Dana describes the gradation of pahoehoe into aa lava. He writes, "a lava stream may change from the smooth-flowing or pahoehoe condition to the aa and back again to the smooth-flowing."[2]

Platania[3] describes from Aci-Trezza and Aci-Castello basalts with globular structure. The interspaces between the globes are filled with silt, or silt and tuff, and the exterior of some of these globes presents a thin vitreous cracked crust (cf. p. 117). These globular basalts are apparently but a modification of the block or aa lavas described by Fouqué and Dana, in which the separate portions of the lava have assumed a sufficiently rounded character to be called globes. However, Platania's further descriptions show this term to be clearly inapplicable unless the word "globe" is used with considerable latitude.

The Santorin block lava, the Hawaiian aa lava, and the Aci-Castello globular lava are all products of a slowly-flowing comparatively viscous mass. They will in the further description be included under the general term "aa lavas," as this is the most common form of occurrence of such viscous lavas.

The ellipsoidal basalts of the Crystal Falls district appear to be comparable to the Hawaiian aa lava and block lavas of the kind described by Fouqué. The lavas have subsequently been exposed to great pressure and are considerably altered. The most obvious character of these masses, their rounded outline, is believed to be due to considerable extent to the onward motion of the stream as described by Dana.

Contraction caused by cooling, accompanied by falling off of fragments from the outside, as observed by Fouqué[4] in the Santorin block lava, would also tend to round blocks which were originally angular. (Pl. XI.) In some cases the separate portions of the lava may have been originally nearly globular, similar to the ones described by Platania. The ellipsoidal basalts, however, are so common in the Crystal Falls district and such globular basalts are so rare that this peculiar form is not considered worthy of much consideration in the further discussion, the first two kinds being chiefly the forms from which these were derived.

[1]Characteristics of Volcanoes, by J. D. Dana, New York, 1890, p. 242; and Am. Jour. Sci., 3d ser., Vol. XXVI, p. 100.

[2]Am. Jour. Sci., 3d ser., Vol. XXXIV, p. 363.

[3]Geological notes of Acireale, by Gaetano Platania: The Southern Italian Volcanoes, H. J. Jolmston-Lavis, editor, Naples, 1891, Chap. II., p. 41.

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

The lava blocks rolling over one another as the lava stream advanced, would lie with their axes in all positions, but pressure and the onward movement of the flow would, in the lower portion of the stream at least, be sure to produce from the blocks ellipsoidal bodies with their two longest axes corresponding—the one to the direction of flow and the other to the lateral extension of the stream. After the stream ceased to flow and the lava solidified, there would be a gradation from the ellipsoidal into the non-ellipsoidal portion of the flow.

An aa stream, such as described and shown in fig. 10, when subjected to great pressure subsequent to burial beneath thick deposits, would be compacted by the breaking up of the jagged outer portions, which, falling down, would fill the spaces between the blocks. This broken material filling the spaces would be most exposed to movement and to the action of percolating waters. It would consequently be very much altered, as in the material described above (p. 119) by Ransome. Such alterations would result in producing a matrix of exactly the same general composition as the altered ellipsoids. It is the common case of metamorphic action producing from rock masses of essentially the same chemical composition, but of different character, similar end products. This brecciated character of parts of this matrix is well shown in parts of Pl. XI, and fig. B) Pl. XXXIV. In this case silica has been introduced, filling the spaces and marking out the outlines of the fragments. Where mashing has been excessive, the outlines of the fragments are obliterated and the matrix rendered schistose. There may even be a gradation from the schistose matrix into the altered basalt of the ellipsoid, which at the center is massive.

Let me recall the statement made on previous pages concerning the distribution of the amygdaloidal cavities in the ellipsoids. This is one of the characteristic features of the lavas. We have (1) amygdaloidal cavities distributed about evenly throughout the ellipsoids, the cavities being somewhat smaller in the center than upon the periphery; (2) the cavities are concentrated upon the periphery with few or only microscopical cavities in the center; (3) they are concentrated on one side of the ellipsoid, this side representing apparently that side of the ellipsoid turned toward the upper surface of the lava stream. The following explanation is offered for this difference in occurrence. The distribution of cavities is determined by three factors: The viscosity of the lava; the difference in specific gravity between the bubbles filling the cavities and the lava; and the expansive action of the gas. In the case of (1) the ellipsoids are considered to have consisted of lava in a viscous condition through which the gas pores formed, but in which, owing to the high degree of viscosity, they remained nearly or quite in the positions in which they were formed. Here viscosity was the determining factor. In case (2) the gas pores, influenced chiefly by the expansion of the gas, collected upon the periphery—just as, for instance, in the steel ingot while the center is compact the outer surface is porous. The lava in this case was probably less viscous than in the former. In the last described condition of distribution (3), where the gas cavities are on one side, which is the upper surface, the lava was still less viscous than in the preceding cases. Here specific gravity was the controlling factor, and, as a result of the specific gravity and the less viscous nature of the lava, the gas bubbles rose and collected upon the upper surface.

The explanation of the ellipsoidal basalts which has been offered—viz, that they are comparable with aa or block lava,—seems to offer a ready explanation for all of the observed characters. On the whole, the ellipsoids owe their origin and certain peculiarities to the viscous nature of the lava. They possess also characters which are due to contraction, others which are due to original flowage, and still others which are the result of subsequent orogenic movements.

In certain places we may find the ellipsoids only half formed—that is, attached by one side to the main unbroken part of the lava flow, the other side showing a rounded outline. This probably represents a place where the aa grades into a pahoehoe or smooth-flowing form. Such an instance is possibly that illustrated by Ransome.[1]

[1]Point Bonita, op. cit., fig. 2, p. 77.

Both Ransome and Teall compare the ellipsoidal basalts studied by them with pahoehoe lava. The latter also suggests a submarine origin for the basalts studied by him. It should be noted that pahoehoe lava in its typical occurrence in Hawaii is found only in dry places, whereas the aa is confined to those parts of the lava stream—which in other portions of its course is perhaps developed as pahoehoe—where it crosses moist valleys or other depressions presumed to have contained a considerable amount of moisture.[1]

In the case of some of the block lava of Saiitorin described by Fouqué,[2] with which this may be compared, the conditions were such that the lava practically welled up through the water.

From Dana's description it appears that lava in the pahoehoe form can not exist in the presence of moisture, being changed to the aa form. It would thus seem that Teal's statement of a submarine origin for the pahoehoe lava is untenable.

Wherever the ellipsoids have been studied in the Crystal Falls district, they have been found to exist as separate units, thus indicating the extremely viscous character of the lava. It would seem that the analogy between these basalts and the aa or block lava is much greater than that which exists between them and the pahoehoe or smooth-flowing lava.

AMYGDALOIDAL STRUCTURE.

The amygdules in the basalts are composed of nearly the same minerals as those which occur secondarily in the rock mass itself. Arranged in order of frequency of occurrence, they are as follows: Chlorite, epidote-zoisite, quartz, calcite, feldspar, iron oxide, and biotite. An amygdule may consist entirely of one of the above minerals, or, as is most commonly the case, of two or more of them. In the latter case the minerals are usually arranged in concentric layers. The nonoccurrence of zeolites is very noticeable. Their absence from these Huronian volcanics is especially striking since they are so common in their altered modern equivalents, and also occur in basalts as old as those of the Keweenawan of Lake Superior[3] and of the South Mountain of Pennsylvania.[4]

[1]Cf. Characteristics of Volcanoes, by J. D. Dana: New York, 1890, p. 243.

[2]Op. cit., Chap. II.

[3]Paragenesis and derivation of copper and its associates on Lake Superior, by Raphael Pumpelly: Am. Jour. Sci., 3d ser., Vol. II, 1871, p. 188; also Geol. Survey. Michigan, Vol. I, part 2, 1873, pp. 19-46; Geol. of Wisconsin, Vol. III, 1880, p. 31.

The copper-bearing rocks of Lake Superior, by R. D. Irving: Mon. U. S. Geol. Survey, Vol. V. 1883, p. 89.

[4]The volcanic rocks of South Mountain in Pennsylvania and Maryland, by G. H. Williams: Am Jour. Sci., 3d ser., Vol. XLIV, 1892, p. 491.

It is also of interest to notice that there is a total absence of indications of copper in these Huronian volcanics, as well as in those of the Penokee-Gogebic, although it is associated with similar rocks in the areas above referred to as well as in many others.

The amygdules, with the exception of those of chlorite and of biotite, are of much lighter color than the body of the rock, and from a short distance give the rock the appearance of a porphyry. Weathering gives the rock a different appearance according to the materials filling the vesicles. Where these weather readily they are removed and the rocks become scoriaceous. Where, on the other hand, as frequently happens, the vesicles are filled with quartz, the matrix weathers more rapidly and the rounded quartz cores stand out on the face of the rock like the quartz pebbles from the softer matrix of a conglomerate.

In a few cases hematite is disseminated through the quartz of the amygdules, giving it the bright-red color of jasper, and by some these amygdaloidal fillings have been taken for included jasper pebbles.

Careful study was made of the filling of the vesicles with the object of determining the order of deposition of the minerals. However, it was found that the amygdules in a single slide contain very different fillings, one chlorite, another calcite, a third epidote, and so on; and that even in the same slide the relations are not always the same, a mineral which here occupied the center of an amygdule being found there on the periphery. Moreover, the same mineral species was found at times occupying the outside and the center of the same amygdule.

It is clear that the fillings are not the result of a solution common to all the lavas, but that the same kinds of solutions were active in the various lavas at different times and even in the same lava at different times. However, the conclusions reached were that the chlorite was generally the first product deposited and the quartz usually the last. From the study of the related amygdaloids upon Keweenawan Point, Pumpelly[1] long ago reached the conclusion that chlorite was the earliest product of alteration—hence we may conclude the first to be deposited in the amygdaloidal cavities; and that the latest mineral deposited in the cavities, omitting copper from consideration, was quartz, the tendency naturally

being to replace more alterable with less alterable minerals.

[1]The paragenesis and derivation of copper and its associates on Lake Superior, by Raphael Pumpelly: Am. Jour. Sci., 3d ser., Vol. II, 1871, p. 29.

Metasomatic development of the copper-bearing rocks of Lake Superior, by Raphael Pumpelly: Proc. Am. Acad. Arts and Sci., Vol. XIII, 1878, p. 307.

Flattening of amygdaloidal cavities.—In some of the amygdaloids (fig. B, Pl. XXV) the cavities retain their circular shape, as though the rock had not flowed to any great extent. More commonly the cavities are drawn out into irregular (fig. A, Pl. XXV) or lenticular shapes, the long axes agreeing with the direction of flowage in case their deformation resulted from this, or with the direction of schistosity in those cases where the rocks have been extensively mashed. In some cases the cavities have been so extremely flattened that the amygdules appear almost the shape of a melon seed, showing a mere streak of chlorite in the sections cut perpendicular to the schistosity, and in the planes of schistosity large lustrous oval areas.

In some few of the basalts the groundmass immediately surrounding the amygdules is characterized by an accumulation of ferruginous matter. In most cases, however, this part of the groundmass does not differ in any respect from the rest of the groundmass of the basalts and points to a very gradual cooling.

ALTERATION OF THE BASALTS.

The descriptions given are of the freshest and most characteristic basalts. As already explained, the mineral constituents in even these freshest ones have undergone a very far-reaching alteration. The rocks which show a more advanced stage of alteration exhibit merely a difference in degree rather than in kind, and the minerals which result are in all cases the same. They are uralite, actinolite, epidote-zoisite, chlorite, white and brown mica, calcite, sphene, quartz, and feldspar.

The amount of these secondary minerals varies greatly, showing that the alteration products resulting from the same kind of original rock may differ very materially according to the process of metamorphism.

In a general way the alteration of the basalts, as observed under the microscope, has taken the following course: Even in the rocks nearest their original condition the augite has largely changed to uralite. The vitreous base, if any was present, has become devitrified. Rocks in this stage of change still show the more important external characters of igneous rocks, including in many cases those which are characteristic of glass. Some of the rocks at this stage are light gray to green and exceedingly tough. Many of these break with a ringing sound almost like phonolites. At a further stage of change the feldspars are partly altered to a granular aggregate of various minerals. In ordinary light the textures of igneous rocks are still preserved, but in polarized light none are seen, with the exception of amygdules which may be present. In some cases even these are obliterated, and the original nature of the rock can only be determined from its mode of occurrence and its association.

Further changes may produce rocks which consist practically of calcite, and may be nearly white.

Again, from these basic rocks there may be produced in extreme cases, by a process of silicification, a rock which consists practically of pure silica.

Description of some phases of alteration.—As illustrating some cases in which the same alteration products, but in different proportions and arrangement, give rocks differing very essentially, there are given the following brief descriptions of some of the rocks studied.

The flow structure was noted as being exceedingly well developed in the microlitic rocks, and in some of them the production of amphibole needles and chlorite flakes has taken place parallel with the long direction of the feldspar microlites (the flowage direction), thus developing, in combination with the unaltered microlites, a well-marked schistosity. The feldspars are still fairly well preserved.

In another case the feldspar microlites have become completely sericitized, the interspaces between them being occupied by epidote, chlorite, and iron oxide. The preservation of the feldspar shapes, showing in ordinary light the igneous texture of the rock, gives the only clue to its original nature. (Figs. *A* and *B*, Pl. XXVIII.) In some of the basalts the feldspar is replaced chiefly by epidote-zoisite, and, as in the above case, such rocks show their igneous character only when examined in ordinary light or by uncrossed nicols. (Figs. *A* and *B*, Pl. XXIX.)

In still other rocks calcite is very abundant. Its occurrence in porphyrinic rhombohedra and scalenohedra was mentioned in the description of some of the rocks. These porphyrinic calcites have thus far been found only in the fine-grained microlitic types of groundmass, the coarser ophitic rocks having it only in the usual granular aggregates. Muscovite, occurring in large porphyritic plates, conforms in occurrence to the calcite. When muscovite is present, calcite is found associated with it in every case, though the calcite may occur alone, and this latter is also by far the more common. These crystals give a secondary porphyritic character to the lavas, and the microscopical appearance of the rocks varies somewhat according to the occurrence of the calcite. Such rocks, for instance where the rhombohedra occur, look on fresh surface by rapid examination like porphyrites in which the feldspar sections are all quadratic. In the others the scalenohedral sections resemble in general lath-shaped feldspar phenocrysts lying scattered in all directions on the surface of the rock.

Another case of extreme alteration is shown in a light greenish-gray, much-altered schistose rock from sec. 21, T. 46 N., R. 32 W. Upon the weathered surface long grooves are noticed—one measuring 60 mm. long by 5

mm. wide—which on the fresh surface are filled with calcite. On faces perpendicular to the long extension of such grooves they appear as narrow slits, with the long direction of the slit, that is, the width of the groove, agreeing with the schistosity. These are clearly flattened amygdaloidal pores, and but for them the igneous nature of the original rock could not have been determined. The extreme flattening of these amygdaloidal cavities and the schistose nature of this rock produced from an original volcanic, points toward mashing as one of the causes, if not the main cause, of its present characters. It is now composed of fairly large automorphic actinolite individuals, a very small amount of biotite and chlorite flakes, and masses of grains of quartz, calcite, epidote-zoisite, magnetite, with ilmenite and hematite in thick plates filling in the spaces between the actinolites. If any feldspar was originally present, it is now entirely concealed by the calcite and epidote-zoisite.

