenocrysts, there began, consequent upon the diminished pressure and temperature and other factors, a rapid crystallization of the mineral elements from the remaining magma. This resulted in the production of the feldspar in very imperfect and small crystal individuals. At the same time the quartz of the phenocrysts continued to grow, and in so doing inclosed these small feldspars in its meshes.

In certain rhyolite-porphyries the micropoikilitic texture is somewhat different from that above described. In these the quartz phenocrysts are surrounded by zones which are illustrated in figs. *A* and *B*, Pl. XXI. These appear to correspond very closely to the ones described by Michel Lévy[1] and Williams,[2] and since described by many other writers. The zones have a much higher index of refraction than the quartz of the phenocrysts, and hence contrast strongly with it. Examined closely, they are

seen to be composed of chlorite, epidote, and black or reddish

[1]Annales des Mines, Vol. VIII, 1875, pp. 378, 381.

[2]Die Eruptivgesteine der Gegend von Triberg im Schwarzwald, by G. H. Williams: N. Jahrb. für Min., Bd. II, 1883, p. 605.

ferruginous grains, which lie in a white matrix. This matrix shows the following characters: The greater part of it extinguishes and lightens simultaneously with the quartz phenocrysts which it surrounds, and is consequently believed to be quartz. When the matrix and quartz phenocrysts are dark, one secs scattered through the matrix, making up a very small proportion of the total zone, certain irregular areas which show polarization effects. These are believed to be feldspar grains, though this could not be determined. With the highest magnification no radial arrangement of the quartz and feldspar could be observed which would warrant the inclusion of these aureoles under Michel Lévy's term "*sphérolites à quartz globulaire*."*1* Where two quartz crystals with different orientation are in juxtaposition, each possesses its own zone corresponding with it in orientation. The way in which the zones about the quartzes are confined to the quartz is clearly shown in one case in which a very much altered feldspar phenocryst was found, one portion possessing a typical coarse micropegmatitic texture. In this case where the quartz of the micropegmatitic intergrowth touches the groundmass, it grades into a micropoikilitic area, whereas the feldspar does not do so.

The texture of the zones about the quartzes is apparently but a fine-grained variety of the micropoikilitic texture, the coarser phases of which are illustrated on Pl. XX.

The groundmass of the rocks showing the texture is composed of roundish areas of exactly the same composition as the zones around the phenocrysts, with a feldspar of small dimensions here and there between these areas. (See fig. *B*, Pl. XXI.) The texture approaches very closely if it does not correspond exactly to the quartz épongeuse phase of the quartz-globulaire texture of the French.[2] In one part of a section of rhyolite-porphyry the quartz phenocrysts have aureoles and the groundmass has the texture just described. In another portion of the section the quartz phenocrysts have no aureoles and the groundmass possesses an imperfect microgranitic texture (structure microgranulitique of Michel Lévy). This shows the passage of a micropoikilitic textured rock into one with a microgranitic texture. I explain the aureoles and the roundish areas in the

[1]Structures et classification des roches éruptives, by A. Michel Lévy, Paris, 1889, p. 21.

[2]It is found to show exactly the same texture as seen in a section obtained from Paris and labeled "Porphyre à quartz globulaire de la Sarthe."

groundmass as original, in exactly the same way as has been suggested by Williams[1] for those which he described. This is essentially the same explanation which I have given on a previous page for the less common, coarse micropoikilitic phase. The cause of the formation of the microgranitic phase appears, however, rather difficult to discern. Its development seems to depend upon peculiar local conditions.

APORHYOLITE-PORPHYRY.

Intimately associated with the rhyolite-porphyries are rocks very similar to them in mineral constituents, both microscopically and microscopically, so that the description of the rhyolite-porphyries will largely answer for the aporhyolite-porphyries. Flow texture, however, is well shown by the aporhyolite-porphyries. A beautifully developed perlitic parting, fig. *A*, Pl. XXII, is taken to indicate the presence of an original glass; hence the rocks are classed with the aporhyolites. The perlitic cracks are well brought out in ordinary light by the chloritic flakes along them. Between crossed nicols these disappear, and the groundmass resolves itself into a fine-grained mosaic of quartz and feldspar. (Fig. *B*, Pl. XXII.) This groundmass has all the characters of that of a microgranite.

No evidence which would point to the devitrification of a glass could be seen other than the presence of a perlitic parting, as described. For recent excellent descriptions of similar devitrified lavas in which various structures characteristic of vitreous lavas have been identified, the reader is referred to the articles already mentioned, and the one by Dr. Bascom,*2* in which a moderately full bibliography is found.

SCHISTOSE ACID LAVAS.

The results of the ordinary alterations of the acid lavas, chiefly meta-somatic in character, by which the phenocrysts and the matrix have been changed, have been briefly described. The results produced by dynamic action are more interesting and perhaps more striking. The mashing, resulting in chemical changes and schistose structure, has in many cases almost obliterated the porphyritic texture, and in extreme cases destroyed all internal evidence of igneous origin. Even the fluxion banding, as is well known, at times simulates very closely sedimentary bedding, and thus increases the difficulty of determining the igneous character of the rock. In the rocks to be described the phenocrysts may still be observed, though more or less deformed, and the fluxion banding has been in one case exceptionally well preserved, so that no doubt is felt as to their igneous character. Dynamically metamorphosed rhyolite-porphyry flows have been found in two areas in the Hemlock formation. In the following each area will be described separately, the one in which the original character of the porphyry is least in doubt being considered first.

[1]Op. cit., p. 607.

[2]Acid volcanic rocks of South Mountain, by Dr. Florence Bascom: Bull. U. S. Geol. Survey No. 136, 1896, p. 87.

The Deer River schistose porphyries are found in the SE. ¼ sec. 36, T. 44 N., R. 32 W., beginning at 400 N.,

250 W., and continuing to 600 N., 350 W., of the southeast corner near the bridge on the Floodwood road. They occur in several outcrops which are practically continuous, being separated by very short distances, and are so much alike both macroscopically and microscopically that there is sufficient reason for the conclusion that they belong together. Their field relations to other rocks have not been observed. No data have been found which offer any clue as to the time of eruption of these rocks other than the fact that they are surrounded by the basic volcanics of the Hemlock formation and have undergone the same dynamic action.

The porphyries are dense, bluish-black rocks, with porphyritic crystals of red feldspar. A fluidal structure is not present in them. The schistose structure is apparent to the eye, especially upon the weathered surface, and the cleavage of the rock also indicates it. The cleavage face of the rock has a silky luster, due to the sericite and biotite flakes parallel to it. The rock breaks readily in various directions at angles to the cleavage, so that it is impossible to obtain well-shaped hand specimens. The schistosity in these porphyries is clearly brought out by weathering, the weathered rocks showing perfect schistosity, while fresh specimens from the same exposure, although splitting easiest in one direction, appear perfectly massive in hand specimens when broken across the schistosity. That the dynamic action was greatest along certain zones of the rock, other portions being more or less exempt, is shown by the fact that of several specimens collected with the view of obtaining different stages of alteration from different portions of the same exposure some are markedly schistose, while the least altered approach a fairly massive character.

I shall give a brief description of this least altered phase, and then consider the changes which have taken place and the character of the rock which has resulted in the more altered phases.

The slightly schistose rock, like all the porphyries, is very fine grained and black, with a more or less silky luster on fresh fractures parallel to the schistosity. The porphyritic character is not very strongly marked. Macroscopically, comparatively few small feldspar phenocrysts are visible. Under the microscope the rock is seen to be a micropegmatitic rhyolite-porphyry in which the silica has not crystallized as quartz phenocrysts, but has remained in the groundmass. The feldspar phenocrysts are both orthoclase and plagioclase. The latter shows its usual characters, but is not present in well-formed crystals. The orthoclase, on the contrary, is well crystallized, occurring in Carlsbad twins. While some of the feldspar crystals are broken, they as a rule do not show many signs of pressure. The fine-grained micropegmatitic groundmass is made up of the quartz and feldspar intergrowth and of secondary mica, both muscovite and biotite, and remnants of iron oxide. Micropegmatitic intergrowths of quartz and feldspar occur in irregularly shaped areas which frequently have a fairly large quartz at the center. Very similar irregular areas which seem to be composed altogether of unstriated feldspar also occur. These two kinds of areas compose the greater part of the rock. The mineral particles frequently show undulatory extinction. Between the micropegmatitic intergrowths one finds here and there granular aggregates of quartz and striated and unstriated feldspar. These feldspar grains, and likewise the feldspar intergrown with the quartz, are considerably altered. Sericite and biotite are present in considerable quantity. The former possesses the better crystallographic outlines, the biotite being usually found in ragged fragments. The two micas occur in the feldspars and lie between the quartz grains, but not in them. They appear to be secondary products from the feldspar. The micas lie with their long directions approximately parallel, and impart to the rock its schistose character. A few automorphic crystals of apatite were found. There occur also a few irregular grains of a dark reddish brown mineral with high single refraction, but which is isotropic. This mineral is presumed to be allanite, though conclusive tests could not be made. Some crystals of zircon were also observed. The iron oxide is evidently titaniferous, probably titaniferous magnetite. Secondary calcite is scattered through the rock in considerable quantity.