The calcite phenocrysts are found in the fairly fresh lavas. They are beautifully automorphic and are certainly not replacement pseudomorphs of some original phenocrysts, but replace the various minerals of the fine-grained mass. Moreover, it is clear that they were formed subsequent to all dynamic action, as their crystal outlines are perfect and they never show any evidence of pressure. This is so even in those cases where the amygdules which have been markedly elongated are filled with calcite. The process of replacement could not be followed, but it is evidently connected with the development of chlorite, those rocks in which a great deal of the calcite occurs having chlorite developed instead of actinolite.

In other sections in which the amount of porpliyritic calcite or calcite and muscovite is much greater than in the rocks just described, the amount of chlorite, iron oxide, rutile, and quartz is also greater. The quartz is in very fine grains. The presence of the feldspar can only be determined with difficulty, and usually only on the edges of the sections, as the large amount of chlorite in the center conceals it. The textures caused by the feldspar and the amygdules still indicate the original character of such extremely altered stages. Figs. *A* and *B*, Pl. XXX, illustrate such a rock, showing the secondary porphyrinic muscovite and calcite, and also the original amygdaloidal character.

A still further stage of alteration gives a rock whose groundmass is composed of the finest-grained quartz and of grains and needles of brown rutile (anatase?). In this lie rhombohedra of ferruginous calcite, plates of muscovite, and irregular flakes of chlorite. The rock is macroscopically gray, hard, and quartzitic, has a ferruginous, brown, weathered crust, effervesces with cold HCl, and yet shows its volcanic character by the numerous beautiful amygdules. These stand out on the surface like pebbles in a conglomerate. In some cases the weathering brings out the concentric character of the filling very nicely. For example, some may be seen in which the core is quartzitic, and is standing surrounded by a ring-like depression, showing by difference in the weathering the different character of the mineral filling. Under the microscope the only amygdules which happened to be cut by the section were found to be filled with fine-grained quartz, with chlorite in automorphic flakes at the center of the amygdules, and lying in the quartzitic mass. The macroscopical appearance of some of the amygdules shows that just the reverse condition also exists, that is, that quartz forms the centers and chlorite surrounds it.

The extreme stage of such an alteration is a rock which shows no amygdules macroscopically or microscopically, but is otherwise like the groundmass of the above last-described rock. It would be impossible to determine the original character of such a rock except by its association.

The extremes of texture obtained in the alteration processes are, on the one hand, a porphyry with eruptive groundmass and secondary phenocrysts; on the other, a porphyrinic schist, in which all elements are secondary. These extremes are connected by gradation varieties, in some of which the calcite and muscovite approach more closely to the size of the elements composing the groundmass, and which consequently approach the ordinary schists in structure.

In these rocks the porphyritic characters are unquestionably due to the production of secondary phenocrysts of mica (muscovite) and calcite, not by contact metamorphism but by dynamic action.[1]

It has not been found possible to determine definitely from a study of the specimens, in many cases from widely separated exposures, on which the above observations were made, whether the process which has taken place in the production of such rocks has been a combination of calcification and silicification, or a process by which carbonate is being replaced by silica or the reverse. The replacement of carbonate by silica, as shown by Irving and Van Hise,[2] has taken place extensively in the case of the ferruginous carbonates of the Penokee-Gogebic and Marquette iron ranges of Wisconsin and Michigan. The automorphic character of the carbonate would seem to point toward calcification as the controlling process in the Crystal Falls rocks.

Though the presence of quartz as the last filling of the amygdaloidal cavities points toward silicification as being the process which would eventually predominate, it is most probable that both processes of calcification and silicification are active; but whether the one or the other is the controlling one depends upon the depth of burial of the rocks which are altering.

This statement appears to be supported by the facts to be described in the following pages. The following observations, which were made upon sections taken from an ellipsoidally-parted basalt occurring on top of the hills to the west of and overlooking Mansfield, illustrate the changes which take place in the passage from the massive rock of the ellipsoids into the schistose material of the matrix. The change is one of increasing alteration. This alteration is largely one of carbonation followed by

silicification. It may be characteristic also of basalts with no ellipsoidal parting, but it has been possible to follow the successive changes only in the ellipsoidal basalts. This is due to the fact that each ellipsoid shows all stages from the comparatively fresh material of the center to the much altered material on the periphery, and to the most altered basaltic material forming the so-called matrix surrounding the ellipsoidal bodies (p. 114).

[1]Metamorphism of clastic feldspar in conglomerate schist, by J. E. Wolff: Bull. Mus. Comp. Zool., Vol. XVI, 1891, pp. 173-183, Pls. I-XI. Cf. also Wolff on Green Mountains, Mon. U. S. Geol. Survey, Vol. XXIII.

Principles of North American pre-Cambrian geology, by C. R. Van Hise: Sixteenth Ann. Rept. U. S. Geol. Survey, Pt. 1, 1896, p. 692.

Phases in the metamorphism of the schists of Southern Berkshire, by W. H. Hobbs: Bull. Geol. Soc. Am., Vol. IV, 1894, pp. 169-177.

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

The iron ores of the Penokee-Gogebic series of Michigan and Wisconsin, by C. R. Van Hise: Am. Jour. Sci., 3d ser., 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, 1889, pp. 341-507; Mon., Vol. XIX, 1892, pp. 254-257.

The freshest part of the interior of an ellipsoid from this occurrence is a very fine-grained micro-amygdaloidal basalt, in which in ordinary light lath-shaped feldspar microlites can be readily distinguished. Upon close examination the feldspars are found to be much altered, and in many cases their crystal outlines are almost completely filled out by grains of calcite and flakes of sericite and chlorite in a quartz-albite (?) aggregate. The spaces between the feldspar laths are now occupied by large crystals of epidote-zoisite, grains of iron oxide, a few flakes of chlorite, and innumera-able small round yellowish-brown and greenish indeterminable bodies. The epidote-zoisite crystals also include large quantities of the brown and green globular bodies, showing that they were produced previous to the epidote-zoisite. The substance in which this aggregate is embedded could not be determined, as the aggregate is either so dense that nothing could be discerned or else underlain by feldspar. In the last case the substance is seen to be clear white. The minerals mentioned, with the exception possibly of the iron oxide, have evidently been produced secondarily from the substance or substances originally filling the spaces between the feldspars. Nothing points toward the original substance or substances having been crystallized, and I am inclined to believe that it was glass.

Toward the exterior of the ellipsoid the rock is more altered. The zoisite and calcite are more abundant. The calcite occurs in the spaces between the feldspars, as well as occupying parts of their outlines. (Figs. *A* and *B*, Pl. XXXI.) All of the other products drop into the background, owing to the fact of nonproduction, or concealment by the zoisite-calcite aggregates.

Still nearer the exterior of the ellipsoid the calcite frequently fills the spaces once occupied by the feldspars with long scalenohedral crystals, which in a way maintain the original igneous structure. The calcite is, however, not confined to these feldspar areas alone, but, as stated above, also occurs between them.

The matrix, representing the most altered phase, is a granular aggregate of calcite, in which one may here and there discern small clear limpid grains of secondary quartz and feldspar (?) and flakes of chlorite. The calcite includes in considerable quantity the globular bodies mentioned. These are found also in the spaces between the calcite grains, as though pushed away from the grains as they crystallized.

Some of the calcite in the first stages of the alteration of the rock may have been derived from a basic feldspar. It is clear, however, that the great mass can not owe its origin to this process, but must be the result of infiltration. The calcite grains derived from, and lying in, the feldspar acted as nuclei, around which the infiltrated calcite was gradually collected, producing pseudomorphs after the feldspar laths. Quite recently Dr. W. S. Bayley[1] has noted in the Clarksburg submarine volcanic formation of the Marquette district, Michigan, the occurrence of tuffs, in which calcite has been introduced in such quantity that they may almost be called limestones.

In another case in which the alteration of the ellipsoid (Pl. XI) apparently proceeded along the lines of shearing, and produced the kind of aggregates of chlorite, including crystals and aggregates of epidote-zoisite, which were described (p. 117) as the usual matrix of such ellipsoids, one can see in thin section the calcite entering the chlorite aggregate along minute fissure lines. The calcite literally eats its way into the chlorite, and produces by an interchange of elements a mass of calcite (magnesian?) and epidote, besides including epidote which originally occurred scattered through the chlorite aggregate.

The carbonation of the original basalt or of the secondary chlorite mass results in producing a mass of carbonate which has associated with it some secondary quartz, chlorite, and epidote. This carbonate mass may be almost massive or it may be decidedly schistose. When schistose, the grains of calcite and quartz have a uniform elongation, and the schistosity is materially enhanced by flakes of chlorite, which are not uncommonly found in thin streamers or thick masses in the carbonate aggregate, at times in sufficient quantity to give it macroscopically a decided green tinge.

I have used the term “carbonate,” although having described in detail above the calcification of the basalt, for the reason that at times, and for no discernible reason, the iron carbonate (siderite) may replace the calcite, in which case we get a dark bluish-black variety of matrix (p. 117). The siderite masses do not differ essentially from the calcite, though in some of them a very small quantity of actinolite is found associated with

the chlorite. As illustrating the purely local development of these two carbonates, I would mention having observed in one section a band of siderite separated from a band of carbonate, which from its color appeared to be quite pure calcite. One may also see commonly in exposures areas of pure white calcite, almost in juxtaposition with areas of siderite.

[1]Mon. U. S. Geol Survey, Vol. XXVIII; p. 473.

It is a fact generally recognized that carbonation is a process confined to the outer crust of the earth, so that we may perhaps best explain the local occurrence of these carbonates replacing the basalt as products of carbonate-bearing waters. That such carbonation of the igneous rocks through which these waters percolate is now taking place seems certain. The carbonate grains in the rocks described are shattered and elongated, or at least show undulatory extinction. They thus give evidence of having been more or less mashed since their production, and this mashing probably took place after they had been more or less deeply buried, and was, as a matter of fact, to some extent due to the pressure of the superincumbent rocks.

The probability that these rocks have been thus deeply buried subsequent to their formation is to be borne in mind with special reference to the next process to which they have been subjected, that of silicification. This process is most clearly shown in the siderites, and the phases of alteration noted in their study will be briefly described.

The microscope shows the siderite matrix to be a coarsely granular aggregate composed essentially of crushed siderite grains. Between these grains in a few places are small grains of quartz, flakes of chlorite, and very rarely needles of actinolite. Large quantities of black ferruginous specks are included in and also lie between the quartz grains, and such specks are also to be seen included in siderite areas, but close inspection shows that they are also associated with blebs of quartz. The chlorite flakes and quartz grains are generally elongated in the same direction, and the quartz shows wavy extinction.

A more advanced stage in the process of silicification was studied in the case of a rock which is bluish-black in color, exceedingly fine grained, and minutely schistose, the schistosity agreeing with the contours of the ellipsoid from around which it was broken. This is essentially an exceedingly fine-grained quartz rock, with chlorite flakes and black ferruginous specks scattered through it, and here and there an irregular oval siderite grain remaining. Very few and unimportant grains of epidote were also noticed. This rock represents nearly the last stage in the process of silicification by which the siderite has been replaced, and a part, probably the greater part, of its iron content oxidized. Some chlorite and epidote has been produced, clearly from the lime and magnesian impurities in the siderite. Essentially the same process of silicification has been described by Van Hise in his various articles on the Penokee-Gogebic and Marquette iron ranges, to which references have been so frequently made. I have desired especially to call attention to it here, however, on account of the fact that it shows the possibility of the production of an iron ore from an original eruptive rock by the combined processes of carbonation and silicification. It is true that the end product in the case described does not contain enough iron to be an ore deposit, but that is a mere detail. May not this serve also to some extent to explain the numerous clearly marked belts of magnetic attraction which occur throughout this area of altered basalts, in which little of the original magnetite remains unaltered to exert an influence upon the magnetic needle? To explain this we must suppose the influence to be exerted by secondary magnetite accumulated along certain lines. The magnetic lines traced out agree in a very marked way with what has been determined to be the trend of the lava flows and tuff beds. The condition which would determine the presence of such a line of carbonation, if we may so put it, may be the presence of a scoriaceous lava flow or a bed of tuff, which offers exceptional facilities for the passage of carbonate-bearing waters. It is thus intimated that there is possibility of finding purely local ore bodies of small size even in the midst of this volcanic area.

The process of silicification is generally considered as a deep-seated one, occurring far below the outer weathering zone.

When the rocks exhibiting these various phases of silicification are exposed in the zone of weathering, certain interesting results are obtained which are worth noticing. Rocks are produced from these which upon the surface strongly resemble amygdaloids, but in which the pseudo-amygdaloidal cavities are of purely secondary origin. For instance, when the siderite mass has become only partially replaced by silica, weathering agencies leach out the remaining siderite areas and leave the thin films of silica which lie between them standing up, thus giving the rock the appearance of a very dark pumice. As the silicification progresses the siderite is very much reduced in quantity, the intervening siliceous areas increasing correspondingly. The pressure exerted upon the rock has caused the isolated siderite areas to take on an oval character, the longer axes in general agreeing and being perpendicular to the pressure. When such siderite areas are leached out, the silica bands remain, and pseudo-amygdaloidal cavities are produced, giving a very perfect pseudo-amygdaloidal structure to the hand specimen. This is the origin of that character of matrix which some of the geologists have described in their field notes as like rotten, worm-eaten wood (fig. *B*, Pl. XXVII).

Although at present the material between the ellipsoids differs so markedly from the rock forming the ellipsoids themselves, nevertheless there is no reason for supposing the original composition of that part of the rock mass to have been essentially different. The change in the character of the basalt in passing from the ellipsoids toward the schistose matrix is in mineralogical

character much as has been described for other basalts from this same district. The reason for the more complete degree of the replacement process in passing away from the ellipsoids may be readily understood from the discussion of the origin of the ellipsoidal parting of the basalts, where the conclusion was reached that the matrix between the ellipsoids resulted from the comminution of basaltic material of the same general character as that of the ellipsoids. This matrix was of course more porous and probably more vitreous than the basalt, and hence more liable to be altered.

PYROCLASTICS.

The majority of the clastic rocks have been derived from the basic volcanic rocks already described. These elastics are very characteristic of the Hemlock formation and constitute the greater part of it. They comprise several classes, the more important of which are the eruptive breccias, volcanic sedimentary rocks, and schistose pyroclastics.

ERUPTIVE BRECCIA.

The term "eruptive breccia" is here used to include those clastic rocks in which angular fragments of an igneous rock are surrounded by a matrix also of igneous origin. In an eruptive breccia the fragments may be like or unlike. Likewise the matrix may be like or unlike the fragments. Where the fragments have been rounded during the movement of the eruptive magma surrounding them, the resulting rock may be called an *eruptive pseudo-conglomerate*.

Eruptive breccias are not very common in the Crystal Falls district. Where they do occur, the fragments, while predominantly angular, are to some extent more or less rounded, and are similar in nature to the matrix in which they lie. Since the rocks which form them preserve the main characters of the massive lava flows which have just been described, they will not be discussed in detail. The exact method of the formation of these breccias could not be told.

In one case, in which both fragments and matrix are amygdaloidal, it appears probable that the occurrence represents a true flow breccia in which the broken surface of a lava flow had been recemented by a later lava flow of the same kind of rock, or that it represents a very possible case in which the lava welled up through and flowed over portions of its own crust, cementing the fragments. In such breccias a flow structure around the fragments is quite plainly shown and the matrix possesses a peculiar ropy appearance. In one instance, in which both the fragments and matrix were macroscopically nonamygdaloidal, it is probable that they were formed under considerable pressure, and that this was a case in which lava was forced up through a previously consolidated mass of rock of like character, and in its passage carried with it various fragments, forming an *eruptive* "*reibung's-breccia*" or *friction breccia*.

VOLCANIC SEDIMENTARY ROCKS.

Under the term "tuffs" have been very generally included all kinds of volcanic clastic rocks.[1] This is probably due to the fact that there is frequently considerable difficulty in discriminating between eolian deposits and those which have been deposited in water. It seems desirable, wherever it is possible, to make this discrimination. To that end I shall in the following pages restrict the term "tuff" to eolian deposits. The term "volcanic conglomerate," or, for the sake of brevity, simply "conglomerate," will be used for those coarse deposits which have been sorted by and deposited in water, and whose fragments show a rounded character. Should the fragments be angular, the rocks may be called "volcanic breccias."

[1]Text-book of Geology, by Sir Archibald Geikie: 3d ed., p. 135.

It has been found practicable to maintain this distinction in earlier studies on Tertiary volcanics,[1] and it is also maintained in the present study of pre-Cambrian volcanics. I am confident the same distinction could be made more generally than it is, and would in that case tend to a greater precision in the separation of rocks of different characters. However, it is rather difficult to separate true eolian deposits of volcanic fragmentary materials from those in which the fragments have been deposited rapidly through water without having embedded organic remains and without having undergone sufficient attrition to be much rounded. More or less rounding, it is well understood, results from the attrition of the volcanic ejectamenta during their ascent and descent through the air, so that they may in this respect resemble many of the sedimentaries. The exact mode of origin of many of the volcanic fragmental deposits of the Michigamme district is not clear. The greater portion appear to be of true eolian origin, and where the origin of any is in doubt it has been put with those of eolian origin.

COARSE TUFFS.

The coarse tuffs include rocks composed of fragments of all sizes, from the large volcanic blocks to the fine-grained particles of sand and dust which fill in the interstices. The ejectamenta may be more or less rounded by attrition during their progress through the air, so that if a refinement of the nomenclature should be needed one might very properly be justified in speaking of tuff breccias and tuff conglomerates.

Tuffs are very common and characteristic for the district. The characters of the beds is best shown on the weathered surfaces. Here the scoriaceous and dense light-green fragments stand out well from the brownish-red matrix of more altered, finer fragments and cement. On a fresh surface the interstitial material usually has a darker green color than the fragments. The fragments have a prevailing green color, but many, especially in sections, are brown, much darker than any of the rocks forming the lava flows. The larger fragments are usually sharply angular, but in many cases are more or less rounded because of attrition during their progress through the air. (Pl. XIII.) They are for the most part not

scoriaceous, though rather commonly amygdaloidal. The macroscopically dense fragments seem to predominate, though the amygdaloidal ones do occur in some specimens in nearly equal quantity.

[1]Die Gesteine des Duppauer Gebirges in Nord-Böhmen, by J. Morgan Clements: Jakrbuch K.-k. geol. Reichsanstalt, Vol. XL, 1890, p. 324.

The fragments of the tuffs are derived from the various kinds of basalt already described as forming the lava flows.

Among the fragments some of the most typical of these rocks have been found, and remarkable as it may seem, some of the thin sections from them show the least-altered basalts.

In addition to the kinds mentioned under the basalts there are a number which differ slightly from them, and apparently represent more glassy modifications of the basalt magma. In one of these the amygdules are more sharply outlined by the accumulation of iron oxide around the edges of the amygdule than is the case in the crystalline flow rocks. An especially well-preserved fragment shows perfectly fresh plagioclase microlites exhibiting well-developed fluidal structure lying in a dark-brown apparently isotropic glassy base. Where the section is thin, globulitic devitrification products can be seen, and there also the base no longer appears isotropic, but very feebly double refracting. There is very frequently found among these tuffs amygdaloidal fragments which appear to have been derived from what was originally a completely glassy rock, no indication of the presence of any original crystals having been preserved. The background of these fragments consists of a fine felt of a green chloritic mineral, dotted with innumerable grains of epidote, in which one may distinctly discern concentric circles and arcs of circles outlined by aggregates of epidote grains. These circles probably represent perlitic partings. (Fig. *A*, Pl. XXXII.) The dark-brown fragments mentioned as occurring with the prevailing green ones are very dense, appear to be very rich in iron, and may possibly represent a very basic devitrified glass. Should accumulations composed essentially of such glassy fragments be found, they could properly be called “palagonite tuffs.”

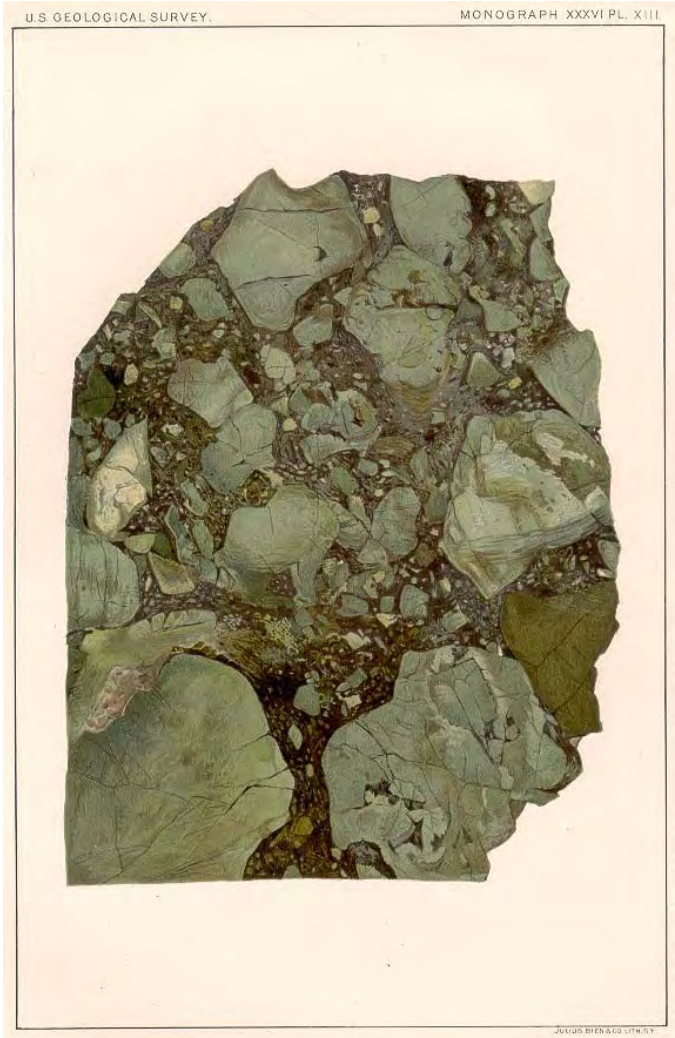
In addition to the rock fragments, a few rare ones of large plagioclase crystals were found, and also in one case a fragment of a violet-brown augite, the only specimen of fresh pyroxene thus far found in any of the volcanics.

The tuffs show in places fairly well-developed banding, caused by the interbedding of layers in which coarse and finer fragments prevail, illustrating well the varying intensity of the volcanic discharges.

PLATE XIII.

(Sp. No. 23644. Natural size.)

This illustration is a faithful representation of the appearance of the polished surface of a pyroclastic from the Hemlock formation. It is somewhat doubtful whether or not the fragments composing the rock have been deposited through the mediation of water or air alone. The larger fragments are rather dense. Vesicular fragments are more common among the smaller particles. Pyroclastics similar in appearance to this are of very common occurrence in the Crystal Falls district, and huge cliffs of it are readily accessible from the railroad.



BASALT TUFF.

Owing to the fragmental nature of the exposures, it is impossible to get a correct idea of the maximum thickness of any of the tuff deposits. Exposures were seen in the north half of sec. 5, T. 43 N , R. 32 W., which gave a thickness of over 500 feet for some of these deposits, but as their farther continuation had been cut off by valleys, most probably eroded in the tuffs, no means was afforded of determining their total thickness.

It is almost needless to state that the most of the tuffs have undergone a great amount of alteration. The alterations were apparently due to an interchange of the various elements without any essential variation in the chemical nature of the rock as a whole. Since water is

the chief agent through which alterations occur, these always begin along the interstices. In the case of the fragments the alteration accordingly proceeds from the outside inward, and ordinarily at an equal rate all around the fragments, following its contours. In this way zones of somewhat different mineralogical composition are formed, surrounding the less altered part of the fragment. This secondary zonal structure may be observed more or less imperfectly in almost all of the sections made from the breccias, but is much better shown in the field, where the concentric zones are well brought out on the large weathered surfaces of the bowlders.

In each case the outside, lighter-colored zone is chiefly made up of chlorite, from which project light-green hornblende needles into the matrix beyond. Less commonly we find it composed of epidote grains and chlorite. Inside of this zone the mineral elements composing the fragments sometimes can not be determined with any great degree of certainty. Where determinable, the alteration products are found to be the same as are produced from the corresponding rocks in the lava flows. As also in the lava flows, some of the fragments of the denser rocks have become almost opaque from the quantity of minute secondary epidote and sphene grains. These have a lighter green color than the less altered fragments.

In examining many of the tuffs, one is repeatedly struck by the large amount of space occupied by the cementing material. In some cases cavities of very considerable size were left between the fragments. It appears that the fragments must have been lying very loosely. This fact tends to confirm the eolian origin of the rocks, since water deposition tends to bring the fragments in close contact, and also to fill the intervening spaces with fine detritus. Those cases must of course be excepted where the material fell upon water so deep that after sinking to the bottom the action of the waves was not felt. Under such circumstances one can imagine the blocks, being partly supported by the water, coming to rest in a more unstable position than they would in the air.

The cement differs in different specimens. The minerals constituting it are quartz, feldspar, calcite, chlorite, epidote, and hornblende. The minerals are found including one another in such a way as to make it probable that they usually formed simultaneously. The calcite is an exception, as it is usually present in greater quantity near the surface of the exposures, and is therefore a weathering product. It was noted above that the hornblende and chlorite frequently extend from the rock fragments into the clearer elements composing the cement. Hornblende needles in many cases constitute a large part of the cement. Where two fragments are very close together, a perfect network of needles may extend from the one across the intervening space and penetrate the other, and the fragments thus practically grow together. The cavities—-especially the large ones mentioned above—have quite frequently been filled with concentric growths of various minerals. In general, chlorite seems to be the first mineral deposited, and quartz the last, but in weathered specimens calcite is the last.

FINE TUFFS OR ASH (DUST) BEDS.

The fine tuffs or “ash” beds occur plentifully in the Crystal Falls district In many cases they possess a very well developed cleavage, and were very puzzling in the field on account of their striking resemblance to true sedimentary slates. They are of interest as emphasizing the resemblance between pre-Cambrian ejectamenta and Tertiary and Recent ones. In one respect they differ from the modern forms. The dust from Krakatao in 1885 and from other volcanic explosions consists mainly of fragments of minerals and glass. The constituents of the Crystal Falls beds are usually fine lava and glass fragments and less commonly minerals.

The rock fragments are angular, vesicular, and completely altered. The glass fragments are likewise angular, and have the characteristic curved shapes from which they are usually described as sickle-shaped bodies. (Fig. *B*, Pl. XXXII.) Such are formed when a pumice is broken up, and each represents a portion of the glass bounding the vesicles. Here and there is a fragment with a more or less perfect vesicle remaining. The few mineral fragments found—feldspar—were angular, but quite fresh. The rocks show no intermixture of rounded fragments, and they are consequently regarded as volcanic dust deposited through the air. These ash beds show a delicate banding of finer and coarser-grained fragments. In a single slide a gradation can be traced from a moderately fine grained sand composed of distinct volcanic fragments into a very fine grained mass composed of hornblende needles, biotite, chlorite, epidote, and sphene, cemented by what is probably quartz, perhaps having associated with it some feldspar whose characters could not be determined.

Relations of tuffs and ash (dust) beds.—The pyroclastics seem to predominate in the northwestern part of the district in the neighborhood of the small town of Amasa. Special opportunities for observing the relations between the tuff and the ash beds are offered by the third cut of the Chicago, Milwaukee and St. Paul Railway west of Balsam, Michigan. Gradation can be traced from coarse tuffs to delicately banded fine tuffs. The average thickness of a single ash bed probably does not exceed 5 feet. In the same exposures the tuff beds are from 50 to 100 feet thick, and even more.

VOLCANIC CONGLOMERATES (TUFFOGENE SEDIMENTS, REYER).

That certain of the pyroclastics have been brought together and rearranged by the agency of water is made clear by their characteristic structure. Such rocks are the volcanic conglomerates. In very many respects they are strikingly like the various eolian deposits, tuffs, etc., described above. They agree with them in color. The same varieties of volcanic rocks are represented that are found in the tuffs. They are true basalt conglomerates.

The pebbles are very commonly sharply outlined by accumulations of epidote grains on the periphery. Some of the fragments have a reddish-brown to purplish-black color, and stand out strongly from the green matrix. Such pebbles are found to contain large quantities of magnetite, the oxide being in beautiful sharp crystals and in absolutely fresh condition, forming a sharp contrast to the altered condition of the fragments in which it occurs. In one case in which the main mass of the fragments now consists of chlorite and epidote, magnetite occurs in large quantity, and in chains of crystals forming dendritic growths. The oxide is clearly secondary in these altered rocks. Since it also occurs secondarily in the cement, it appears highly probable that it is an infiltration product formed during or after the metasomatic process.

In these conglomerates feldspar fragments are far more common than they are in the tuffs, and they show a well-defined, round, waterworn character. (Fig. *A*, Pl. XXXIII.) Likewise masses of uralite are commonly associated with the rounded feldspar. The uralite is taken to be altered pyroxene fragments, though no proof of this beyond its association could be offered, as the fragments show no characteristic pyroxene outlines. The well-rounded nature of the volcanic pebbles makes it certain that they have been deposited through the mediation of water and enables one easily to distinguish the typical examples in the field.

In size the fragments differ from one another just as they do in the case of the eolian deposits (fig. *B*, Pl. XXXIII). Many of the largest are several feet in diameter, but more commonly they vary from a couple of feet in diameter to small pebbles. Partly filling the interspaces and aiding in cementing the larger fragments, with which they are associated, are very fine grained fragments derived from the trituration of the water-worn lapilli and blocks. The coarse bowlder conglomerates grade through finer conglomerates into very fine material. This fine material shows beautifully marked false bedding. (Fig. *C*, Pl. XXVII.)

In one of the finer-grained rocks, in addition to the usual sedimentary banding, there are bands which appear to have been caused by a further sorting of the materials, some of these bands being composed almost exclusively of uralite. They consequently represent bands which were originally composed mainly of pyroxene fragments. In this case, when the fine ejectamenta settled through the water they were separated according to size of grain and specific gravity, as in ore-dressing processes.

Under the microscope other points of difference in addition to those above mentioned are noted between the conglomerates and the tuffs or eolian deposits. The fine-grained rocks corresponding nearly to the volcanic sand, do not consist of distinguishable rock fragments, but of clearly rounded feldspar grains which have been enlarged by peripheral additions of feldspar substance, bunches of uralite, some chlorite, and of sphene secondary after titanic iron. The photomicrograph, Fig. *A*, Pl. XXXIII, illustrates the appearance of the thin section of such consolidated sand, which possesses in no place the structure of an igneous rock, and which, moreover, grades into a finely banded rock composed of minute needles of hornblende, chlorite, and grains of epidote, lying in a clear minutely crystalline groundmass of quartz or of feldspar, or possibly of both.

The finer material cementing the recognizable fragments is the same as it is in the tuffs. The large bowlders and pebbles lie in a matrix of smaller pebbles, and these in turn lie close together in a paste which has been completely altered, and does not in all cases show clastic characters. The cement is composed of hornblende, chlorite, sericite, epidote, feldspar, and quartz, and in one case large porphyritic rhombs of a ferruginous carbonate are scattered through the finer-grained material of the cement.