In a more altered phase of the porphyry exhibited in a number of specimens, the schistose structure is much better marked both macroscopically and microscopically. The macroscopical appearance is otherwise quite similar to the one just described. Under the microscope the phenocrysts show up well. These are rounded and shattered orthoclase and plagioclase feldspars. They lie usually with their long direction in the lines of marked schistosity of the rock. The larger crystals have been much more generally fractured than have the smaller ones, and seem to have obtained relief from strain in that way, the individual fragments not showing very strong dynamic effects. The small crystals are more or less rounded. The crushing to which the rock has been subjected has severed the fragments in a number of cases. Triangular areas on two sides of the broken or unbroken feldspars in the direction of schistosity are filled with what appear to be secondary quartz and flakes of biotite. The feldspars as a whole have undergone considerable chemical changes, the freshest being red and very cloudy. Those more altered show secondary muscovite and biotite scattered through them. The character of the triclinic feldspar could not be determined. It appears, however, to be very rich in calcium, as in some of the badly weathered sections the feldspar fragments may almost be said to lie in a calcite matrix, resulting apparently from the alteration of the feldspar and not from infiltration. No quartz phenocrysts retaining their normal character are found. There occur here and there, however, small rounded mosaics of quartz, the individual grains of which show undulatory extinction. These are evidently the result of the granulation of quartz grains, such as occur in the freshest specimens. It is well known that the quartz is

more easily affected by pressure than feldspar, and Futterer[1] has shown that they may be found in a completely crushed condition, in the same section with feldspars which still retain their regular crystal contours.

[1]Die "Ganggranite" von Grosssachsen, und die Quartzporphyre von Thal im Thüringerwald, by Karl Futterer, Heidelberg, 1890, pp. 31, 126.

The groundmass of the porphyry is made up of quartz and feldspar, in and between which lie leaflets of biotite and sericite. The holocrystalline granular mixture of quartz and feldspar is very fine grained, and the presence of the feldspar was only determined by difference in the refraction of the two minerals. No striated feldspar grains were observed. The secondary micas appear usually in ragged flakes, though the slightly greenish-yellow sericite flakes approach crystal outlines rather frequently. The biotite is brownish-green and strongly pleochroic. A few spots of brown iron hydroxide and small heaps of grains of sphene probably indicate the former presence of titaniferous iron ore. The few crystals of apatite present are broken and separated, but otherwise retain the usual characters of this mineral.

The groundmass has a very marked schistose structure, brought out especially well by the parallel arrangement of the mica flakes. The way in which these lines of schistosity flow around the mashed phenocrysts, one line never coalescing with another, but remaining continuous, may be seen with great distinctness where the lines abut sharply against the crystal at a very obtuse angle. As the angle becomes less and less obtuse, the ends of these lines bend up slightly in the direction which would enable them to pass the crystal, and then end, so that along the face of the crystal one can follow them, as it were, in a series of steps until those lines which strike the crystal near enough the edge to flow around it bend slightly, and passing around continue on the opposite side. The fact noted by Fütterer[1] that an increased amount of sericite occurs on the two sides of the feldspar crystals parallel to the schistosity is very patent in these porphyries. The diminution in grain of quartz and feldspar seems to accompany the increase in the amount of the sericite. The slides are crossed by narrow fractures cutting the planes of schistosity, which are filled with secondary quartz, showing marked strain effects. Associated with the quartz were observed some crystals of brown rutile. In one of the more altered slides these fissures have been filled with calcite, whether or not as a replacement of the quartz could not be told.

Schistose porphyries showing the extreme alteration phases are found from N. 300, W. 300, to N. 400, W. 250, in the SE. ¼ sec. 4, T. 44 N., R. 32 W. They form a rough escarpment upon the southeast side of and near the base of a large hill, and overlook McCutcheon's Lake. The exposure is not continuous throughout, though practically so3 but the unexposed parts are sufficient to prevent a perfect sequence being traced. The appearance of the rock is strongly like that of sedimentary rocks. Different bands nearly on edge may be seen, dipping 60°-90° SW. and striking N. 30° W.

[1]Op. cit., p. 40.

At a point about 100 feet higher and three-fourths of a mile distant, on the very northwest flank of the same hill, at N. 1725, W. 775, from the southeast corner of sec. 4, T. 44 N., R. 32 W., there is a small ledge of schistose porphyry, macroscopically and microscopically similar to those to the southeast of it, and with its schistosity striking N. 20° W. and dipping 80° SW. The striking agreement in strike, dip, and general character of these two separated outcrops points to their being merely isolated portions of the same mass. There seems to be no discrepancy between the dip and strike of the schistosity and that given above for the bands.

The most striking macroscopical characteristic of these mashed porphyry flows is the occurrence of phenocrysts in a schistose and beautifully banded rock. These phenocrysts stand out clearly from the groundmass in all cases. The general appearance of the rocks is that of the well-known very dense banded hälleflintas of Elfdalen, Sweden. The bands vary in color, ranging on the weathered surface from light creamy white, through light greenish, to red and almost black. The rocks which have very light colored weathered surfaces are always bluish black on a fresh fracture, and very dense, and those weathering red are usually cream colored on freshly fractured faces. Many of the areas which appear macroscopically to be single phenocrysts are resolved under the microscope into tangled groups of individuals, though in rare cases the individuals show the imperfect radial arrangement rather frequent in medium-grained micropegmatitic rhyolite-porphyries.

The feldspar has undergone considerable alteration. In the least-changed grains there is a cloudiness caused by numerous indeterminable specks, probably of iron oxide, which give a reddish tinge to the mineral. Further changes result in the production of muscovite and epidote, with biotite in rare cases, accompanied by the obliteration of the twinning lamellæ. The greater part of the phenocrysts seem to be orthoclase, though associated with them are found pieces which show indistinct traces of the polysynthetic twinning of plagioclase feldspar. The feldspars exhibit marked strain effects, especially in their flattening into long oval and spindle-shaped areas. Some crystals have been broken and separated perpendicular to the direction of the schistosity. The spaces between the fragments are filled with secondary muscovite, quartz, and feldspar. Surrounding the phenocrysts—that is, between the phenocrysts and the ground-mass proper—we find a mass of small angular, finely striated, limpid grains of feldspar, associated with similar grains of quartz, the two having in places between them sericitic flakes. In one especially clear case, this secondary aggregate fills half the space formerly occupied by an individual feldspar, the other half being still occupied by the remnant of the apparently simply twinned feldspar from which it was derived. (Fig. *A*, Pl. XXIII.)

While no large quartz phenocrysts were observed, a mosaic of quartz is found in small round or oval areas in

various sections. The individual fragments exhibit the usual strain effects of crushed minerals. (Figs. *A*, *B*, Pl. XXIV.)

The groundmass consists of the same preponderant minerals as the schistose porphyries, which have been previously described. The accessory minerals are apatite, which is present in very small quantity, and rutile, which in one of the slides is present in very considerable quantity in the form known as "thonshiefer-nädelchen." Calcite is found in all of the slides, the amount varying very much. Those which contain a great deal have a scoriaceous-looking surface, due to weathering out of the calcite.

The flow structure mentioned as having been observed in the schistose porphyries of the Hemlock formation is perhaps of sufficient general interest to warrant a few comments. This is well marked only on one hand specimen. In this there is an alternation of pink and dark grayish-blue bands which are rarely more than a fraction of an inch thick. Some, especially the thicker bands, are remarkably persistent. Even macroscopically on the weathered surface the pinkish bands can be distinctly seen to wrap around the pink feldspar phenocrysts and oval areas of the grayish-blue part of the rock. Under the microscope the bands which macroscopically are the darkest are clear and transparent, while the pink bands are much less transparent. The microscope shows the difference in the color of the bands to be due chiefly to the fineness of grain, and brings out the flow structure even more clearly than the weathered surface. (Figs. *A* and *B*, Pl. XXIV.) Accompanying this variation of grain there is also a difference in mineralogical composition. The dark bands are composed essentially of quartz grains, with feldspar, sericite, some magnetite, considerable calcite, and rare crystals of apatite and rutile, the quartz including many black and indeterminable specks. The pink bands are very fine grained, so much so that the clear white mineral grains composing it can not be determined, though probably both quartz and feldspar are present. These bands are darkened by innumerable black indeterminable specks and long rutile needles, with a small amount of biotite. It is possible that some of the minute biotite flakes have been mistaken for rutile needles when viewed on edge, but it is certain that these bands contain a great deal more rutile than do the others. Whether or not there is a still more essential chemical difference between the bands than that indicated by the increased quantity of rutile, was not determined.

It has become more or less common of late to attribute the banding found in metamorphosed eruptives altogether to the pressure to which they have been subjected. In the present instance I can not but consider the banding as being an original fluxion structure, with the slight original differences between the bands emphasized, as it were, by subsequent pressure. It appears highly probable that the rock was originally more or less glassy and showed a flowage structure, and that the present mineralogical character of the groundmass is due to the process of devitrification which did not destroy the banding of the original glass.

ACID PYROCLASTICS.

The only acid pyroclastic rock found was formed from the aporhyolite-porphyry. This is a true eruptive breccia. The fragments are angular to rounded in shape, weather to a pure white color, and have an exceedingly rough surface. This roughness is due to a great extent to perlitic partings, which are macroscopically visible, and give the rock an almost scoriaceous appearance. Other inequalities on the surface adding to its roughness are caused by the leaching out of feldspars, and by the fact that many of the quartz phenocrysts have fallen out of the inclosing matrix. The fragments are all aporhyolite-porphyry, containing a very large proportion of quartz and feldspar phenocrysts. The cement of the breccia is aporhyolite. This contains far less numerous phenocrysts, and is, therefore, on the whole much finer grained than the fragments. The weathered surface of the cementing aporhyolite appears a bluish gray, and is very smooth compared to the scoriaceous appearing surface of the fragments already described. This difference in weathering shows the brecciated character admirably, as the finer-grained matrix stands out sharply and delimits the contours of the fragments.

Movements of the magma are shown by a flowage structure in the matrix and by the fracturing of the quartz and feldspar phenocrysts and separation of the pieces in both the cement and fragments. (Fig. *B*, Pl. XXIII.)

This eruptive breccia can be seen in its best development in the NW.-SE. trending ridge, just west of the small lake, crossed by the Chicago, Milwaukee and St. Paul track in sec. 32, T. 44 N., R 32 W.

BASIC VOLCANICS.

The basic volcanics are considered under the main headings of lavas, pyroclastics, and Bone Lake crystalline schists.

BASIC LAVAS.

GENERAL CHARACTERS.

The basic lavas are so very characteristically developed that no one could for a moment doubt their true nature, even upon the most superficial examination. One of the nearly general characters is the presence of a well-marked amygdaloidal texture. (Figs. *A*, *B*, Pls. XXV and XXVI, and fig. *A*, Pl. XXVII.) Some of the lavas are so full of amygdules that they may be correctly said to have been scoriaceous. The amygdaloidal portions of the rock masses—which may be considered the surface parts— grade over into other portions, the interiors of the lava flows, which are, macroscopically at least, nonamygdaloidal. Owing to the homogeneous character of the basic magmas, a fluxion structure is rarely shown macroscopically, though microscopically it may be more or less well developed. Columnar jointing was nowhere

observed. An ellipsoidal parting, on the other hand, is common.

NOMENCLATURE.

In a preliminary article on the Hemlock volcanics,[1] I made a brief mention of the occurrence on the Upper Peninsula of Michigan of the basic pre-Tertiary equivalents of the post-Tertiary and Recent family of basalts. Following the Danas, Wadsworth, Williams, Iddings, Kemp, Darton, and Diller, some of the most influential of the men who, in the

[1]The volcanics of the Michigamme district of Michigan, by J. Morgan Clements: Jour. Geol., Vol. III, 1895, pp. 801-822.

United States, have advocated the simplification of petrographical nomenclature, I used the term basalt, now ordinarily used for the Tertiary or post-Tertiary basic rocks. This term was, however, modified by the prefix "apo," as indicating their altered condition and the presumed presence of a glassy base.[1] This was a logical continuation of the use of the prefix as proposed by Dr. Bascom[2] for devitrified acid lavas.

More detailed studies upon the Hemlock volcanics have shown the presence of rocks which were apparently originally holocrystalline, and therefore do not belong with the altered vitreous basalts, the apobasalts, and others in which some of the glass is apparently unaltered. Consequently, since the apobasalts comprise only a portion of the Hemlock volcanics, the replacement of that term as a general heading by the older, more general, one of basalt was considered.

The use of this term is, however, not altogether satisfactory, for the rocks, while clearly recognizable as basalt derivatives, do not possess the mineralogical composition of the basalts. The term "apo" having been restricted, as above indicated, can not be applied to them, for their alteration is in many cases metasomatic and dynamic, and in most cases not devitrification. If we adopt the prefix "meta" to indicate alteration of all kinds, then these rocks could be called "metabasalts."

The terms "metadolerite," "metadiabase," etc., were proposed by Dana[3] for metamorphic dolerites, diabases, etc., and first used by Hawes[4] in the description of the altered rocks around New Haven. Recently these terms have been revived, but with a very different significance from that with which they were first used. It is proposed to designate by such terms "rocks now similar in mineralogical composition and structure to certain igneous rocks, but derived by metamorphism from something else."[5] Following this suggestion, an uralitized dolerite (diabase) would be called a metadiorite. Such a use of the term does not seem justified, and the

[1]Loc. cit., p. 805.

[2]The structures, origin, and nomenclature of the acid volcanic rocks of South Mountain, by Florence Bascom. Jour. Geol., Vol. 1, 1893, p. 828.

[3]Chloritic formation of New Haven, Connecticut, by J. D. Dana: Am. Jour. Sci., 3d ser., Vol. XI, 1876, pp. 119-122.

[4]The rocks of the "chloritic formation" on the western border of the New Haven region, by G. W. Hawes: Am. Jour. Sci., 3d ser., Vol. XI, 1876, pp. 122-126.

[5]On a series of peculiar schists near Salida, Colorado, by Whitman Cross: Proc. Colo. Sci. Soc. p. 6, footnote. Paper read Jan. 2, 1893.

objection to it can not be given better than by quoting-the words which Zirkel uses in the discussion of the metamorphism of rocks:[1]

> Bei solchen metamorphisch veränderten Gesteinen ist es nicht zweckmässig, sie mit dein Namen desjenigen Typus zu belegen, dem sie durch die Veränderung ähnlich, oft bios scheinbar ähnlich geworden sind. Eine solche Bezeichnung werde nur zu missverständlichen Auffassung der von dem Gestein gespielten geologischen Rolle führen, welche menials ausser Acht gelassen werden darf. Und so ist es denn entschieden vorzuziehen, der Beneunung soldier Gesteine eine Form zu geben, in whelcher zuvörderst auch zum Ausdruck kommt, was sie früher gewesen sind, und nicht einen Namen zu wählen, der sie in erster Linie zu etwas stempelt, mit welchem sie genetisch keine Gemeinschaft haben.

Using these terms in the way suggested by Cross, attention is most pointedly directed to that variety of rock which the secondary product now resembles mineralogically, rather than to the type from which it was derived, and which in all likelihood it still resembles most closely in its chemical constitution. Whether or not a petrographer will use the term "metadiorite" or the term "metadolerite" (diabase) for a metamorphosed dolerite will depend on whether or not he prefers to emphasize the present mineralogical composition of the rock, or its original characters, and thereby its chemical constitution and genetical relations. In the present report the terms "metabasalt" and "metadolerite" are used as including all those altered rocks which demonstrably were originally basalts and dolerites.

[1]Lehrbuch der Petrographie, F. Zirkel: 2d ed., Vol. 1, p. 573.

These same strictures hold good in the case of Gümbel's term "epidiorite" when used, as it is very commonly, in the literature of the Lake Superior region and elsewhere, for rocks avowedly derived from dolerites (diabases), and characterized by the presence of fibrous secondary amphibole. It is preferred, in accordance with the above statement, to use the term "epidolerite" (epidiabase) instead of "epidiorite" for such altered dolerites. None of these rocks, unless extremely changed, would resemble chemically a diorite, and we have come of late years to rely more and more upon the chemical composition, combined of course with the mineralogical composition and textures of the rocks, to separate the various kinds from one another. As stated above, the term "epi," associated with the rock name, has come more and more to be restricted in its use solely to a rock, the epidiorite, characterized by a specific alteration product, the amphibole. In respect to this restriction to specific alteration, the term corresponds to "apo," and it is unfortunate that these two terms should have been so narrowly confined. As it is, the epi- and apo-basalts would be subordinate to and therefore included under the metabasalts, as this term is used in this report. In the first the production of

secondary hornblende is characteristic; in the second the process of devitrification, and hence the original presence of a vitreous base, is the chief characteristic.[1]

METABASALTS.

All of the basalts belong to the plagioclase type. They may be most conveniently divided into nonporphyritic and porphyritic kinds, according to their most obvious macroscopical characters. There has also been found a single occurrence of a spherulitic basalt, which will be described under the head "variolite."

NONPORPHYRITIC METABASALT.

The nonporphyritic rocks possess a fine-grained or aphanitic structure and are amygdaloidal or nonamygdaloidal. There are included under this general name the microophitic-textured fine-grained pre-Cambrian basalts (diabases in part), the very amygdaloidal forms of the basalts (spilites),[2] and the melaphyres in part. In these rocks the former presence of a considerable amount of original glass is probable, and they show the various textures known as navitic, intersertal, pilotaxitic, and hyalopilitic.

With the nonporphyritic basalts there have been included some rocks which are to a considerable extent devitrified glasses, and others in which only a few microlites have developed. These last two vitreous types occur more especially in fragments in the tuffs, and are quantitatively unimportant.

Petrographical characters.—In color the nonporphyritic basalts on fresh fracture show various uniform shades of green, dark olive green usually prevailing. Much less common are purplish-black rocks, and these are much more variable in color. In one of them is seen lighter-colored schlieren, which pass over into the ordinary dark colors. The lighter-colored portions are seen on microscopical examination to be due to a smaller quantity of the iron in them and to a greater quantity of chlorite than occurs in the rest of the rock mass. Where weathered, the rocks are usually covered by a thin crust, in which gray, brown, and pinkish tints prevail.

[1]The above discussion was written and the determination to use the terms porphyry—without textural significance, as in rhyolite-porphyry—metabasalt, etc., was reached, in 1896, before the committee on petrographic nomenclature of geologic folios was appointed by the Director of the United States Geological Survey.