In the cement of the tuffs hornblende is present in large quantity and feldspar is not so abundant. In the cement of the conglomerates feldspar seems to be rather plentiful, hornblende is present in a comparatively small quantity, and chlorite is more abundant, thus reversing the order of these minerals in the conglomerates.

SCHISTOSE PYROCLASTICS.

At various places in the Hemlock formation there occur clastic rocks which have become schistose. Two isolated exposures of pyroclastics are known whose characteristics have been so changed that, while recognizable as elastics, it is impossible to say whether they belong to the eolian or the water-deposited class. Upon weathered surface the rock is covered with brownish ochre, and on fresh fracture it is dark green and very schistose. Neither in exposures nor in hand specimens does it give any indication of its origin.

In thin section, however, one may see macroscopically the fragmental characters. The fragments are elongated and rounded. The amygdaloidal texture is also seen, showing the volcanic nature of the fragments, though the majority of the fragments are dense. Under the microscope the fragmental nature of the rocks as a whole and the volcanic character of the fragments forming it are still more clearly seen. In the centers the fragments are seen to be composed of chlorite flakes in such great quantity as partly to conceal the character of the clear white cement, which is supposed to consist for the most part of quartz, though lath-shaped areas with polysynthetic twinning, showing the presence of plagioclastic feldspar, were seen in places on the edge of the section. In the chlorite and quartz occur large grains of fresh titaniferous iron ore, altering on edge to sphene, and, most striking of all, large porphyritic, beautifully automorphic calcite rhombs and muscovite plates in isolated individuals as well as in heaps of crystals. The carbonate, which predominates, effervesces readily with cold HCl, but is evidently ferruginous as it is yellowish when altered, and from it results some of the ochre which colors the weathered surface of the rock. In other sections the calcite

phenocrysts are scalenohedra, with very few rhombohedra. The terminal faces are not sharply defined. The sections resulting from the scalenohedra are long, lath-shaped, and have pointed or irregular ends, parallel extinction, and oblique cleavage.

In passing from the centers toward the edges of the fragments, we note a marked diminution in the amount of carbonate, musccvite, chlorite, and iron oxide, causing a consequent lightening in color of the periphery. This gives the zonal structure noticeable upon the macroscopical examination of the thin section. The schistose character of the fragments is caused by the parallelism of the chlorite flakes.

The cement between the fragments is composed of quartz in rather coarse grains, chlorite in larger flakes than in the fragments, and carbonate in large porphyritic crystals, and also in minute rhombs included in the quartz grains. Another phase contains considerable secondary plagioclastic feldspar associated with the quartz in the coarser-grained portion of the cement. As in some of the conglomerates and tuffs, the fragments are observed lying in juxtaposition, the only cement between them being the secondary interpenetrating minerals. In some cases the edges of the fragments have been so welded that one may pass from one pebble to the adjoining one across an inter veiling lighter zone without detecting the transition, unless changes in the amount of chlorite, iron oxide, and carbonate are noticed.

Nothing thus far mentioned would indicate the igneous origin of the fragments, but that is indisputably proven by the amygdaloidal texture of the specimens, than which I have seen none better, even in the freshest volcanics. The outline of the cavities is marked by an accumulation of grains of iron oxide, and the cavities themselves are filled by fine-grained quartz having a small amount of .chlorite associated with it. (Figs. *A* and *B*, Pl. XXX.) These specimens have the characters of the porphyritic schistose lavas described above, but show clearly that they have been derived from igneous clastic rocks.

Other schistose elastics occur in large quantities in sec. 24, T. 46 N., R. 33 W. They are penetrated by a boss of coarse poikilitic dolerite which may have aided in rendering them schistose, though their schistosity agrees with the general strike of that of the rest of the district, and is probably chiefly due to the general folding.

Macroscopically their clastic structure may be clearly seen. The pebbles are dense greenish gray in color and oval in outline. The matrix is a much darker green. The schistosity of the rock is marked. The pebbles are uniformly elongated, and they have the appearance of having been mashed. The schistosity agrees in direction with the elongation of the pebbles.

The microscope shows the pebbles to be basaltic, with a type of structure intermediate between the navitic and intersertal structures, and another with approach to the trachytic structure. Considerable brown mica is present in both kinds, and occurs in flakes which are probably secondary, though the pebbles show few traces of alteration. The matrix consists essentially of actinolite in rather coarse needles, large grains of fresh magnetite, but very little mica, and that such as is seen in the pebbles, all lying in a cement of quartz and calcite. The passage between the cement and the pebbles is a more or less gradual one, there being a change as we pass from the center of the pebble, where isolated actinolite needles and epidote grains occur, toward the edge, where these minerals increase in amount until between them here and there are twinned feldspars. In the matrix proper the quartz is the predominant white silicate, though here and there limpid feldspar is also seen. The pebbles are gradually being eaten up, so to speak, by the actinolite, and we can imagine the final result to be an actinolite-schist showing no clastic structure, and giving absolutely no indication as to the rock from which it originated.

There is no microscopical evidence of mashing in the minerals, and since this is absent from the quartz in the cement, I conclude that no original clastic cement is now present, and that the quartz is a secondary crystallization product derived from infiltrated material and from material obtained from the adjacent pebbles. Whether the rock is an eolian deposit or a waterworn sediment can not now be definitely determined, though that it belongs to the first appears more probable.

Still another rock very similar in general character but differing in detail, and showing a slightly different result, has been examined. The pebbles are basalt, and in them the secondary nature of the biotite, which has chlorite associated with it, is clearly shown. Near the centers of the pebbles very little is present, but it rapidly increases in amount toward the periphery, until at the edge only here and there the feldspars may be seen between the mica and chlorite flakes. The cement between the pebbles consists of angular fragments of altered orthoclase feldspar, quartz, and a great quantity of chlorite, and some biotite. This cement is present in large quantity.

In both of these last the secondary minerals are parallel, and produce rocks of most decided schistose character. These schistose pyroclastics may be compared with the rocks described by Williams[1] and Bayley[2] from the related rocks in the adjoining Marquette district.

THE BONE LAKE CRYSTALLINE SCHISTS.

Under this name are included certain crystalline schists which are best developed in the northern part of the Crystal Falls district, in the vicinity of Bone Lake. If one examined isolated specimens of certain of these rocks, it would be impossible to determine their origin. Studied in connection with the alteration of the altered and schistose lavas and pyroclastics already described, the problem becomes greatly simplified. These schists, as will be shown on the following pages, are but extremely metamorphosed members of the Hemlock volcanic formation. Since in the limited area in which the rocks

occur the secondary characters are dominant, while the primary volcanic characters have nearly all disappeared, a brief separate description of these rocks seems warranted, but they are not represented by a separate symbol on the map.

DISTRIBUTION.

The crystalline schists predominate in T. 46 N., R. 32 W. Near the western limit of this township the belt occupied by these rocks is about 2 miles wide. As it is followed to the east past Bone Lake, and then to the southeast, it gradually narrows, until in sec. 36, T. 46 N., R. 32 W., the eastern limit of the area studied by me, it is only about half a mile wide. Except in the vicinity of Bone Lake, where erosion has uncovered some of the knobs, outcrops are very scarce, since the drift is very heavy, and the drainage is poorly developed.

[1]Bull. U. S. Geol. Survey, No. 62, cit., pp. 185-191.

[2]Mon. U. S. Geol. Survey, Vol. XXVIII, cit., pp. 160-169.

FIELD EVIDENCE OF CONNECTION WITH THE VOLCANICS.

If one examines attentively the Hemlock formation in its typical development, beginning, say, in sec. 27, T. 45 N., R. 33 W., and following its northward extension through secs. 22, 16, and 15 of the same township, he will observe instances of banding in the tuffs and of schistosity in the amygdaloidal lavas and pyroclastics. The strikes and dips of the primary and secondary structures approximately coincide, both having a general north-south strike and dipping high to the west. Throughout this area, however, the unmistakable massive volcanics are the predominant rocks. Continuing the examination farther north into sec. 34, T. 46 N., R. 33 W., rocks are found which possess almost invariably a strongly marked schistosity, but with their volcanic origin clearly shown by the flattened amygdules. This is also true for the exposures east of this place on the under side of the Hemlock belt, in sec, 31, T. 46 N., R. 32 W. The strike of the schistosity of the amygdaloids varies from N. 30° to 70° E., and the dip is high to the northwest. Farther along this belt to the northeast, in sec. 24, T. 46 N., R. 33 W., schistose pyroclastics were observed striking N. 80° E. The original characters of these pyroclastics have been almost entirely obliterated. The exposures next to the east in sec. 16, T. 46 N., R. 32 W., possess all the characters of crystalline schists. Somewhat farther east, however, associated with these schists are isolated outcrops in which traces of flow structure and remnants of amygdules were observed, and, in some, traces of igneous textures were seen under the microscope. The schistosity of these rocks strikes for the most part south of east, varying from N. 65° to 80° W. and dipping to the northeast. Following the belt as it now turns to the southeast, the crystalline schist characters prevail, the volcanic characters being obliterated. The schistosity at the same time bends farther around to the southeast, pointing toward the continuation of this area of volcanics to the southeast, outside of the area studied.

From field observations the conclusion seems necessary that these schists are metamorphosed volcanic rocks, and this conclusion is strengthened by detailed petrographical examination.

PETROGRAPHICAL CHARACTERS.

The crystalline schists are fine to medium grained schistose rocks which vary in color from a moderately light green for the more chloritic phases to a very dark green and purplish-black for those in which the hornblende, mica, and iron ores are prominent. The minerals of winch the rocks are composed, arranged in order of importance, are hornblende, biotite, feldspar, chlorite, epidote muscovite, quartz, magnetite, hematite, ilmenite, and rutile. Under the microscope the schistose structure is seen to be produced by the general parallelism of the bisilicate constituents. The porphyrinic texture is seen in a few specimens, and hornblende forms the phenocrysts.

Hornblende occurs in fine needles and also in coarse crystals which are automorphic in the prismatic zone, but on which no terminations have been observed. It also occurs rather commonly in sheaf-like bundles of ragged crystals. The marked orthopinacoidal development so common for actinolite is quite noticeable. The crystals show the usual strong pleochroism: $\mathfrak{c}$=bluish-green, $\mathfrak{b}$=olive green, $\mathfrak{a}$=yellow, whereby $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. The hornblende crystals frequently contain large quantities of the minerals of the groundmass, many of them in such quantity that there are really only skeleton hornblende crystals present. The general character of the hornblende in all these rocks is that of a secondary porphyntic constituent, and seems to be analogous to such minerals as garnet, staurolite, etc., which are produced in clearly metamorphic rocks.

Brown biotite is rather common in some of the rocks. Though usually subordinate to the hornblende, it is at times the predominate bisilicate. It is light brown and shows the usual characters of biotite. It is present in small irregular flakes, and also in larger individuals which show poor pinacoidal development. In one case such a mica individual in perfectly fresh condition may be seen with its ragged edges interlocking with the fringed periphery of an altering feldspar crystal. The biotite appears to have derived some of its necessary elements from the feldspar and to be eating into it, and consequently to be a secondary product.

Feldspar is not found as an original mineral in any of the crystalline schists. It occurs as a secondary constituent. It is found, however, as a primary constituent in a few rocks which, as they still possess remnants of original igneous textures, strictly speaking, should not perhaps be included with the crystalline schists. They represent more properly the transition stages to the crystalline schists, but the process of the alteration of the feldspar is so well shown in these that it is considered expedient to mention it at this place. The original feldspar occurs in this transition phase in the large tangled intergrowths commonly seen in andesitic and basaltic rocks, as

individual phenocrysts, and as microlitic lath-shaped individuals in the groundmass. The greatest interest centers in the phenocrysts, as in them the changes which take place are more clearly seen. The feldspar phenocrysts are always cloudy, due to numberless black ferruginous inclusions. They also inclose the various secondary dark silicates composing the groundmass, grains of epidote, flakes of biotite, and crystals of hornblende. These are usually surrounded by very narrow clear zones, apparently feldspar. Near the edges of such altered crystals, and especially in the more altered individuals, these inclusions are more numerous, and are accompanied by grains of quartz and new feldspar (albite?). These last two have certainly been derived from the alteration of the feldspar, but that mineral may possibly also have contributed something to the production of the dark silicates.

The secondary feldspar, that of the schists proper, is found in grains usually unstriated, though in a few cases striations were observed. This feldspar was not determined, but is probably albite. The chlorite is in flakes scattered through the schists, showing the usual characters.

Epidote, muscovite, quartz, and rutile appear as usual.

Ilmenite is present in one case as micaceous titanic iron oxide, and is then in extremely thin plates which show a beautiful hexagonal development, though more frequently the plates are rounded. They are transparent with the characteristic clove-brown color. The thicker plates are thin enough to be transparent only along the edges.

The iron oxides, magnetite, and hematite occur in some of these rocks in large quantity. In certain parts of the area underlain by these schists considerable excavations have been made in search of iron, the presence of which was indicated by the magnetic needle, and moderately large bodies of ore have been found, though in no case in sufficient quantity to admit of successful mining. Such ore bodies probably owe their presence in great part to processes active subsequent to the formation of the schists. (See p. 134.)

According to the quantity and association of the minerals described above as occurring in the schists, the following rocks may result from the complete metamorphism of the basic volcanics: Amphibolites, chlorite-schists, epidote-schists, mica-schists, mica-gneisses, and possibly siliceous hematite and magnetite ore. The complete metamorphism of dense basic lava flows into crystalline schists has been described by Williams[1] for the Menominee and Marquette districts, and also by Van Hise and Bayley[2] for the Marquette district. Williams[3] has also described the production of schists from the igneous elastics in the Menominee district and similar products have been described from the Marquette district both by Williams[4] and by Bayley.[5]

The above-described schists cover a considerable area, with only isolated exposures of rocks associated with them in which volcanic characters are recognizable. They are confidently believed to represent extremely metamorphosed volcanics of the same general original character as those constituting the Hemlock formation and belonging to the same relative period of extrusion.

The same conclusions have been reached by Smyth for similar schists along the Fence River to the southeast of those described. It is noticeable that the most intense metamorphism of the volcanics has taken place in the northern and northeastern part of the Crystal Falls district, that part in which the crystalline schists have been produced, though the explanation for this can not be offered.

NORMAL SEDIMENTARIES OF THE HEMLOCK FORMATION.

The normal sedimentaries are in small quantity. It has been seen (pp. 64, 78) that the Mansfield slate is overlain by a conglomerate in which volcanic material predominates, but which contains partly rounded fragments of chert and slate and round quartz grains derived from the underlying sedimentaries. But for the intermingling of this normal clastic debris with the pyroclastics, the conglomerate shows nothing different from the volcanic conglomerate already described. It is a transition rock between the tuffs and the normal sedimentaries.

[1]Bull. U. S. Geol. Survey No. 62, cit.

[2]Mon. U. S. Geol. Survey, Vol. XXVIII, cit., pp. 152-159.

[3]Op. cit., p. 133.

[4]Op. cit., p. 158.

[5]Op. cit., pp. 160-169.

Similarly, in sec. 34, T. 45 N., R. 33 W., a gradation occurs in the upper horizon of the Hemlock formation from the volcanic conglomerates to the true normal sediments. The sediments are slates about 175 feet thick, containing lenticular masses of limestone. These beds dip 80° to the west, generally strike north, but vary in places a few degrees to the west. They are underlain by conglomerates containing well-rounded volcanic pebbles. This volcanic conglomerate grades from the coarse conglomerate up into what might be termed a water-deposited volcanic sand. The pebbles are all of volcanic material. Between the conglomerates and slates is a small area without outcrop. Overlying the slates is a succession of tuffs and lava flows.