[2]Microscopic characters of rocks and minerals of Michigan, by A. C. Lane: Rept. State Board of Geol. Survey for 1891-92, 1893, p. 182.

The rocks vary in texture very much, from the dense aphanitic kinds to medium fine-grained varieties. The latter are usually less amygdaloidal than are the aphanitic forms, and approach in appearance both macroscopically and microscopically the coarser-grained basalts or dolerites represented in the Michigamme district by the coarse-grained intrusives. Owing to the basic nature of the rocks, they have generally suffered much alteration, and as a result the original texture is in many cases poorly preserved. On the whole, however, it is remarkable, considering their age and basic character, how well preserved it is. Where it is preserved it varies from the microophitic to the various microlitic textures, such as intersertal, navitic, pilotaxitic, and hyalopilitic, and lastly glassy. In places a flowage structure is beautifully brought out by the position of the feldspar microlites, especially around the amygdules.

The constituents present are plagioclase, light-green fibrous hornblende, epidote-zoisite, chlorite, calcite, muscovite, apatite, sphene, quartz, magnetite, and pyrite. Of these the feldspar, apatite, and iron oxide alone are original. In some places the hornblende is wanting, the chlorite then appearing in correspondingly greater quantity.

The feldspar ordinarily occurs in lath-shaped crystals showing twins of the albite type, but where the texture is fine the feldspars are microlitic, and, while showing their prominent long extension, the edges of the various crystals interfere, and the outlines consequently are less sharp.

In some of the rocks which appear to have been vitreous the feldspar forms feather and sheaf like aggregates (figs. *A*, *B*, Pl. XXVI), apparently quite similar to those described by Ransome in rocks from Point Bonita, California.[1] No reliable measurements could be made upon the microlites, and consequently their character could not be determined. The feldspar is more or less completely altered to aggregates of epidote-zoisite which have chlorite associated with them or are altered to sericite. In a number of places minute limpid spots of secondary quartz and albite are present. The very small quantity of apatite present shows its usual characters. Titaniferous magnetite ore is apparently the only oxide present. It occurs in crystals and in irregular grains, which in a few cases are not entirely altered, though in most cases they are replaced by sphene. In some cases the alteration product is not well enough individualized for one to diagnose it as sphene, and it should perhaps be called leucoxene. In some of the finegrained rocks the material in the angles between the feldspars consists predominately of grains of magnetite. This abundant magnetite renders the rock very dark, giving the rare purplish-black lavas.

[1]Eruptive rocks of Point Bonita, by F. Leslie Ransome: Bull. Univ. of Cal., Vol. I. 1893, p. 84, fig. 6.

The most of the hornblende has a light-green color. A lesser portion shows a decided bluish tinge, and gives fairly strong pleochroism. This resembles the hornblende, which in the coarse dolerites is undoubtedly secondary after the augite and it is considered to be secondary after the original augite in these rocks.

The original augite was presumably in most cases present in wedge-shaped pieces filling the spaces between the feldspars, and consequently the hornblende pseudomorphs never show augite outlines. No unaltered augite was observed amongst the hornblende fibers. The fine fibers frequently form a fringe beyond the original boundaries of the pieces and penetrate the adjacent feldspar. Quite frequently the secondary

hornblende shows partial alteration to chlorite and epidote.

Though careful search was made for olivine or indications of its presence, no traces of it were found, and I have concluded that these basic volcanics were essentially nonolivine bearing, though it would be rash to state that such rocks did not contain some olivine.

The calcite is usually found in irregular secondary granular aggregates scattered through the rock, and evidently replaces the other minerals. Less commonly it is seen as an infiltration product along fissures.

A second form of the occurrence of calcite in the nonporphyritic meta-basalts, and one not so common as the granular aggregate, is that of large porphyritic automorphic rhombohedra and scalenohedra which lie embedded in the eruptive groundmass. Such a rock, as, for instance, Sp. 32472, shows macroscopically large rhombohedral phenocrysts in a green groundmass. On the weathered surface are ferruginous rhombohedral cavities, once occupied by the carbonates. The groundmass consists of rather fresh plagioclase microlites, between which are observed some quartz, fresh magnetite crystals, and lastly chlorite flakes as alteration products of originally present bisilicates or glass, or both. The texture is undoubtedly that of an eruptive. The carbonate is more or less ferruginous, brown iron hydroxide resulting from its alteration, and as it effervesces quite readily with cold HCl, it is supposed to be ferruginous calcite.

Sericite is found in minute flakes replacing the feldspars, and it is also found in large porphyrinic plates occurring in the eruptive groundmass associated with the porphyrinic carbonate above described. In some cases we find epidote in these altered basalts, in others zoisite. In a great number of instances the same individual exhibits the high interference colors of epidote and the low blue interference color of zoisite in different parts. These different portions, formed respectively of the epidote and zoisite molecules, are most closely intergrown, and I have therefore used the compound term “epidote-zoisite,” indicating this fact. Associated with this, one finds in many of the specimens small mineral aggregates which merit somewhat further notice. These aggregates have a brownish-yellow color and possess a very high single and also a high double refraction. In these masses the single and double refractions of the granules composing the aggregates appear to be higher than that of epidote. In shape the aggregates vary from perfectly round, zonally arranged spheres and irregular, elongated, rounded aggregates to forms giving oblique quadratic sections. All of these aggregates are found at times included in the epidote-zoisite crystals. In a few cases the oblique quadratic sections were seen to occupy the centers of the epidote-zoisite crystals, having exactly identical outlines. It is believed that they are composed of an epidote much richer in iron than the common variety with which they are associated. This increase in iron explains the darker color and the increase in single and double refraction, as shown by Forbes.[1] Why it should appear, especially in the aggregates, can not be explained.

The chlorite does not appear to be entirely an alteration product of the secondary hornblende with which it is associated. There is usually rather more chlorite than it would seem could possibly have been formed from the alteration of the hornblende alone. In some of the rocks the larger angles, as well as the extremely fine areas between adjacent feldspars, are occupied by a very fine felt-like chloritic mass. The chlorite which is not secondary after hornblende is considered as the product of an altered glassy base.

No glass was observed in the nonporphyritic basalts occurring in large masses, but in one of the fragments of basalt in a tuff a dark chocolate-brown glass forms the matrix in which are lying well-developed plagioclase microlites. The glass where thick appears isotropic, but where thin appears to be full of globulitic devitrification products, which show slight polarization effects between crossed nicols.

[1]Epidote and its optical properties, by E. H. Forbes: Am. Jour. Sci., 4th ser., Vol. 1, 1896, p. 30.

The original presence of glass in other basalts is considered to be indicated by the occurrence of amygdaloidal cavities, with very sharply defined walls marked by accumulations of magnetite.

The character of one basalt points strongly toward its glassy condition. It is amygdaloidal, the amygdaloidal cavities being sharply defined. The groundmass contains at present no indication of the existence of any originally crystalline elements whatever. It is now a dense mass of felty chlorite and minute epidote grains. Through this mass and around the amygdaloidal cavities wind lines which are somewhat differently colored from the rest of the matrix, and seem to indicate the direction of flowage. The amygdules are not all elongated, though some are, and these agree in direction of elongation. It is really impossible to describe the groundmass so as to do justice to its appearance and convince one who has not seen it of its devitrified character. The general impression it makes is that of a devitrified glass, and the photomicrograph (fig. *B*, Pl. XXV) gives a fairly good idea of its appearance under the microscope, and will probably prove more convincing than any description that might be given. Fig. *A*, Pl. XXVII, represents a polished face of the specimen in its natural size.

Another kind of glassy basalt is represented in this district. This rock resembles the one just described, but differs from it in that it was not altogether glassy. In it one sees long, slender, much-altered feldspar microlites scattered through the matrix. These feldspars occur in needles, which fringe out at the ends. They do not give the groundmass textures usually found in the basalts, but occur in sheaves and imperfect spherulitic forms; the rock thus approaches in texture the variolites. The base in which the feldspars lie is brownish gray, and consists of recognizable chlorite, epidote, some clear mineral in minute particles, probably quartz or feldspar, or both,

and aggregates of yellowish granules, which are apparently of a single kind and are so minute as not to permit of determination. The granules show very slight polarization effects under crossed nicols, and the groundmass in many places where they occur in great quantity appears almost isotropic. It seems highly probable that a large portion, if not all, of the groundmass was originally a glass. Further evidence of the originally glassy microlites. The glass where thick appears isotropic, but where thin appears to be full of globulitic devitrification products, which show slight polarization effects between crossed nicols.

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Chemical composition.—The following complete analysis, for which I am indebted to Dr. Henry Stokes, of the United States Geological Survey, shows the chemical composition of one of these pre-Cambrian nonporphyritic metabasalts. The rock is very fine grained and microophitic, with a marked amygdaloidal character. The amygdaloidal cavities are filled with chlorite, into which project crystals of epidote-zoisite and calcite. The altered condition of the basalt is very clearly shown by the high percentages of water and carbon dioxide. The other oxides show nothing remarkable except that the percentage of titanium oxide is quite high. On the whole, however, the analysis is very similar to those of recent fresh rocks of the same character.

Analysis of pre-Cambrian nonporphyritic metabasalt.

Constituent.	Per cent.	Constituent.	Per cent.
SiO_2	46.47	K_2O	0.21
TiO_2	1.28	P_2O_5	.13
Al_2O_3	16.28	CO_2	1.26
Fe_2O_3	3.15	Cl	
FeO	8.96	SO_3	
MnO	.09	H_2O at 110°	.28
MgO	6.56	H_2O above 110°	3.89
CaO	7.90	Total	100.11
Na_2O	3.64		

PORPHYRITIC METABASALT.

The porphyritic rocks are fine grained, and may be or may not be amygdaloidal. They include diabase porphyrites and porphyritic forms of the melaphyres. These last in the textures of their groundmass correspond to the labradorite-porphyrites, the equivalents of the andesite-porphyries, though more basic than they. The phenocrysts lie in a fine groundmass which shows the same kinds of texture already mentioned as having been observed in the corresponding nonporphyritic basalts, the microophitic, inter-sertal, navitic, pilotaxitic, and hyalopilitic. The various basalts are connected by transition phases. The close connection between the different varieties is well shown where one passes from the fine-grained amygdaloidal rock through the fine-grained nonamygdaloidal over to the porphyritic macroscopically nonamygdaloidal type.

Petrographical characters.—As stated in the general description, these rocks do not differ essentially from the nonporphyritic basalts just described. The most important difference is in the presence of the feldspar phenocrysts, giving them a porphyritic texture.

Measurements upon the phenocrysts, made against the albite twinning plane on zone ⊥ to 010, according to the Michel Lévy method, give an average extinction angle of about 18°, which points toward its character as

labradorite. However, angles obtained lower than this indicate the possibility of the association of andesine with the predominant labradorite. The feldspars show the usual alteration products. One very infrequently finds augite phenocrysts which have been completely uralitized associated with the feldspars. Other phenocrysts are now represented by masses of chlorite, with or without epidote, evidently pointing toward the basic and magnesian nature of the original mineral. As uralite is the common secondary product of pyroxene in these volcanics, the altered phenocrysts represented by chlorite masses are not believed to have been pyroxene. The original mineral was perhaps olivine. The very noticeable scarcity of augite phenocrysts in the basalts stamps them as different from the great majority of basaltic rocks and as being very similar to the basalts described by Judd,[1] from the Brito-Icelandic petrographical province, in which porphyritic crystals of augite are seldom if ever seen and in which the phenocrysts are feldspar and sometimes olivine.

The groundmass in which the phenocrysts lie have generally the same mineralogical composition and texture as the nonporphyritic rocks already described, and the two kinds are supposed to have been originally similar.[2] Measurements made on the feldspar microlites of the groundmass gave 17° as the maximum extinction in zone perpendicular to 010. This angle points toward the microlites being acid labradorite. The microlites thus seem to agree essentially with the phenocrysts in composition. Flowage structure around the phenocrysts is most distinctly shown by the arrangement of the feldspar microlites. In one case in which the porphyritic texture and the flowage structure are very good, secondary actinolite crystals have developed parallel to one another and parallel to the flowage direction, giving the rock under the microscope a distinctly schistose appearance.

[1]On the gabbros, dolerites, and basalts of Tertiary age in Scotland and Ireland, by J. W. Judd: Quart. Jour. Geol. Soc., Vol. XLII, 1886, p. 79.

[2]The groundmass of one of these porphyritic forms differs somewhat in one important respect. In it were observed numerous round areas of small size occupied by a clear white aggregate, polarizing in low gray colors. The centers of some of the areas were occupied by clumps of yellow grains, with here and there a minute flake of chlorite. Others contain only the white material, which is apparently secondary. The round areas are not sharply delimited, and hence are most probably not microamygdules. Their general appearance is strikingly like that of leucite in those plagioclase basalts in which it is present in very small quantity, filling irregular hut in general rounded areas between the other constituents. It would, of course, be impossible to base the determination of the former presence of leucite in these pre-Cambrian rocks upon such scant evidence as has been obtained. Still it is worth while to notice even such a doubtful indication of its former presence as has been mentioned above.

Chemical composition.—In the preliminary article upon these Hemlock volcanics published in 1895,[1] the occurrence of andesites as well as basalts was mentioned. This determination was based solely on the microscopical study of the rocks, and the rocks which were presumed to be andesites were those porphyritic forms which have just been described. Since the publication of that article the following analyses (Nos. 1 and 2) have been obtained of the porphyritic rocks. The rocks selected for analysis were those which appeared to be especially rich in feldspar, and, having a rather lighter color than the others, seem to be somewhat more acid than the average. These, it was thought, might have the composition of andesite.

The comparison of series of rocks derived presumably from the same magma is more profitable than the study of single analyses. This line of investigation, as followed by Rosenbusch,[2] Iddings,[3] Lang,[4] Broegger,[5] Becke,[6] and Michel Lévy,[7] has been very fruitful.

[1]Jour. Geol., cit. pp. 805-806.

[2]Ueber die chemischen Beziehungen der Eruptivgesteine, by H. Rosenbusch: Tsch. Min. u. Pet. Mitt., Vol. II, 1889, pp. 144-178.

[3]Origin of igneous rocks, by J. P. Iddings: Bull. Phil. Soc. Wash., Vol. XII, 1892, pp. 88-214. The eruptive rocks of Electric Peak and Sepulchre Mountain, by J. P. Iddings: Twelfth Ann. Rept. U. S. Geol. Survey, 1892, pp. 571-664.

[4]Ordnung der Eruptivgesteine nach ihrem chemischen Bestand, by H. Otto Lang: Tsch. Min. u. Pet. Mitt., Vol. XII, pp. 199-252. Beitrage zur Systematic der Eruptivgesteine, by H. Otto Lang: Tsch. Min. u. Pet. Mitt., Vol. XIII, 1892, pp. 115-169.

[5]Die Eruptivgesteine des Kristianiagebietes, by W. C. Broegger. I. Die Gesteine der Grorudit-Tinguait serie. II. Die Eruptionsfolge der triadischen Eruptivgesteine bei Predazzo in Südtyrol. Videnskabsselskabets Skrifter, I Mathematisk-naturv. klasse. No. 4, 1894; No. 7, 1895.

[6]Gesteine der Columbretes, by F. Becke: Tsch. Min. u. Pet. Mitt., Vol. XVI, 1896, pp. 308-336.

[7]Note sur la Classification des Magmas des Roches Éruptives, by A. Michel Lévy; Bull, de la Soc. Géol. de France, 3d ser., Vol. XXV, No. 4. July, 1897, pp. 326-377.

The value of such an investigation largely depends on the freshness of the rocks examined and the amount of variation. The Hemlock volcanics are all more or less altered, and the variation in character is slight. I wish, however, to call attention to the close relationship exhibited by the types of which analyses were made, and to that end the analysis of the nonporphyritic very basic appearing basalt (No. 3 of Table I) is repeated and is placed by the side of the analyses of the porphyritic ones. The complete analyses made by Dr. Henry M. Stokes, of the United States Geological Survey, are found in the first table. In the second table there is given the molecular proportion of the chief oxides, those which are not here represented having been first proportioned among them. From this table, following Rosenbusch,[1] there were obtained the figures in the third table, showing the atomic proportions of the metals present.[2]

The analyses are arranged according to the increasing percentage of calcium.

Analyses of porphyritic metabasalt.

TABLE I.—COMPLETE ANALYSES.

Constituent.	1.	2.	a 3.
SiO_2	47.20	52.59	46.47
TiO_2	3.30	1.36	1.28
Al_2O_3	15.36	15.93	16.28
Fe_2O_3	3.06	6.12	3.15
FeO	8.87	3.96	8.96
MnO	.20	.25	.09
CaO	5.05	5.55	7.90
MgO	4.20	5.04	6.56
Na_2O	4.72	5.79	3.64
K_2O	1.40	.67	.21
P_2O_5	.36	.15	.13
Cl			
SO_3			
CO_2	3.34	None.	1.26
H_2O at 110°	.16	.16	.28
H_2O above 110°	3.04	2.16	3.89
Total	100.26	99.73	100.11

a No. 3 is the analysis by Dr. Stokes of the nonporphyritic basalt, and is given for comparison.

[1]Uber die chemischen Beziehungen der Eruptivgesteine, by H. Rosenbusch: Tsch. Min. u. Pet. Mitt., Vol. XI, 1890, p. 144.

[2]Tables Nos. II and III were calculated for me by Mr. Victor H. Bassett, assistant in chemistry in the University of Wisconsin.

TABLE II.—MOLECULAR PROPORTION OF THE CHIEF OXIDES.

SiO_2	50.55	54.07	49.15
TiO_2	3.54	1.40	1.35
Al_2O_3	16.45	16.38	17.22
Fe_2O_3	3.28	6.29	3.33
FeO	9.72	4.33	9.57
CaO	5.41	5.71	8.36
MgO	4.50	5.18	6.94
Na_2O	5.05	5.95	3.85
K_2O	1.50	.69	.22
Total	100.00	100.00	100.00

TABLE III.—ATOMIC PROPORTION OF METALS.