The slates in color range from light gray and green to purplish red, and the lenses of limestone vary from cream color to purplish red. In thin section the slates are seen to be composed of a felt of sericite, chlorite, and quartz, with associated innumerable minute rutile crystals, and here and there a large spot of limpid quartz. A ferruginous carbonate is present in all of them in porphyritic rhombs. Where chlorite is abundant, the slates are a light green. Where iron oxide is abundant and the chlorite less plentiful, the slates are purplish.

The lenses of limestone are rather pure, consisting mainly of calcite, with some few scattered areas of cherty silica. On the edges of the lenses some of the slate material is found forming bands in the carbonate. These intermediate phases grade on the one hand into the pure carbonate, and on the other hand into the slate beds. From the crust of limonite, which may be seen on the weathered surface of the rock, the calcite is evidently rather ferruginous. The process of alteration is clearly seen under the microscope, where many of the grains are surrounded by rims of hydrated oxide of iron and hematite.

ECONOMIC PRODUCTS.

BUILDING AND ORNAMENTAL STONES.

The rocks of the Hemlock formation are not likely to be much used for building purposes. The compact basalts possess in a high degree the two essential features of strength and durability. For trimming in contrast with lighter stones they might be found desirable, and it may be suggested that they are especially suitable for mosaics in which rich greens are desired. They are of too somber a color to be used in large quantity for anything else than foundations. Moreover, the difficulty and consequent expense of quarrying them, and their remoteness from cities of large size, will operate strongly against their use.

The pyroclastics are natural mosaics, and some of them have a very pleasing appearance (Pl. XIII) and are suitable for table tops, wainscoting, etc.

ROAD MATERIALS.

The importance of good roads in aiding in the material development of a region can hardly be overestimated, and in the building of good roads, especially in thinly inhabited regions, the proximity of good road material is of prime importance.

Thus far the 15 miles of good road between Crystal Falls and the adjacent mining villages have been covered with the ferruginous chert and slates from the dumps of the mines, and unroll themselves to the traveler like red ribbons laid through the green woods.

No rock is better suited for use in building macadamized roads than the basalt, and of this the Hemlock formation offers an inexhaustible supply. The fine-grained compact basalts are by far the best rocks obtainable, and, other things being equal, should of course be chosen rather than the scoriaceous and consequently weaker facies, but these weaker kinds and also the pyroclastics are preferable to the cherts and slates which have been used. The cherts are very hard and durable, but the dust and sand from them possess but slight capacity for cementation. Consequently the roadways upon which quartzite and chert have been used are more likely to wash out than are the roads macadamized with basalt, since the dust in this latter case serves as a cement which binds the larger fragments more firmly together. The road commissioners have thus far used very little basalt, chiefly for the reasons that no crusher was at their disposal, and the chert and slates were at hand ready for use.

CHAPTER V.
THE UPPER HURONIAN SERIES.

The upper series of this district is connected in the northeastern part of the area with the Upper Marquette series of the Marquette district already described in the Fifteenth Annual Report and Monograph XXVIII. In these reports the Upper Marquette series is regarded as part of the Upper Huronian. As has been stated, the Crystal Falls district is the southwestern extension of the Marquette district, and consequently we should expect the chief formations of the two districts to be continuous, as they are. Because of the drift and because of a change in the character of the rocks, in mapping the western part of the Crystal Falls district it has not been practicable to divide the Upper Huronian into several formations, corresponding to those in the Marquette district. No independent name will be given to it, but it will simply be called Upper Huronian, with the understanding that it corresponds stratigraphically to the Upper Marquette series.

DISTRIBUTION, EXPOSURES, AND TOPOGRAPHY.

Beginning in the northeastern part of the area discussed by me (see Pl. III), this series covers the southern parts of T. 46 N., Rs. 31 and 32, where it is only 4 miles in width. It is here a northwest-southeast syncline. From this place it stretches beyond the northern limit of the map. With slight interruptions where intrusives occur, it extends in a broad area to the west and south about the Hemlock volcanics to a point lying beyond the limit of the map. On the eastern side of the district it abuts against and is folded in synclines in the Archean granite.

Exposures are scanty for the greater part of the area in the Crystal Falls district underlain by the Upper Huronian series. This is due to two conditions, first, to the soft character of the rocks constituting the series, and, second, to the presence in places of the Cambrian sandstone, and more especially to the deep covering of glacial drift which is found spread over the entire district. The Upper Huronian is composed in great measure of slates, which are interbedded with much smaller quantities of graywackes and chert. The slates are eroded much more readily than the associated harder beds, and therefore, except along valleys, we rarely find the soft slates exposed. The graywackes and cherty rocks are the ones which form the striking topographical features of the landscape, the slates forming softly-rounded hills. The drift is also an important factor in the scarcity of outcrops. In the northern and western parts of the districts especially the drift is very heavy. In this portion the youthfulness of the topography is emphasized by numerous swamps, lakes, and generally

imperfect drainage. In the southern and southwestern parts of the district, owing to the presence of larger streams, and consequently more advanced erosion, the drift has been removed to a greater or less extent, so that the topographical forms approach much nearer to those of an unglaciated region. For instance, the general strike of the graywacke and cherty ferruginous slate beds in the southern portion of the area, T. 42 N., Rs. 32 and 33 W., can be closely followed by the north-south to northwest-southeast ridges which they form, the intervening valleys being in all probability underlain by the softer carbonaceous clay slates. Also in this vicinity, from the Chicago and Northwestern Railway eastward to the Michigamme River, exposures of intrusives with some sedimentaries stand out from the sand plains as rounded knobs.

MAGNETIC LINES.

A considerable amount of detail magnetic work has been done in the vicinity of the ore-bearing areas, in the hope that with the assistance afforded by the magnetic needle the iron belts might be better traced than they could be by means of the very scanty outcrops. I shall here describe those lines of magnetic disturbance which have been traced for considerable distances. They are indicated on the map, Pl. III, by solid blue lines.

Magnetic line D..—This line of maximum magnetic disturbance was traced northwest from near the southeast corner of T. 46 N., R. 32 W., around Bone Lake, then southwest and south through T. 46 N., R. 33 W., until finally lost near the south side of sec. 34 of the same township. The tracing of this line was begun where outcrops were wanting, and it was not possible to connect it directly with any magnetic formation until sec. 34, T. 46 N., R. 33 W., was reached. Here it was connected with outcrops of magnetitic slate and graywacke which overlie the Hemlock formation, but with no contact exposed. Throughout its extent the line of disturbance is separated from the line of outcrops of the Hemlock volcanics by a short interval. It is, however, always distinctly separated from them.

Magnetic line D.—This magnetic line passes directly through the open pits at the Hemlock. As the line is traced north from this point it passes just west of an amygdaloidal lava one-half mile north of the mine. From this point until it is lost in sec. 16, T. 45 N., R. 33 W., there is no evidence in regard to the nature of the rock causing the attraction. Tracing the line south from the Hemlock mine it is found to swing about 200 paces east of the Michigan mine, near the north line of sec. 9, T. 45 N., R. 33 W. A quarter of a mile farther south it swings back again, apparently in the line of the continuation of the iron-bearing formation, which it follows for one-half mile farther, where it is lost. The only place along this line where it has been possible to determine the rock causing the attraction is at the Hemlock mine. Here it was found that it is not the ore formation proper which is magnetic, but that it is the foot wall. This is a magnetitic slate, about 42 feet in thickness, as shown by the diamond-drill borings.

The above are the only lines of maximum magnetic disturbance of this part of the Crystal Falls district which it has been found possible to connect in any way closely with the iron-bearing rocks. A large number of lines of disturbance, however, were traced within the limits of the Hemlock formation, but on account of their slight economic importance they are not inserted on the map. In these cases the influence on the needle is evidently exerted by the magnetite of the lavas and pyroclastics, and in proof of this the lines can very commonly be connected with exposures of the various volcanic rocks. It is of interest to note that the trend of the lines in the volcanics invariably agrees with that of the tuff beds, and with the general strike of the formations of the district, and the reader is reminded of the suggestion already offered (p. 134) that they may be caused by magnetite accumulated by secondary processes, especially active in the tuff beds and scoriaceous portions of the lava flows.

THICKNESS.

Since the Upper Huronian sediments cover a broad area, their thickness must be very considerable. Owing, however, to the scarcity of exposures, it is impossible to give even an approximate estimate.

FOLDING.

The extreme northwestern part of the area has not been studied in such detail as to enable the minor folds to be determined. In general, the series may be said to fold around the Lower Huronian, following the general outline Indicated by its color, as shown on Pl. III, and having a steep dip away from it. In sec. 20, T. 45 N., R 33 W., large outcrops of chert are folded in a most complicated fashion and are locally brecciated. South from this point the evidence of subordinate cross folds is marked. As a result, the line between the Lower Huronian and Upper Huronian is undulatory. The indentations in the Lower Huronian represent minor cross synclines, and the protuberances represent minor cross anticlines.

CRYSTAL FALLS SYNCLINE.

Near Crystal Falls is the most important of these synclines. This town and a number of small outlying mining villages are situated on a syncline. The character of this syncline is shown better by the distribution of the Hemlock volcanics than by the sedimentaries, owing to the scarcity of the outcrops of the latter (Pls. XVII and XVIII). The broad belt of northwest-southeast trending volcanics, situated 3 miles northeast of Crystal Falls, bends in secs. 11, 12, and 13, T. 43 N., R 32 W., to the south, and gradually changes to a slight southwest trend. In the reentrant angle of this volcanic formation is the Crystal Falls syncline, its course being that of a southwestward-opening U. The axial line of this U probably has a westward pitch, corresponding with the general folding of this part of the district.

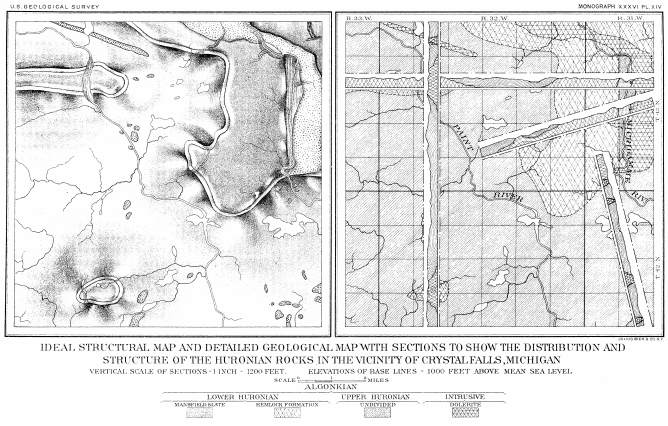
Near the center of the U and just a little northwest of Crystal Falls, in secs. 17 and 20, T. 43 N., R. 32 W., is an area underlain by volcanics, which trends east and west, and can be followed westward into sec. 1, T. 43, R 35, beyond the limits of the area represented on the map. It varies in width from one-fourth mile to 4 miles, averaging about 2 miles. The contacts of these volcanics with the overlying Upper Huronian sediments are not exposed. Hence definite proofs of their interrelations can not be given. The volcanics have been folded with the sediments, and subsequent erosion has exposed them along the axis of an anticline.

The southern arm of the curved syncline bends around the extreme southern projection of the Hemlock volcanics in secs. 1 and 2, T. 42 N., R. 31 W., and swings east north of Lake Mary into sec. 32, T. 43 N., R. 31 W. Here ferruginous slates are exposed, bordering the Michigamme River at the so-called Glidden exploration. The extension of these lowermost Upper Huronian beds east from this point soon passes under the sand plains and drift hills and is lost. The higher beds of the series are, however, exposed in the lower course of the Michigamme, Paint, and Brule rivers, which give good sections across them. In this portion of the area discussed the extension of even these higher parts of the formation can not, however, be followed farther east than the Michigamme River.

PLATE XIV.
IDEALIZED STRUCTURAL MAP AND DETAIL GEOLOGICAL MAP, WITH SECTIONS, TO SHOW THE DISTRIBUTION AND STRUCTURE OF THE HURONIAN ROCKS IN THE VICINITY OF CRYSTAL FALLS, MICHIGAN.

Idealized structural map of the vicinity of Crystal Falls. An attempt has been made to illustrate upon this map the distribution of the Huronian rocks, and at the same time our conception of the general features of the structure of this area. The drainage is merely introduced for the purpose of orientation. The topography as here represented does not agree with the true topography of the area. The bottom of the geological basin now occupies, as the result of erosion, the highest places topographically.

Detail geological map, with sections, to show the distribution and structure of the Huronian rocks in the immediate vicinity of Crystal Falls. This serves as a key to the accompanying idealized structural map.



That the Crystal Falls synclinal basin is not simple, but has minor rolls, is shown by the way in which the Upper Huronian series indents the Lower Huronian at the eastern end. Also the close and complicated folding is shown by mining work, and can be nicely seen in the open pits of the Columbia and Crystal Falls mines, in the exposures in the railroad cut near the Crystal Falls mine, and also along both banks of the Paint River near the town of Crystal Falls. Pl. XIV shows the general character of this syncline. The folding has produced extensive “reibungs-breccias.” Near Crystal Falls, along the river bank, about one-fourth mile south of the railroad bridge, may be seen such a breccia, which has been formed at the junction of a chert with the slates.

TIME OF FOLDING OF THE UPPER HURONIAN.

The latest folding to which the rock of the Crystal Falls district has been subjected is that which affected the Upper Huronian and likewise involved the underlying Archean and Lower Huronian rocks. Therefore the determination of this period of folding is of especial interest, as marking the close of orogenic movements in this district.

Overlying the Upper Huronian is the Potsdam Cambrian, or Lake Superior sandstone. The beds of this formation are horizontal, or else show a very slight tilting, following the general inclination of the district, which perhaps to a great extent may be explained by the initial dips of the beds. They overlie with strong unconformity the upturned and strongly plicated beds of the Upper Huronian. This unconformity marks a lapse of time represented in other districts by the following events: (1) A period of upheaval and denudation of the Upper Huronian; (2) the subsidence and deposition upon the truncated Upper Huronian sediments of the heterogeneous volcanic and sedimentary Keweenawan series; (3) the upheaval and truncation of the Keweenawan, in which movement of course the Upper Huronian in the Keweenawan areas was likewise involved. Subsidence of the land areas and the transgression of the Cambrian sea followed, with deposition of the horizontal Lake Superior sandstone upon the inclined Keweenawan and Upper Huronian rocks. The Upper Huronian of the Crystal Falls district may have been involved in one or both of the foldings which took place prior and subsequent to the Keweenawan; or, second, since no Keweenawan deposits are known in the Crystal Falls district, it may be that it suffered an early period of powerful orogenic movement, which raised the rocks above the sea, and was synchronous with the pre-Keweenawan upheaval. A long period of erosion, accompanied perhaps by other less important orogenic movements, may have followed contemporaneous with the activity of the Keweenawan volcanoes and the oscillatory movements of the Keweenawan region. The latter I conceive to be the more probable view. If this is correct, the intense folding of the Upper Huronian sediments in the Crystal Falls district took place immediately preceding the deposition

of the Keweenawan series in other parts of the Lake Superior region.

RELATIONS TO OTHER SERIES.

It has been seen that in the western part of the district the Hemlock volcanics are the highest member of the Lower Huronian. At the end of the volcanic activity there must have taken place a very general transgression of the sea, as is evidenced by the continuous belt of sedimentary rocks which encircle the volcanics. The very marked change in the character of the rocks from subaerial volcanics to true sedimentaries partly marks the division of the Upper Huronian and Lower Huronian series. The determining points in favor of this subdivision are found in the eastern part of the district described by Smyth, and in the Marquette district still farther northeast. In only one place in the western part of the Crystal Falls district, in sec. 26, T. 44 N., R. 33 W., has a contact between the two series been obtained. A drill hole here passed through a mottled slate just before entering the Lower Huronian volcanics. A similar slate was obtained at Amasa overlying conglomeratic volcanic material, which outcrops at the surface, but no direct contact has been found. With most careful examination I have been unable to determine whether the conglomeratic rock is a true volcanic tuff deposited upon the land, or is water-deposited volcanic material, and thus possibly a basal conglomerate of the Upper Huronian.