Si	46.97	49.49	45.41
Ti	2.48	.97	.94
Al	18.07	17.73	18.80
Fe	9.87	7.67	9.74
Ca	5.42	5.63	8.33
Mg	6.25	7.09	9.58
Na	9.16	10.61	6.93
K	1.78	.81	.27
Total	100.00	100.00	100.00

As the calcium increases there is a corresponding increase of magnesium and a diminution in potassium. A decrease in sodium is also shown if Nos. 1 and 3 alone are compared. The percentage of sodium present is rather high and with the potassium indicates a magma family rich in alkalies. The magnesium is notably high; such high percentages as we have here usually accompanying much lower percentages of alkali. It may also be noted here that the presence of the magnesium in such amounts indicates the former presence of olivine or the presence still of its alteration products, a point to which attention was directed in the microscopic description of the rocks. No. 1 is remarkable for its percentage of titanium, which is very high, even when compared with that contained in the others, which are themselves considerably above the average. All of the rocks contain a large amount of water of hydration. The percentage of CO_2 contained in Nos. 1 and 2 indicates also that they are much altered.

These analyses show that the rocks can not be classed with the typical andesites. Should they be called andesites at all, they must be classed with the augite-andesites, and placed on the border line between them and the plagioclase basalts. It is preferred to include them under the basalts, though it can not be doubted but that if analyses of perfectly fresh rocks could be obtained, there would be found some which would incline more decidedly toward andesites than do the above specimens.

VARIOLITIC METABASALTS.

Variolites are spherulitic basalts, usually very vitreous. Since the tendency to crystallization is so much stronger in the basic than in the acid rocks, it is not surprising that they should be far less common than the corresponding acid kind. Moreover, the basic glasses are very susceptible to alteration, which naturally obscures the original characters of the rocks. This probably partly accounts for the fact that they are very infrequently observed. This spherulitic phase of the basalts is well known in Europe, but there has thus far been found only one reference to its occurrence in the United States. Ransome[1] has described a variolite from Point Bonita, California. To this there may now be added a single occurrence in the Crystal Falls district of Michigan. This variolite exposure occurs at N.375, W. 900, sec. 4, T. 44 N., R. 33 W., in close proximity to the remnant of a basalt stream which shows well-marked flowage structure. The relations of the two rocks are not determinable from the exposures.

The rock presents a very rough mammillated surface, due to differential weathering. The varioles, being more resistant than the groundmass surrounding them, form the protuberances. These protuberances vary in shape from round to oval, and very rarely are irregular. The varioles vary also in size from minute ones to those about one-half inch in diameter, and constitute by far the greater part of the rock. These general characters may be seen on the photograph, fig. *A*, Pl. X, taken from the hand specimen. The color of the weathered surface of the rock is gray or light brown, while the fresh surface is in general a dark green. Upon the polished surface of a fresh rock the varioles have an olive-green color, with, in the majority of cases, a distinctly darker center of purplish color. Less frequently this center is lighter green than the remainder of the variole. The varioles are usually separated from each other by narrow areas of groundmass, darker than the varioles themselves, with a purplish or very dark olive-green color. In places the varioles are in juxtaposition. However, they do not coalesce, but each is separate and distinct (fig. *B*, Pl. X).

[1]The eruptive rocks of Point Bonita, California, by F. Leslie Ransome: Bull. Dept. Geol. Univ. of Cal., Vol. 1, 1893, p. 99.

PLATE X.

FIG. *A*.

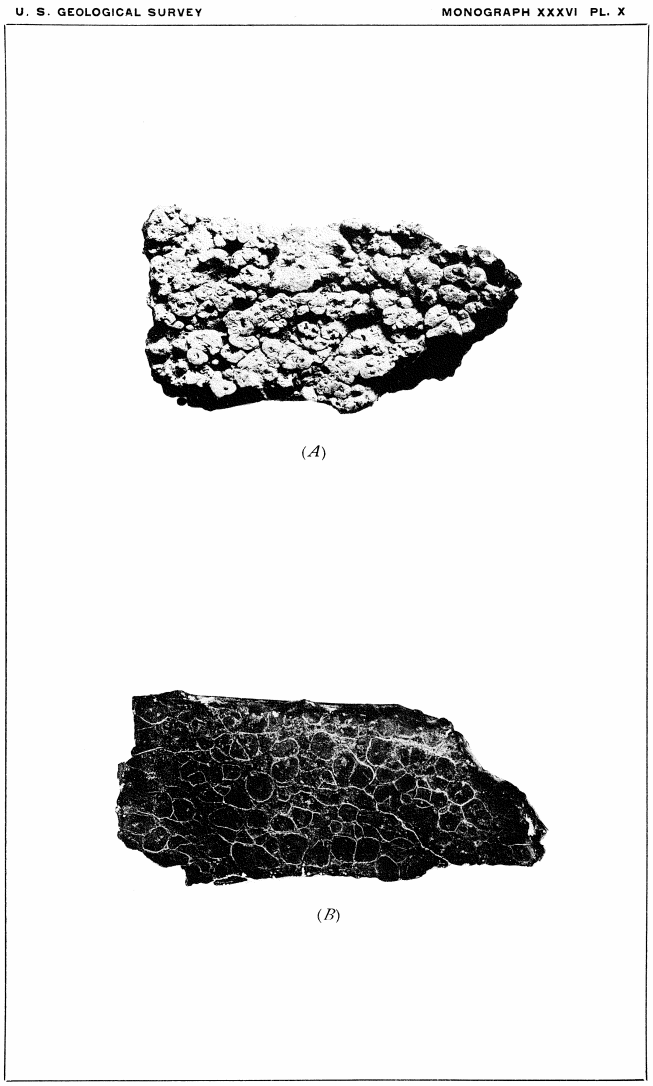
(Sp. No. 32273. Natural size.)

Photographic reproduction of the weathered surface of a variolite. This brings out very clearly the mammillated surface of the rock, which is due to the differential weathering of the varioles and of the groundmass between them. The rounded character of the varioles, and their gradation from those of very small to those of much larger size can readily be seen. (Desc, p. 108.)

FIG. *B*.

(Sp. No. 32273. Natural size.)

Reproduction of the polished surface of a variolite. This is designed to show the circular character of the varioles, and the fact that each is separate and distinct from the one adjoining it. It can be seen that some of the varioles have very dark and others much lighter centers. (Desc, p. 108.)



(*A*) Weathered surface of variolite.
(*B*) Polished surface of variolite.

The rock when examined under the microscope is seen to be extremely altered. The only original minerals present are feldspar, apatite, and possibly some magnetite.

The groundmass consists of a finely crystalline secondary aggregate of flakes of chlorite, associated with minute limpid grains, some of which are probably quartz and others feldspar. Scattered through this aggregate are grains of epidote, calcite, a few crystals of original apatite, and magnetite, and numerous dark reddish brown and black ferruginous specks.

The varioles are readily distinguishable from the matrix. From this, as well as from each other, they are invariably separated by a crack, along which reddish-brown ferruginous matter has been infiltrated. The varioles are in general much finer grained than the groundmass, and at times exhibit phenocrysts of feldspar. The composition of the varioles is the same as that of the groundmass, except that apatite is more common in them, and that in addition to the minerals mentioned as occurring in the groundmass a small quantity of original feldspar may be recognized, both as phenocrysts and as part of the groundmass of the varioles. Where these feldspars occur, they are to a great extent replaced by a mass of epidote, chlorite, sericite, quartz, and feldspar. The phenocrysts are found near the center of the varioles, and the occasional light-colored centers, which were observed macroscopically are due to the presence of these altered feldspar phenocrysts. The more frequent dark centers are due to an accumulation of the dark ferruginous specks in varioles in which the phenocrysts are wanting.

No textures could be determined from the remnants of the original minerals. In one variole aggregates of secondary epidote grains and ferruginous specks lie in such a position as to produce a distinct radial arrangement. With advancing alteration, spherulites in acid rocks are frequently found to have between their radial fibers secondary deposits of epidote and ferruginous matter, which mark very clearly their radial arrangement. The similar radial arrangement in these varioles of epidote and ferruginous matter seems to point to the varioles having possessed the spherulitic character, though it is now impossible to determine the nature of the fibers forming the spherulites.

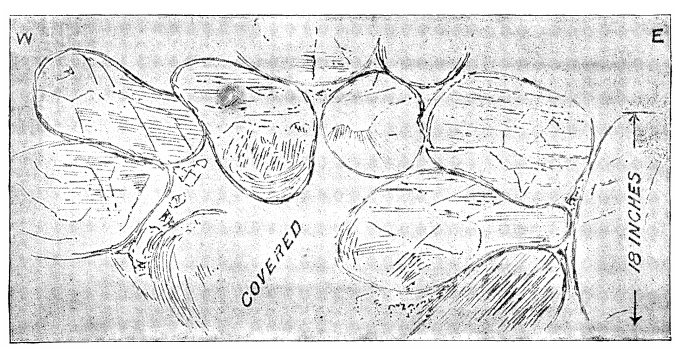


FIG. 7.—Sketch of the surface of the outcrop of an ellipsoidal basalt, showing the general character of the ellipsoids and matrix.

THE ELLIPSOIDAL STRUCTURE IN THE METABASALTS.

Upon examining the flat surfaces of many of the lavas one is immediately struck by their resemblance to a conglomerate formed of round bowlders, all of the same kind of rock, lying in a matrix of very small quantity and of very different color.