In sec. 34, T. 46 N., R. 33 W., the Lower Huronian and Upper Huronian are found in very close proximity. Here the Upper Huronian is a ferruginous graywacke and is separated by only about 10 yards from the schistose volcanics. In this case careful search failed to reveal the intermediate rock. In only one case in addition to the Amasa instance has a distinct conglomerate been found which can be considered as a possible basal conglomerate. This is in sec. 9, T. 42 N., R. 31 W., along the Michigamme River. Here there is a thick mass of conglomerate overlain by southward-dipping schists. The conglomerate contains pebbles of extremely altered basic amygdaloidal rocks and of acid rocks which rest in a matrix of chlorite-schist. This detrital rock is such as might be derived from the Hemlock volcanics, but between it and these volcanics is found a mass of ferruginous muscovitic and chloritic schists at the Glidden exploration (sec. 32, T. 43 N., R. 31 W.), which are very similar to those occurring immediately south of the conglomerate, and like them have apparently a southern dip. The true relations between this conglomerate and the schists at the Glidden workings are not certain. The conglomerate may be below them. In that case the Glidden schists would correspond to those south of the conglomerate, the beds having received their present distribution from the close folding to which they have been subjected.

If such be the case, the schists at the Glidden are the northern limb of a syncline, and the conglomerate and the overlying schists, with an average dip of 70° S., represent the southern limb of a steep anticline, whose crest and northern limb have been cut off and covered up. The considerable width of the conglomerate exposed may be partly due to the fact that it has been doubled upon itself.

That the folding in this part of the district was probably fully sufficient to produce such structural relations and also the petrographical changes of the conglomerate matrix to a chloritic schistose mass is shown by the changes which the sedimentaries south of them in this part of the district have undergone. If this interpretation is correct, the space between the schists at the Glidden exploration and the Hemlock volcanics should be occupied by the equivalents of the conglomerate. Section K-L, Pl. VI, embodies this idea of the structure.

RELATIONS TO INTRUSIVES.

The Upper Huronian, as well as the Lower Huronian, has been penetrated by intrusive rocks. The difference in the character of the intrusives of the two series is, however, interesting. As has been seen (p. 77), the Lower Huronian is cut by vast masses of basic rocks and by rare dikes of acid rocks. In the Upper Huronian of the southern part of the district the acid rocks are more abundant but still subordinate to the basic intrusives. North of Crystal Falls is a great east and west basic dike. Similar rocks are known in a few small bosses near Crystal Falls. Moreover, on the Michigamme River, in secs. 31 and 32, T. 43 N., R. 31 W., and in a few places to the southeast of this area, the Upper Huronian is cut by the southern continuation of the basic masses whose principal occurrence is in the Lower Huronian area. Finally basic and ultrabasic intrusives pierce the Upper Huronian sediments in secs. 15, 28, and 29, T. 42 N., R. 31 W., and in a few other places. The acid rocks occur in isolated knobs near Crystal Falls, in sec. 28, T. 43 N., R. 32 W., and in sec. 4, T. 42 N., R. 32 W. They increase in quantity toward the southeast, and in the vicinity of Lake Tobin, in secs. 21 and 28, 42 T. N., R. 32 W., they form a series of small hills rising boldly out of the sand plains; and finally they occur in large quantity in secs. 19, 20, and 29, T. 42 N., R. 31 W., between the Paint and the Michigamme rivers.

CORRELATION.

The Upper Huronian sedimentary rocks were first studied in the field by Brooks, and the conclusion reached by him that they are late Huronian.[1]

Rominger correlates these same rocks very correctly with the schists exposed around Lake Michigamme, although he has the erroneous idea that they follow down the Michigamme River, instead of making a wide curve to the west, as subsequent study of the area has shown.[2] He considers the rocks as forming the middle portion, of his Arenaceous Slate group.[3]

[1]Geology of the Menominee region, by T. B. Brooks: Geol. of Wisconsin, Vol. III, 1880, p. 44.

[2]The mica-schists seem to continue southward along the course of the Michigamme River, as we find in its lower course, 5 or 6 miles north from its entrance into the Brule River, and from there down to the mouth, mica-schist to he the prevailing surface rock. Along the lower course of the adjoining Paint River the mica-schists likewise are the only rocks seen in the exposures." (Geol. of Michigan, Vol. V, 1895. p. 81.)

[3]Op. cit., p. 79.

Recent work in the district has shown the Upper Huronian rocks to be unquestionably the western continuation of the Michigamme formation, to which the rocks correspond petrographically. The Michigamme formation has recently been carefully studied by Van Hise, and described by him in detail in Monograph XXVIII (Chap. IV). A less detailed description is given in the Fifteenth Annual Report (pp. 598-604). Since such great petrographical similarity between the Upper Huronian deposits in the western half of the Crystal Falls district and the above formation in the adjoining districts exists, and since nothing of exceptional interest has been observed in their study, the reader is referred to the articles mentioned for details. The following general description, while based upon the study of many exposures, specimens, and 75 sections of these Crystal Falls rocks, may still be considered to some extent as an abstract of the above articles in which the few changes made necessary by the slightly different characters have been incorporated.

PETROGRAPHICAL CHARACTERS.

From the above general statement it is seen that the Upper Huronian comprises rocks both of sedimentary and of igneous origin.

The preponderant deposits of the western half of the Crystal Falls district were muds and grits. With these were subordinate quantities of carbonates. In a few places sheets of basic rocks were intruded between the sedimentary beds and are now found alternating with them. Widely distributed basal conglomerates, coarse quartzitic conglomerates, and quartzites, such as characterize the lowest horizon (the Goodrich quartzite) of the Upper Huronian of the Marquette district, are absent. Work already-completed outside of the immediate area covered by this report shows the presence of a small area of surface volcanics associated with the modified Upper Huronian sediments. This evidence of contemporaneous volcanic activity is closely paralleled by the Clarksburg volcanics of the Upper Marquette of the adjoining district.[1]

SEDIMENTARY ROCKS.

The sedimentary rocks of the Upper Huronian series in the western part of the Crystal Falls district are graywackes, ferruginous graywackes; micaceous, carbonaceous, and ferruginous clay slates and their crystalline derivatives; and thinly laminated cherty siderite-slate, ferruginous chert, and iron ores. With these we find only in two places rocks of a well-developed conglomeratic nature.

[1]Fifteenth Ann. Rept. U. S. Geol. Survey, cit., pp. 604-607; Monograph U. S. Geo]. Survey, Vol. XXVIII, cit., pp. 460-486.

Some of the rocks have undergone great metamorphism, and we find the graywackes and slates passing into chlorite-schists, mica-schists, and mica-gneisses. The ore deposits of the district are associated with the least altered sedimentaries.

The graywackes and slates are found chiefly in the northern and western parts of the district, while the single conglomerate, the metamorphosed or micaceous graywackes and slates, the mica-schists, and the mica-gneisses are confined to the southern portion.

Near Crystal Falls on both banks of the river, between the wagon and railroad bridges, there is exposed a conglomeratic phase of graywacke. Several bands of these coarse conglomeratic graywackes are interlaminated with bands of fine-grained graywacke and chert. A well-developed chert reibungsbreccia is also associated with these. I do not consider this conglomeratic graywacke as representing anything more than a purely local and very slight unconformity. This is evidently the same occurrence of conglomerate which has already been mentioned by Wadsworth.[1]

The well-developed conglomerate found in sec. 9, T. 42 N., R. 31 W., along the Michigamme River, contains pebbles of both basic and acid eruptive rocks in a chlorite-schist matrix. Toward the south the rock grades up into chloritic graywackes and chlorite-schists, which possess the ordinary characters of similar rocks in other portions of the area. The graywackes and slates of the district in general differ from each other chiefly in coarseness of grain. They are commonly interbedded in the same exposures. The rocks vary in coarseness from medium-grained graywacke to aphanitic slates, and in color from gray to green and black, the aphanitic slates being usually the darkest. These fine-grained rocks always show well-developed slaty cleavage. Throughout the area the rocks are very thoroughly consolidated, and in places where they have been most altered they are completely crystalline schists.

[1]Sketch of the geology of the iron, gold, .and copper districts of Michigan, by M. E. Wadsworth: Ann. Rept, State Board of Geol. Survey for 1891-92, 1893, p. 128.

The crystalline rocks which are believed to have developed from the elastics are found in the southern portion of the district, beginning in sec. 16, T. 42 N., R. 31 W., and are well exposed in the river section at Norway carry (portage). The rocks at this point are an alternating succession of mica-schists, some of which are very quartzitic, and hornblende-gneisses (altered igneous rocks) in thick beds. In these the bedding and schistosity agree, or else differ so slightly as not to be noticeable. These rocks outcrop in bold knobs for some distance away from and on both sides of the Michigamme River at the carry and also form the steep cliffs between which the river flows. In some places they are more or less ferruginous, and at one point near the head of the rapids exploring for iron has been done.

These crystalline schists are separated from the undoubted sedimentaries at the north by an interval of about one-half mile, and are separated to the south by a smaller interval from the next rocks, which are also of sedimentary origin, though of highly metamorphosed character. These latter consist of micaceous graywackes which grade over by increasing metamorphism into rocks which are indistinguishable from mica-schists and mica-gneisses. There can be no doubt as to the clastic character of these rocks, as one may see on the outcrops of the least altered phases the normal as well as the false bedding. The bedding of these micaceous graywackes agrees with that of the mica-schists at the Norway carry, and in them the schistosity is usually nearly parallel to the bedding, though at times cutting it at varying angles. These rocks vary in grain from fine to very coarse. They are most all a light-gray color. In two cases the presence of large porphyritic crystals of staurolite was observed. Garnet was found in but a single specimen, and no andalusite was seen. The scarcity or absence of such minerals is made noticeable by the fact that they are so abundant in the adjoining Marquette district. The contrast is the more marked since the Crystal Falls rocks are cut by and included in granite, and in the Marquette district these intrusives are absent. Splendid sections through the metamorphosed sediments are offered by the river sections in secs. 14, 24, 35, and 36, T. 42 N., R. 32 W., on Paint River, and at Peevie[1] Falls, sec. 32, T. 42 N., R. 31 W., on the Michigamme River.

It should be noted that thus far no grünerite-schists which owe their origin to the metamorphism of ferruginous sediments have been observed in the Crystal Falls district; nor does the brilliant red jasper—jaspilite— which accompanies certain of the ores in the Marquette district, occur associated in large quantity with them in the Crystal Falls district.

[1]This name has been given by the lumbermen to the falls as they lose so many peevies here in breaking jams.

The iron-bearing rocks of the Upper Huronian comprise cherts, siderite-slates, ferruginous cherts, iron ores, and subordinate quantities of ferruginous graywackes and clay slates.

The least altered of these is a siderite-slate. This is a fine-grained gray rock composed almost entirely of siderite, usually in rounded rhombohedral crystals, with very little minutely crystallized silica between them in places. Wherever they have been exposed to the weather any length of time, these rocks have a deep reddish-brown oxidation crust. Alteration also follows along crevices, and thus the siderite is rapidly oxidized. The main products derived from these siderites are like those of the more important ore-producing parts of the Penokee and Marquette districts, namely, hematite and limonite. Little magnetite has been found. These siderites are interbanded with the black carbonaceous clay slates. In some cases the dividing line is sharp. In others, as the siderite lessens in quantity, fragmental material increases until only a few crystals of siderite are found scattered through the elastics. Their association with the carbonaceous fragmentals would seem to indicate, as pointed out by Van Hise,[1] that the siderite owes its formation to the presence of organic material.

The ferruginous cherts (the term is here used as defined by Van Hise) are banded chert and hematite, with some magnetite, in which the iron oxide is derived from a previously existing siderite, and the cherty bands are not of fragmental origin. This alteration from the siderite to hematite may be easily followed from the fresh siderite through that which is slightly discolored, to the reddish-brown earthy mass, and then to the crystalline hematite. Such alteration processes have been illustrated and clearly described a number of times by Van Hise, so that no further mention will be made of them.

The ferruginous graywackes may be described as rocks which are partly of fragmental and partly of chemical origin. For instance, the transition may be traced from a rather micaceous magnetitic graywacke, in which ordinary and false bedding may be seen, to a rather schistose rock, in which magnetite is predominant, but in which is considerable fragmental quartz and secondary muscovite and chlorite. This rock represents an original grit containing more or less siderite. Metamorphism has changed the siderite to magnetite, and produced from the fine fragmental mud the muscovite and chlorite.

[1]Fifteenth Ann. Rept. U. S. Geol. Survey, cit., p. 601; Mon. U. S. Geol. Survey, Vol. XXVIII, cit., p. 447.

MICROSCOPICAL DESCRIPTION OF CERTAIN OF THE SEDIMENTARIES.

In the following pages I shall describe in a brief way the graywackes and slates, the most common rocks of the district, and the rocks which have been produced from them by metamorphism.

The graywackes and slates consist chiefly of readily distinguishable fragmental quartz and feldspar grains, which are embedded in a matrix consisting of fine-grained quartz, feldspar (?), biotite, muscovite, chlorite, some siderite, epidote, small quantities of magnetite, hematite, and iron pyrites, and a dark clayey mass. This mass appears to contain a considerable amount of black carbonaceous material and reddish-brown ferruginous matter in finely disseminated specks. The greater the quantity and finer the character of this matrix the more difficult it becomes to determine its constituents with any degree of certainty. In the slates the matrix plays the chief role, while in the graywackes the large fragmental grains form the predominant material. By a diminution in quantity of the matrix and fragmental feldspar grains, the coarser-grained elastics approach very closely to true quartzites, but in no case was a pure quartzite found.

The constituents which can be recognized without difficulty as original ones are the larger grains of feldspar and quartz. These show pressure phenomena of all grades, from slight, wavy extinction to complete granulation. Many of the large fragmental quartzes are mashed into oval-shaped areas or are broken into

numbers of fragments. The large feldspars are broken, and are altering to quartz and secondary clear feldspar with a simultaneous production of epidote and mica. In their least altered condition the original feldspars are cloudy, and hence may be readily distinguished from the limpid secondary grains.

The small mineral particles of the matrix, including the mica, do not show undulatory extinction like the large fragmental quartzes and feldspars. These micaceous minerals are in automorphic plates, and wrap around the quartz grains, and in some cases likewise project into them. These constituents of the matrix are all believed to be secondary minerals derived from the original clayey matrix, and from the alteration of the feldspar fragments, with the possible addition of infiltrated material. At places all of these minerals occur together, but more commonly one finds various combinations of certain of them. When muscovite is present in large quantity, it is usually not accompanied by biotite or chlorite, the iron and magnesium necessary for the production of biotite and chlorite evidently not having been present. These last two, however, are always associated. As the mica increases, the schistosity of the rock increases in a, corresponding manner, and the rocks become those which may be spoken of as micaceous graywackes.

These micaceous graywackes represent a somewhat more advanced stage of metamorphism of the rocks than the graywackes just described, and the extremely altered varieties of these are very close to the mica-schists and mica-gneisses, according to the respective amounts of secondary feldspar present. No distinction, however, can be made in the field between some of the less metamorphosed graywackes and these micaceous ones. The chief difference appears to be in the fact that in the micaceous graywackes the larger feldspars are almost completely altered and the finer matrix completely recrystallized into readily distinguishable mineral particles. In these more metamorphosed rocks the parallel intergrowth of secondary muscovite and biotite is nicely shown, a thin leaf of biotite being included between two lamellæ of muscovite. A considerable quantity of epidote is scattered in large grains through the micaceous graywackes, besides occurring in aggregates of small grains. Some crystals of apatite and tourmaline were observed. Rutile is found in some quantity, and with it is also sphene, both of them possibly resulting from the alteration of titanium-bearing iron ores in the original graywackes. The iron present in the original graywackes as siderite and the minute specks of oxide have been collected into large crystals of magnetite and also into aggregates of smaller, well-defined magnetite crystals.

The alteration of the feldspar and the production from it of quartz, secondary feldspar, epidote, and mica is well shown in one case. In this the nucleus of original feldspar, in the center, contains minute grains of epidote and flakes of muscovite, besides reddish, presumably ferruginous, specks. These with a low power cause the feldspar to appear cloudy. Surrounding this core is a mottled zone in which secondary feldspar and quartz occur. In one place in this zone a flake of biotite is observed. Some epidote also occurs in it, but no muscovite.

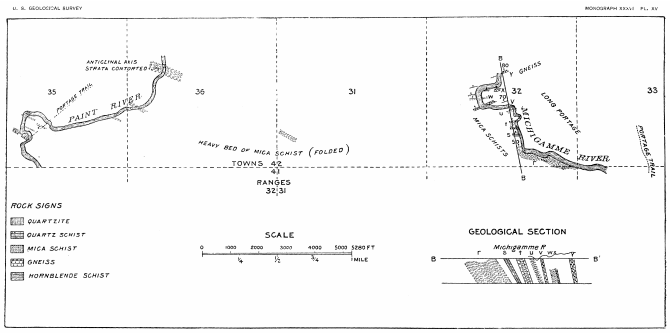
The alteration of the feldspar usually begins at the periphery, and gradually advances toward the center. It thus breaks the original grain up into irregular areas and stringers of feldspar, many of which are attached to the unaltered center. Between these residual areas of feldspar there are irregular grains of secondary limpid feldspar and quartz. The farther the alteration is advanced the less of the irregular center may be seen, and in the final stage the feldspar core disappears.

While the alteration nearly always begins at the periphery, one case was noticed where it apparently began at various places in the grain, the result being the production of a secondary micropoikilitic structure. This original feldspar is cloudy, with the usual alteration products, but scattered through this are a number of more or less roundish spots of quartz, the majority of which extinguish simultaneously, and have a different position of extinction from the including feldspar. Considering these two elements alone, the structure is near the micropegmatitic; but there are other areas which extinguish in different positions from both the quartz and the original feldspar. These are of decidedly more angular shape than the secondary quartzes, and appear to be secondary acid feldspar. The small size of these secondary minerals prevents the use of any physical tests other than the differences in refraction. The rounded quartz appears in many respects very much like the corrosion quartz of the French petrographers. The majority of the secondary feldspars are unstriated, but a few show striations. No satisfactory sections upon which to make measurements were found. Biotite and muscovite flakes are included in the quartz, and smaller automorphic plates of biotite may be seen lying partly within the altered feldspar grain, as though growing partly at its expense.

These highly metamorphosed micaceous rocks included under the general term “micaceous graywackes” have the interlocking groundmass structure of the schists, but some of the larger grains show clastic forms. No sharp line can be drawn between these metamorphosed sediments on the one hand and the mica-schists and mica-gneisses on the other.

In the mica-schists and mica-gneisses all of the original mineral grains have been completely crushed and recrystallized, and we can find no microscopical criteria which enable us to class them with the sedimentary rocks. Dynamic action in the district had sufficient power and duration to complete locally the metamorphism of the original sedimentaries and produce perfectly crystalline schists, as described by Van Hise in the Penokee and Marquette districts.[1] No rocks corresponding in content of carbon to the carbonaceous slates which occur among the rocks around Crystal Falls and south of that town have been found among these

crystalline schists. These crystalline schists are throughout moderately fine grained, and consist of quartz, feldspar, and mica, with associated epidote, rutile, tourmaline, and iron oxides, and in a few exceptional cases crystals of staurolite and garnet. In some of the rocks quartz and mica are preponderant and feldspar is practically wanting, and we have mica-schists. In others all three essential minerals are present, and we have mica-gneisses. The presence of the feldspar, and to some extent the proportion of the mica and other minerals, depend on the character of the original sediments. Conclusive evidence of the sedimentary origin of these schists is furnished by their occurrence in the field, where are found all gradations between them and rocks of unquestionably sedimentary character.



PORTION OF BROOKS'S PL. IX, VOL. III, WISCONSIN GEOLOGICAL SURVEY, SHOWING DETAILS ON PAINT AND MICHIGAMME RIVERS.

[Plate XV. Portion of Brook's Pl. IX, Vol. III, Wisconsin Geological Survey]

In Pl. XV there is reproduced the part of Brooks's Pl. IX in Vol. Ill of the Geological Survey of Wisconsin which comes within the Crystal Falls district and includes a part of the area underlain by the Huronian sediments. There is here given his macroscopical description[2] of the rocks collected in his study of the area.

Brooks's macroscopical description of rocks collected in the Crystal Falls district.

No. of bed.		Thickness in feet.
r.	*Mica-schist*, alternating with *gneiss*, generally flaggy or schistose (2452) ..... About 1¾ miles west and a little north is an outcrop of *mica-schist* containing staurolite (2160). The same rock crosses the Paint 1 mile farther west and north, where it also contains staurolite. This is important and interesting, since this mineral characterizes the same bed of mica-schist (XIX) in the Marquette region, where it is associated with andalusite. Neither mineral has been observed elsewhere in the series.	1,250

Brooks's macroscopical description of rocks, etc.—Continued.

No. of bed.		Thickness in feet.
s.	*Hornblende-schist* or *gneiss*, black, slaty, banded with gneissic layers (2453)	100
t.	*Gneiss* and *mica-schist*	300
	Covered	150
u.	*Staurolitic mica-schist* on south, overlaid with *mica-schist* and *gneiss* (2455)	400
	Covered	150
v.	*Gneiss*	100
w.	*Mica-schist*	100
x.	*Micaceous quartz-schist* or *gneiss* (2381, 2457)	250
	Covered	500
y.	*Gneiss*	150

[1]Mon. U. S. Geol. Survey, Vol. XIX, cit., pp. 332-343; Mon. U. S. Geol. Survey. Vol. XXVIII, cit., pp. 449-450.

[2]Geology of the Menominee iron region, by T. B. Brooks: Geol. of Wis., Vol. III. 1880, Pt. VII, p. 496.

He then mentions the occurrence farther up the Michigamme River of exposures of "a heavy bed of *gneiss*, clipping north at a high angle," and also speaks of "outcrops along the river of hornblendic and other rocks, often *granitic* in appearance." He writes also of "chloritic and hornblende schists exposed for a thickness of over 1,000 feet" at the Norway portage, farther up the river. "They dip south at a high angle under the granite hornblende belt just described, and are probably the equivalents of some portion of the Long Portage series on the opposite side of this synclinal, although these differ from the prevailing rocks of that series in being decidedly more chloritic and hornblendic.[1]

It is seen from the above quotations that the general characters of the rocks were recognized by Brooks. His schists are for the most part the metamorphosed sediments, and the hornblendic and granitic rocks are the various basic and acid rocks which intrude them.

Specimens from these interesting beds were collected by the Michigan and Wisconsin surveys, and were described by Julien, Wichmann, and Wright in lithological reports appended to the reports of those surveys.[2]

[1]Geology of Menominee iron region, by T. B. Brooks: Geol. of Wis., Vol. Ill, 1880, Pt. VII, p. 497.

[2]Microscopical observations on the iron-bearing rocks from the region south of Lake Superior, by Arthur Wichmann: Chapter V of Brooks's Geology of the Menominee iron region, Geol. Survey of Wis., Vol. Ill, 1880, pp. 600-656.

Lithology, by A. A. Julien: Geol. of Mich., Vol. II, 1873, pp. 1-197. Appendix A.

Geology of the Menominee iron region, by C. E. Wright: Geol. Survey of Wis., 1880, part 8, pp. 690-717.

Specimens of these mica-schists and chlorite-schists were regarded by Wichmann as nonfragmental.[1] This is little to be wondered at, since he had never studied their field relations. In the field these rocks can, however, be traced into rocks of unquestionably fragmental origin. The same specimens were described as "micaceous quartz-schists" by Wright.[2] Wright also mentions a staurolitiferous mica-schist in the Michigamme River, and also in the Paint River. The second occurrence is 2½ miles northwest from the first and in the direction of its strike. Julien describes metamorphic rocks from Long Portage as "fine-grained grayish black gneisses."[3] From these descriptions it is seen that the least altered sedimentaries on the one hand and the crystalline schists on the other were recognized by these earliest students of the metamorphic rocks. However, the fact to which I would especially call attention, that the crystalline schists are derived from the clastic rocks by metamorphism, was evidently not understood.

The contact action produced by igneous intrusions into these series of sedimentaries will be discussed in connection with the intrusive rocks (p. 194 et seq.).

IGNEOUS ROCKS.

The igneous rocks which are found to have penetrated the Upper Huronian after the important folding of the rocks took place are not included here, but may be found described under the heading "Intrusives" (p. 187). In this place it is desired to call attention to certain hornblende-gneisses which occur near Norway carry, on the Michigamme River, and also extend in large outcrops west of the river for about 2 miles and east for about a mile. These are interlaminated in thick masses with the mica-schists. They are perfectly crystalline hornblende-gneisses. They consist of common hornblende, quartz, feldspar, and some iron oxide. The hornblende is present in large quantity, the parallel plates of that mineral giving the rock its schistosity. None of the minerals are automorphic, but all occur in interlocking grains. Without going into a detail description of these rocks, it will suffice perhaps to state that they are similar in all respects to hornblende-gneisses which in other parts of the Lake Superior region have been traced into igneous rocks.[4] These gneisses are believed to be igneous rocks, either intrusives which were injected parallel to the bedding of the Upper Huronian sediments prior to the folding, or contemporaneous volcanics. They have been metamorphosed and rendered schistose by the same forces which metamorphosed the sediments. This explains the perfect agreement of their schistosity with that of the adjacent sediments.

[1]Op. cit., pp. 635, 646.

[2]Op. cit., p. 693.

[3]Op. cit., p. 130.

[4]Bull. U. S. Geol. Survey No. 62, by G. H. Williams, 1890; Mon. U. S. Geol. Survey, Vol. XXVIII, pp. 152-159, 203, 208.

ORE DEPOSITS.

HISTORY OF OPENING OF THE DISTRICT.

For a number of years after the opening of the mines of the Menominee range, prospectors worked in various places, among others in the vicinity of Crystal Falls, seeking to follow the iron range west of the Menominee River. As a result of this endeavor, the deposits at Florence, Wisconsin, and then those farther north and west at Crystal Falls, Michigan, were in turn located. It was not until 1881 that sufficient exploratory work had been done at Crystal Falls to warrant a belief in the future of this iron-bearing area. In April, 1882, the Chicago and Northwestern Railway completed its branch to Crystal Falls, and the shipment of ore began. The Amasa deposits were not exploited to any great extent until the year 1888, when the Chicago and Northwestern Railway built a branch from Crystal Falls to Amasa. The Chicago, Milwaukee and St. Paul Railway, in 1893, completed a line from Channing to Sidnaw, which runs through Amasa.

DISTRIBUTION.

The iron-bearing rocks trend northwest and southeast from Crystal Falls. East of Crystal Falls some of the ore deposits are found in proximity to the Hemlock volcanics, and follow along a line located a short distance from them. Other deposits are those at Amasa, about 12 miles northwest of Crystal Falls. These are near the contact between the Upper Huronian and Lower Huronian, and above the Hemlock volcanics, like the deposits east of Crystal Falls. Four miles north of Amasa are the explorations in sec. 20, T. 45 N., R. 33 W., in which the iron-bearing beds are exposed. Another exposure of the iron-bearing formation is in sec. 34, T. 46 N., R. 33 W., about 4 miles still farther north.

These are the northernmost known exposures of the iron-bearing rocks of the Upper Huronian in the Crystal Falls district. However, dial-compass and dip-needle work has located a line of magnetic attraction for about 12 miles to the north and east. By means of this line of magnetic attraction, with the assistance afforded by occasional outcrops of Lower Huronian, Hemlock volcanics, the possible continuation of the iron-bearing belt was approximately located.

I shall take up the four localities mentioned in which an iron-bearing formation has been found, and discuss them in some detail, beginning at the northern and least important and passing to the southern and most important part of the district.

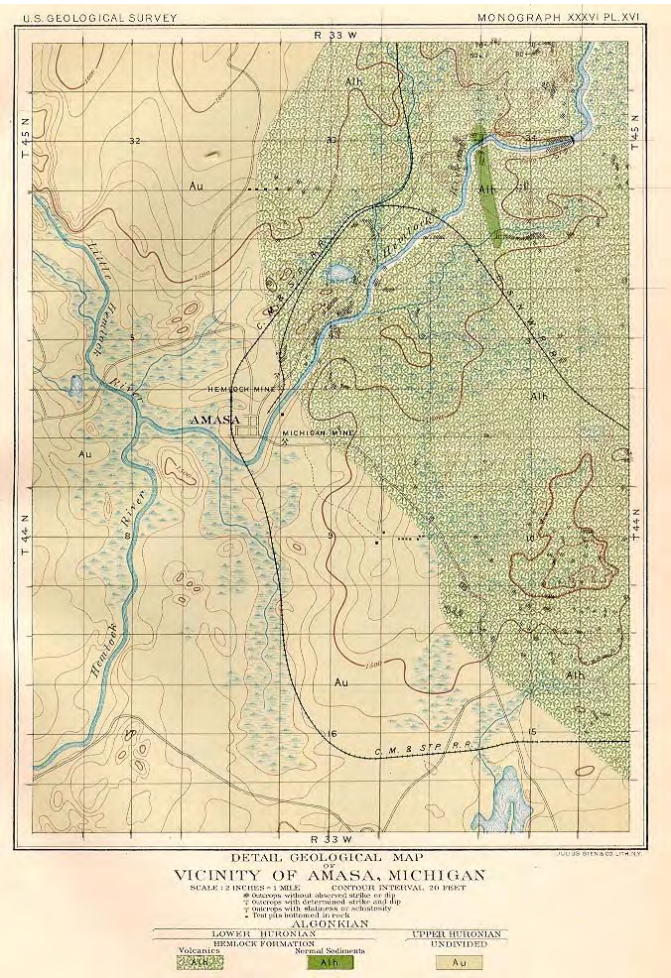
WESTERN HALF OF SEC. 34, T. 46 N., R. 33 W.

In the western half of sec. 34, T. 46 N., R. 33 W., there are outcrops of a magnetic graywacke which grades into a rock that might properly be called a magnetite-schist but for the fact that its partial fragmental nature is still apparent. The rock contains a varying quantity of magnetite, always enough to exercise great influence over the magnetic needle. However, in no case have true ore deposits been found in it, although the vicinity has been extensively test pitted. The strike is in general north and south, with a high dip to the west, thus agreeing in general character with the trend of the Hemlock volcanics. The highest outcrop of the volcanics is a schistose amygdaloid. After an interval of no exposure of about 30 feet, graywacke appears, and this grades up into the magnetitic beds.

SEC. 20, T. 45 N., R. 33 W.