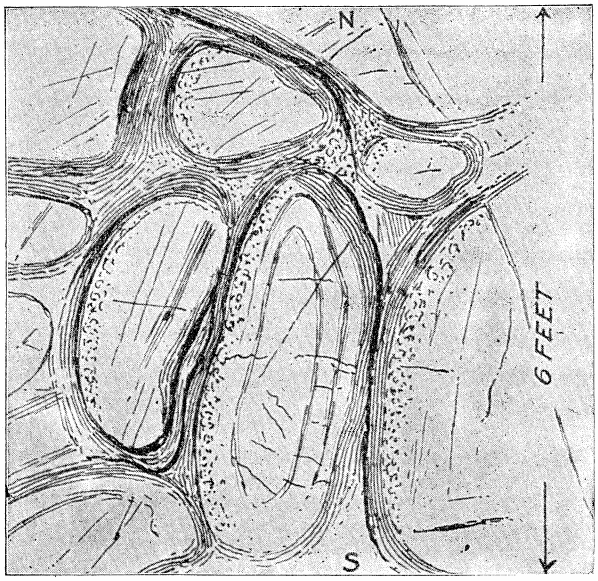


FIG. 8.—Sketch showing the concentration of the amygdaloidal cavities on one side of an ellipsoid, this side probably repressing the side nearest the surface of the flow.

Fig. 7 is a sketch showing a portion of such a lava flow. I find that these ellipsoidally parted rocks have been called "massive conglomerates," and the blocks have been spoken of as-"bombs" in the manuscript notes of some of the men who have worked among them. The latter term was undoubtedly due to the resemblance of the ellipsoids to the spindle-shaped pieces of lava which one finds around the modern volcanoes. Ellipsoidal basalt is very common throughout the Hemlock volcanic area. It is found most frequently in isolated ledges. However, it is also associated with and grades into non-ellipsoidal varieties. In one good exposure it is overlain by a fragmental scoriaceous mass which separates it from another mass of similar ellipsoidal basalt. While the scoriaceous portion may represent the brecciated surface of a lava flow, it is not so considered, but is presumed to be a tuff deposited upon the flow represented by the ellipsoidal basalt. According to this view the ellipsoidal basalt is on the surface. In another exposure an ellipsoidal basalt overlies a bed of water-deposited clastic rock. There is no passage between the two kinds of rock. The contact between the two is an undulating one, and is marked by a mass of schistose material about 2 inches thick and similar to that which is between the ellipsoids. This particular basalt is very dense, with only occasionally small chlorite-filled vesicles in it, and there is no true flow structure observable. The facts cited seem to show that this ellipsoidal portion was the surface of a lava flow, whether the top or the bottom is immaterial. In certain cases the ellipsoidal fades may constitute an entire flow. Where the direction of flow could with any degree of certainty be determined, it was seen that the two longer axes of the ellipsoids are in the plane of the flow.

The ellipsoids vary in size from a few inches to 6 or 8 feet in diameter, and are usually spoken of as spheroids. Attention has already been called to the incorrect usage of this term by F. Leslie Ransome, in his interesting paper on "The eruptive rocks of Point Bonita, California."[1] The outlines of the bodies are circular only in exceptional cases. On the other hand, sections in all directions through them give almost invariably ellipses, and therefore they are more properly ellipsoids than spheroids. On the surfaces exposed the long axes of the ellipses lie in the same general direction.

The ellipsoids are formed of a very fine-grained porphyritic or nonporphyritic rock. This is amygdaloidal or non-amygdaloidal. Where amygdaloidal, the amygdules are as a rule distributed throughout the ellipsoids, though on the whole the masses are more scoriaceous on the periphery than near the center. In exceptional cases, the amygdules are much more numerous on the west side of the ellipsoids than on the east side (fig. 8). In such cases the west sides are toward the tops of the lava flows. The ellipsoids are very commonly split up by cracks. Some of them have a roughly radiate arrangement. These may be due to the effects of contraction in the early stages of the existence of the ellipsoids. Others, and by far the greater number, have one set of lines parallel and another parallel set which in different cases cut the first set at different angles, very rarely at a right angle (figs. 8, 9). One of these sets is usually tranverse to the long axes of the ellipsoids (figs. 7, 8).

[1]Op. cit., p. 75.

The blocks are separated from one another by a thin laver of a schistose matrix, rarely more than 3 inches in thickness, though exceptionally nearly 8 inches thick. (Of figs. 7 and 8 of this paper, and fig. 1 by Ransome.[1])

Since the above description of the Crystal Falls ellipsoidal lavas was written in 1896, there has appeared Sir Archibald Greikie's valuable work on the Ancient Volcanoes of Great Britain,[2] in which several similar occurrences are mentioned. His illustration of this structure on page 184, as can readily be seen on comparison, would answer, but for the absence of a well-defined schistose matrix between the ellipsoids, very well for a sketch of a Michigan pre-cambrian ellipsoidal lava.

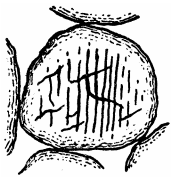


FIG. 9.—Ellipsoids with sets of parallel lines cutting each other at an angle.

The schistose matrix between the ellipsoids upon the weathered surface is seen to be made up of layers concentric with the ellipsoids. It is possible that these layers are not absolutely concentric in the third dimension. However, no exposure permitted of the determination of this point. Frequently certain layers seem to grade off into others of a somewhat different character. The matrix between any two ellipsoids usually separates near the center; where apparently the greatest movement having occurred the schistosity is most developed. One can often as easily knock an ellipsoid out of its encircling matrix as one can the kernel out of a nut. In some cases there is no absolutely sharp line of demarcation between matrix and ellipsoid, but a gradation from one into the other. At the places where three blocks are in juxtaposition one frequently finds, instead of a triangular space entirely filled by the matrix, in the center of the matrix a triangular area of infiltrated vein quartz (figs. 7, 8).

In certain cases the minerals which compose the schistose matrix are not thoroughly cemented and give it a somewhat friable character, causing it on weathered surface to appear granular.

In very rare cases a matrix with a distinctly brecciated character was observed, but in this as well as in the cases above described a certain degree of schistosity is noticeable. The matrix between the ellipsoids varies very much in degree of schistosity, color, and composition.

[1]Op. cit., p. 76.

[2]Ancient Volcanoes of Great Britain, by Sir Archibald Geikie, Vol. I, 1897, pp. 26, 184, 193.

PLATE XI.

(Sp. No. 23675. Natural size.)

This colored plate represents the polished surface of an ellipsoid with a portion of the matrix which surrounds it and separates it from the adjacent ellipsoids. The dense character of the center is nicely shown. Around this oval area we get narrow concentric zones of alternating light-green and dark-green material. The light-green material corresponds to that in the center, and represents the least-altered basalt of the ellipsoids. The dark-green areas are the chloritized basalt. Beyond this, forming the outermost greenish-gray zone, one finds the matrix, which possesses distinctly fragmental characters, though in spite of this with a marked schistose character. The schistosity of the matrix conforms to the contours of the ellipsoid.

BASALT ELLIPSOID WITH MATRIX.

The most schistose, and by far the most common variety, is the dark green matrix, which consists essentially of chlorite, epidote, and zoisite. This material is clearly the result of the chloritization and the epidotization of the original basalt constituting1 the ellipsoids, for we see it alternating with bands of and grading into the less altered basalt. (Pl. XI.)

A second facies of the matrix is that which possesses only a moderate degree of schistosity, and appears at

times almost massive. This matrix may be light colored, almost white or greenish, or a dark bluish-black. It is medium grained or aphanitic. The light-colored matrix consists essentially of quartz and calcite. When a little chlorite or epidote is present, it has a greenish tinge. The very dark variety consists of quartz and siderite, colored with minute particles of iron oxide. The quartz-calcite or quartz-siderite aggregates owe their origin to essentially the same processes, calcification, or sideritization, respectively, followed by silicification of the original basaltic material. They are therefore briefly described together here. Their characters and origin will be found discussed in detail on page 130 et seq. Some of the peculiar characters of this matrix are illustrated in fig. *B*, Pl. XXVII.

The least common variety of matrix found between the ellipsoids is of a light greenish-gray or brownish color, and possesses a noticeably brecciated character (fig. *B*, Pl. XXXIV, and Pl. XI), but with at the same time a certain degree of schistosity. Its characters are best seen under the microscope by moderate magnification. Its brecciated character is then well shown.

The fragments of such a matrix are of all sizes and are angular. They show quite commonly a separation into zones. The fragments now consist of chlorite and epidote, and in the fragments with zonal arrangement chlorite in exceedingly fine flaky aggregates occupies the center and epidote the outside. Now and then there may be several alternating zones of chlorite and epidote. In all cases both epidote and chlorite are present in the zones, but the one mentioned is in great quantity, while the other is very subordinate. The epidote is very commonly the dark ferruginous kind mentioned on page 101, and marks off the outer limits of the fragments. Now and then the limits are outlined by a zone of brownish ferruginous material, whose exact character could not be determined. The fragments of the breccia show now neither original minerals nor textures. To judge from the uniform character of the zones in the fragments, the original material was very homogeneous, most probably a basalt glass.

The spaces between the fragments are occupied by a finely crystalline aggregate of quartz and chlorite, with a small amount of epidote. This aggregate outlining the original fragments owes its origin most probably to the process of infiltration. The long axes of the quartz grains and chlorite flakes in this aggregate usually show a general parallel arrangement. Moreover, the long directions of the fragments are in general parallel with each other, and with the quartz-chlorite aggregate between them. This parallelism results in giving an imperfect schistosity to the matrix. The schistosity of the matrix is in general parallel to the contours of the ellipsoids which it surrounds.

Origin of the ellipsoidal structure.—Ellipsoidal structures similar to those just considered have been described by various authors.[1]

[1]On columnar, fissile, and spheroidal structure, by T. G. Bonney: Quart. Jour. Geol. Soc, Vol. XXXII, 1876, pp. 140-154.

Ueber mechanische Gesteinsumwandlungen bei Hainichen in Saehsen, by A. Rothpletz: Zeitschr. dent. Geol. Gesell., Vol. XXXI, 1879, pp. 374-397; Vol. XXXII, 1880, p. 447.

Report on the geology of northern New Brunswick, by R. W. Ells: Ann. Rept. Geol. and Nat. Hist. Survey of Canada, 1879-80, D, p. 24.

E. Dathe: Jarb. K. prenss. geol. Landesanstalt, 1883, p. 432.

K. Dalmer: Cf. Zirkel Pet., Vol. II, p. 650.

Report on the geology of the Lake of the Woods region, by A. C. Lawson: Geol. and Nat. Hist. Survey of Canada, 1885, CC, pp. 51-53.

The greenstone-schist areas of the Menominee and Marquette regions, by G. H. Williams: Bull. U. S. Geol. Survey, No. 62, 1890, pp. 137, 166-168, 175, and 203.

On the variolitic rocks of Mont Genevre, by G. A. J. Cole and J. W. Gregory: Quart. Jour. Geol. Soc, Vol. XLVI, 1890, pp. 295-332.

On a variolitic diabase of the Fichtelgebirge, by J. W. Gregory: Quart. Jour. Geol. Soc, Vol. XLVII, 1891, pp. 45-62.

The Kawishiwin agglomerate at Ely, Minnesota, by N. H. Winchell: Am. Geol., Vol. IX, 1892, pp. 359-368.

The eruptive rocks of Point Bonita, California, by F. L. Ransome: Bull. Dept. of Geol. Univ. of Cal., Vol. I, 1893, pp. 71-114.

Editorial note on the above paper, by N. H. Winchell: Am. Geol., Vol. XIV, 1894, p. 321.

The geology of Angel Island, by F. L. Ransome: Bull. Dept. Geol. Univ. of Cal., No. 7, 1894, p. 202.

Variolite of the Lleyn and associated volcanic rocks, by C. Raisin: Quart. Jour. Geol. Soc, Vol. XLIX, 1893, pp. 145-165.

On a radiolarian chert from Mullion Island, by H. Fox and J. J. H. Teall: Quart. Jour. Geol. Soc, Vol. XLIX, 1893, p. 211.

On greenstone associated with radiolarian chert, by J. J. H. Teall: Trans. Roy. Geol. Soc. of Cornwall, 1894: Cf. Rosenbusch, Mikroskopische Physiographie, 3d ed., p. 1064.

The volcanic rocks of the Michigamme district, by J. M. Clements: Jour. Geol., Vol. III, 1895, p. 808.

The geology of Point Sal, by H. W. Fairbanks: Bull. Dept. Geol. Univ. of Cal., Vol. II, 1896, p. 40.

Geology of the Fox Islands, Maine, by G. O. Smith, 1896, pp. 16-18.

The Ancient Volcanoes of Great Britain, by Sir Archibald Geikie, London and New York, 1897, pp. 26, 184, and 193.

Various attempts have been made to explain this peculiar structure. Bonney, Dathe, and Raisin regard contraction as the force which produced the rounded masses.

Dathe and Dalmer show by the presence of the concentrically arranged amygdules that the ellipsoids were units, and were formed before solidification of the rock. This arrangement of the amygdules, as well as the arrangement illustrated in fig. 8 on page 113, precludes at once the idea that the structure owes its origin to the well-known weathering process which by exfoliation produces spheroidal blocks.

Rothpletz and Williams look upon the ellipsoids as due to mechanical forces which ground down the angles and edges of a fractured lava flow, the idea of both authors apparently being that the fractures were long subsequent to the movement of the flow.

Ells and Lawson mention the structure as concretionary.

Winchell considers the cases described by him as agglomeratic accumulations.

Cole and Gregory see in the masses evidence of lavas rolling over among themselves. In the later paper, published alone, Gregory definitely states that the lava first contracted into spheroids, which then rolled over one another.

Ransome explained the Point Bonita occurrence as a basalt which flowed "as a viscous pahoehoe, one sluggish outwelling of lava being piled upon another to form the whole mass of the flow."[1] In the description of the basalts, he writes: "A certain amount of crushed and sheared material fills the interstices between the spheroids and seems to be made up of comminuted fragments of the same rock. It is, however, too crumbling and too full of secondary products for a satisfactory determination."[2] In the second occurrence, in a fourchite (augitite?), the relations of the rocks are such as to prove "conclusively that such structure can not be rigidly restricted to surface flows, although it is still believed that lavas exhibiting it must have been erupted under very nearly surface conditions."[3]

Teall agrees with Ransome in comparing the ellipsoidally parted masses of basalt to pahoehoe lava. Teall concludes that such ellipsoidally parted basalts are submarine flows.

In a recent paper Smith has described from certain volcanics bodies which in cross section give elliptical figures, but whose indeterminate downward extension shows them to be columns. The rounding of the columns, which were presumably originally prismatic, he ascribes to dynamic action. He also suggests that ellipsoidal masses could result from a similar dynamic modification of a mass of lava parted into shorter prisms, or even ellipsoids.

[1]Op. cit., p. 112.

[2]Op. cit., p 78.

[3]Angel Island, op. cit., p. 202.

In the description of the eruption at Santorin, Fouqué[1] mentions a viscous lava exuded in the form of a mass of blocks. These blocks, tumbling over one another as the mass is pushed from behind, have accumulated in a rough pile, Pl. XII. Fouqué climbed these piles of block lava shortly after their production, and noticed the breaking off of pieces from the sides, due to the cooling and contraction of the individual blocks.[2]

FIG. 10.—Reproduction of illustration of aa lava, after Dana (Characteristics of Volcanoes).

In general this character agrees well with that of the aa lava of Hawaii, as described by the late Prof. J. D. Dana.[3] He describes the formation of the blocks as due to the slow forward movement and contemporaneous breaking up of the viscous lava. The surface contrasts with the ropy surface of the more liquid pahoehoe. The aa is as a rule compact as compared with the pahoehoe, though the exterior "is roughly cavernous, horribly jagged, with projections often a foot or more long that are bristled all over with points and angles." From the illustrations of this lava (see fig. 10, taken from Dana) the blocks may be seen to be, while irregular, still in general distinctly rounded. This is the shape which viscous material would naturally tend to take when subjected to the rolling action attendant upon the onward motion of the stream of which they form an outer portion, or in certain cases the entire thickness. This is clearly shown from the following quotation from Dana's description of the constitution and condi-

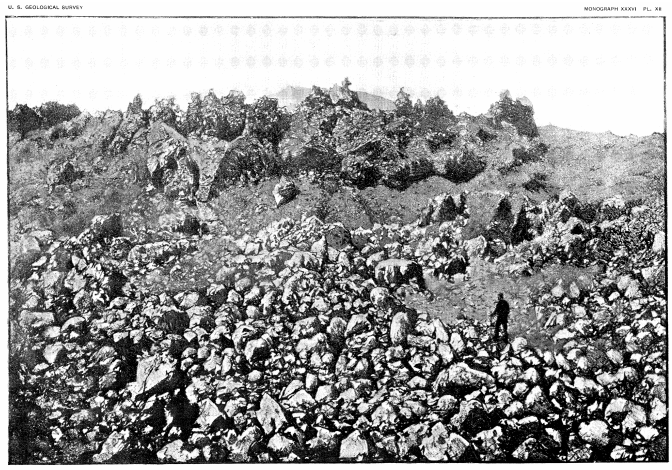
[1]Santorin ét des Eruptions, by F. Fouqué: Paris, 1879, Chap. II. Compare especially Pls. VIII and XIII.

[2]Op. cit., p. 54.

[3]Characteristics of Volcanoes, by J. D. Dana: New York, 1890, pp. 9, 241, and Am. Jour. Sci., 3d ser., Vol. XXXIV, 1887, p. 362.

"An *aa* or *arate* lava stream consists of detached masses of lava as far as is visible from the outside. The masses are of very irregular shapes and confusedly piled up to nearly a common level, although often covering areas many miles long and half a mile to a mile or more wide. The size of the masses in the coarser kind varies from a few inches across to several yards."

tion of the aa stream when in motion:[1] "(1) A mass of rough blocks outside, precisely like the cooled aa stream; (2) the motion extremely slow, indicating a semifluid condition beneath: . . . (5) the blocks of the upper part of the front, as the stream creeps on, tumbling down the high slope, owing to retardation at bottom from friction, and thus a rolling action in the front part."



MOUNT GIORGIOS, VIEWED FROM ITS WEST FLANK, IN APRIL, 1866, ILLUSTRATING THE CHARACTERISTIC BLOCK LAVAS.
Reproduction of Pl. VIII from "Santorin et ses Eruptions," by F. Fouqué.

[Plate XII. Mount Giorgios, viewed from its west flank, in April, 1866, illustrating the characteristic block lavas, from Fouqué's Santorin et ses Éruptions, Pl. VIII]