To the south, in sec. 20, T. 45 N., R. 33 W., are outcrops of ferruginous chert, which in places contains "bands and shots" of ore, the thicker bands being an inch and a half across. These outcrops have tempted prospectors to do considerable exploring by means of both test pits and diamond-drill holes. The results have been negative. The general map, Pl. III, shows that the Upper Huronian at this place indents the Lower Huronian series, indicating, as has already been said, the presence of a westward-pitching syncline. The presence of this syncline is further shown by the strike obtained on the outcrops of chert found at this locality. For the most

part, a nearly north-south strike prevails. The greater part of the northern ledges give an east-west strike, with a variation of but a few degrees to the north of east. The southernmost outcrops show a strike which varies from N. 27° E. to N. 34° W. The dip is in all cases high, ranging from 80° to 87°. The severe deformation is clearly shown by the plication of the beds, and by faults whose extent can not be determined, but which are accompanied by rather extensive reibungsbreccias. The breccias are cemented by iron oxide.



[Plate XVI. Detail geological map of the vicinity of Amasa, Michigan]

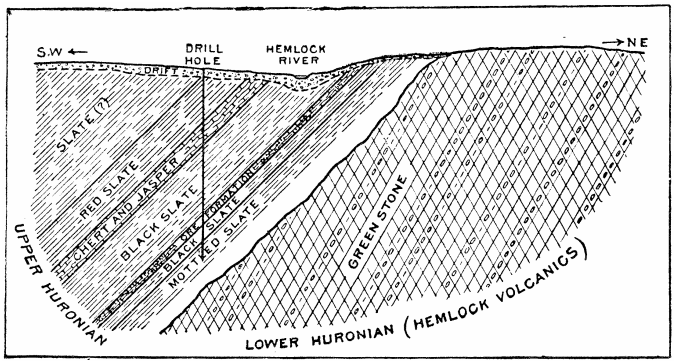


FIG. 11.—Profile section illustrating results of diamond-drill work.

THE AMASA AREA.

The Amasa deposits must of necessity be very briefly described, as I have been unable to obtain much information concerning the relations of the rocks as shown in the closed mine. In the early days of the mine it was thought by the mine captain that the volcanics formed the foot wall of the ore, and on his authority Van Hise says, "The ore of the Hemlock mine rests upon a stratum consisting of surface volcanic material."[1]

Probably this is a mistake, for the section from west to east (fig. 11), i. e., from the higher to the lower beds, obtained in two drill holes, is as follows:

	Feet.
Gray sericitic slate, discolored by iron	115
Chert and jasper	59
Pyritiferous black slate and quartzite	180
Ore formation	30½
Magnetitic slate	42
Mottled slates, red and green, containing iron. Drilling ceased after passing through	70

The thickness of the beds given is the true one and not the thickness passed through by the drill, which cut through the beds at an angle. These beds projected to the surface are found to be immediately underlain by greenstone, in some places massive, in others tufaceous. Moreover, an identical section is shown by a drill hole 4 miles southeast of Amasa, in sec. 26, T. 44 N., R. 33 W. It was carried deeper, however, and after passing through the mottled slate was bottomed in greenstone. From these drill holes it appears certain that the ore formation is immediately underlain and overlain by black slates. The foot and hanging slates are much alike, the hanging, however, being very pyritiferous, and the foot containing much more iron than the hanging. This iron is in the form of hematite and magnetite. Below the black magnetic slate is the ferruginous mottled slate, which apparently lies next to the Lower Huronian Hemlock volcanics. The so-called ore formation consists of banded chert and jasper, with which the hematite bodies are associated.

[1]The iron ores of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., vol. 43, 1892, p. 130.

The results obtained from these holes show the lenticular character of the ore bodies and the difficulty in finding them. One of the holes passed through the ore formation, but missed the ore body, which subsequent underground work showed it would have struck had it cut the formation 50 feet farther north.

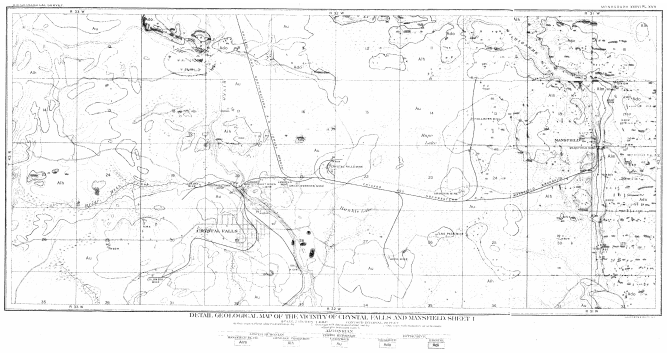
The distribution of the Huronian rocks in the vicinity of Amasa is shown on the map, PI. XVI.

THE CRYSTAL FALLS AREA.

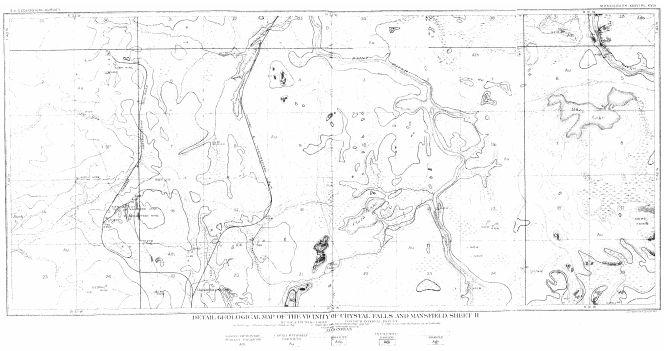
The most of the observations upon the ore bodies and their relations to surrounding beds have naturally been made in the vicinity of the town of Crystal Falls, where, owing to the extensive development of the mines, the underground conditions could best be studied. The conclusions reached, however, are confidently believed to hold good for the entire Upper Huronian of the district.

In the description of the folding of the Upper Huronian it was stated that the Crystal Falls area is in a synclinorium

forking as the result of a subordinate central anticline so as to produce a U opening to the south of west. It is in this basin that the important mines of the Crystal Falls district are situated. One row of mines—the Hollister, Armenia, Lee Peck, and Hope—as shown by the map (Pl. XVII), lies to the west and northwest of the main mass of Hemlock volcanics between Crystal Falls and Mansfield. A second and more important set of mines follows an east-west line south of the subordinate area of volcanics, which lie just north of Crystal Falls in the midst of the Upper Huronian sediments. The second set of mines, including the Crystal Falls, Great Western, Lincoln, Paint River, Lamont, Youngstown, and Claire, lies near the axis of the syncline—that is, along the line of major folding, and consequently greatest mashing. The Columbia, Dunn, Mastodon, and others to the west (Pl. XVIII), are probably the western continuation of this line of mines, and follow the trend of the main synclinal axis of the district. The position of these mines with reference to the main structural features of the district can be seen on the relief map and the sketch map corresponding to it, Pl. XIV.



[Plate XVII. Detailed geological map of the vicinity of Crystal Falls and Mansfield, Sheet I]



[Plate XVIII. Detailed geological map of the vicinity of Crystal Falls and Mansfield, Sheet II]

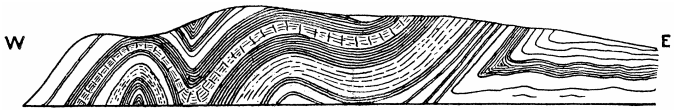


FIG. 12.—Sketch illustrating contortion of Upper Huronian strata.

The section made through the closely folded Upper Huronian beds by the Paint River affords the best opportunity in the district for studying the rocks, but the rocks are so crumpled that even here the succession was not made out with certainty.

The sketch fig. 12, by W. N. Merriam,[1] shows the folding of the slate and chert strata as seen in the railroad cut between the Paint River and the Lincoln mine. The strike of the rocks is about N. 80° E. The sketch is taken looking almost along the strike of the beds. In fig. 13 a second sketch is given, also by W. N. Merriam, which illustrates the rapid change in strike in these beds, due to the contortion of the strata. This change is seen near the east end of the wagon bridge just across the Paint River from Crystal Falls. At this point the beds bend from a strike of S. 40° E. to W. 10° S. The change takes place by means of three very sharp bends.

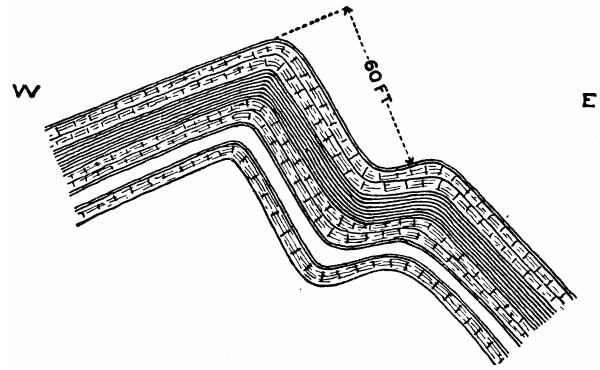


FIG. 13.—Sketch showing change of strike of Upper Huronian beds due to the folds.

The following are the observations made by Rominger upon these exposures near Crystal Falls:

Among the recently discovered productive fields for iron mining, the vicinity of Crystal Falls has become famous for its wealth in ore. The formation enclosing the ore deposits, has there a great thickness, but its determination by actual measurement is impossible, on account of the much folded condition of the strata, and for want of connected exposures transverse to the stratification. Estimating its thickness to several thousand feet is surely not far beyond the truth. This folded condition of the strata is in many instances an obstacle in the decision, whether in a. given locality we have under observation a descending or an ascending succession of beds.

[1]Manuscript notes.

If we follow the railroad from Crystal Falls village upward along the bed of Paint River, we find, in the first cut the road makes into rock beds, a series of hard, black slates, transversely intersected in almost vertical positions, and, according to their cleavage planes, dipping in southwest direction. This cross cut is 210 steps long; thence, for the distance of 100 steps, no rock ledges are touched by the roadbed, but on the left side of the road similar slate rocks are denuded, which apparently represent a continuation of the former succession. From here for eighty steps a cut is made through similar slate rocks, but interlaminated with numerous quartzite seams; further on, the intersection of slates in alternation with quartz seams continues for quite a while, but these slate rocks are more graphitic than the former and readily disintegrate, on exposure, into splintery fragments, as they contain a large proportion of iron pyrites and rusty ferruginous seams causing the decay. By this time we have reached close to the river below its falls, and find, laid open in its embankments formed by the bluffs

thirty feet high, a further conformable series of graphite-schists, 300 feet wide. Beneath the graphite-schists, close to the water level at the foot of the falls, succeeds an ore belt six feet wide at the surface, but widening to fifteen feet, followed into the hillside.[1]

Below the ore belt follows an immensely large succession of thinly laminated banded ferruginous quartz-schists of dark, rusty color, which beds, in steeply erected position crossing the river bed diagonally, give a cause to falls eight or ten feet in height. The exposed succession of beds amounts at the falls to a thickness of over 800 feet. Intermixture of pyritous shaly seams with the quartzite beds, induces their rapid disintegration on exposure, into shelly fragments covered with an iridescent varnish like coating of oxide-hydrate. These beds are, in the embankments on the opposite river side, remarkably corrugated, describing in their flections perfect coils.[2]

[1]Iron and copper regions of the Upper and Lower Peninsulas of Michigan, by C. Rominger: Geol. of Mich., Vol. V, 1895, Pt. 1, p. 74.

[2]Ibid., p.75.

CHARACTER OF THE ORE.

The ore obtained from the Crystal Falls district is chiefly soft red hematite, though in places it is hydrated and graded as brown hematite (limonite). The ore is very porous and shows many crystal-lined cavities. At places a hard steel hematite ore is found, which runs as high as 70 per cent metallic iron. This ore occurs in very small quantities associated with the soft ores, and appears for the most part to have formed in geodal cavities. When the cavities are still partly open, the ore has botryoidal and stalactitic forms. The ores are very similar to the ores of the Michigamme slates of the Upper Marquette series, but differ very considerably from those of the Lower Marquette series, in which the hard hematites and magnetites are important ores, and from the ores of the Menominee district, which produces large quantities of soft blue hematite, some martite, and also some specular ore.

The following figures show the average composition of the ores for the district. They were taken from analyses furnished by the management of the various mines and from the reports of the State commissioner of mineral statistics of Michigan.

The metallic iron of the ores ranges from 54 to 63 per cent, the average being about 59 per cent. Phosphorus in exceptional cases is as low as 0.05 per cent, though usually ranging from 0.1 to 0.7 per cent, most commonly approaching the higher figure. Silica averages about 3 per cent. These analyses show the ore to be rather low grade.[1] It is due to this that this district has been so sensitive to the prices of iron ores. A low market price makes the cost of production exceed the selling value, and under these conditions work necessarily stops.

Some of the ores in the Crystal Falls district contain a very high percentage of Al_2O_3, CaO, and also of manganese. It is reported that some very good deposits of manganese have been found, one unauthenticated statement beings to the effect that an analysis of the ore runs as follows: Metallic iron, 17.46; manganese, 29.81; phosphorus, 0.064; silica, 0.009(?).

[1]Brooks states that "the ores are unlike those in the more easterly part of the Menominee region in being richer in iron, freer from silica, and in containing more water." (Analysis 68, p. 302.) Geology of Michigan, Vol. I, part 1, p. 182.

Since the above was written the volume on Mineral Resources of the United States, 1896, Part V, of the Eighteenth Annual Report of the United States Geological Survey, has appeared, and the following analyses of ores from the Crystal Falls district are taken from Mr. John Birkinbine's article on iron ores in that report.

The analyses were prepared for the ore association at Cleveland, Ohio, and show the average cargo analyses of iron ore as shipped from the various mines. The analyses were made from ores dried at 212°, the amount of natural moisture being added.

	Iron.	Silica.	Phosphorus.	Manganese.	Alumina.	Lime.	Magnesia.	Sulphur.	Organic and volatile matter.	Moisture.
Crystal Falls	58.55	4.25	.721	.20	1.16	2.64	.77	.008	2.92	7.20
Dunn	58.61	3.88	.573	.58	1.88	1.80	.83	.033	5.44	8.70
Hemlock.....	60.20	4.71	.309	.39	2.81	1.87	1.32	.010	.....	6.62
Lincoln	60.86	3.86	.240	.45	1.67	2.14	1.73	.010	.....	6.50
Mastodon.....	61.00	4.50	.350	.30	2.75	.50	.30	.075	.....	9.00

One of the best results gives as high as 61.5 per cent metallic Mn. The ores thus range from a manganiferous iron ore to a manganese ore. The further statement is made that the bed lies very close to the surface, and is from 6 inches to 3 feet in thickness. From 4 to 6 feet of bog iron is found underlying the bed of manganese.

RELATIONS TO ADJACENT ROCKS.

The ore is associated with white or reddish chert, which in places is jaspery. The cherty iron formation passes into ore by a decrease of the silica. An intermediate phase is chert with "bands and shots" of ore. In places the chert is more or less brecciated, and the ore often has a similar character. Commonly the ore is completely surrounded by the chert beds, or chert and ore, forming the so-called mixed and lean ore. In such cases they form both the foot and hanging walls of the ore body. But the ore-bearing chert formation is always associated with black carbonaceous slates, which constitute the base on which the ore-bearing formation rests. In the Youngstown mine 3 feet of so-called "graphite" was passed through before the usual carbonaceous slates were reached.[1] The hanging wall is also carbonaceous slate. At places thin quartzitic beds which approach a true quartzite are associated with the slate.

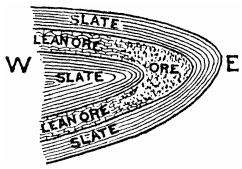


FIG. 14.—Sketch to illustrate the occurrence of ore bodies.

The ores occur in the cherts in pockets and lenticular masses, which always agree in greater dimensions with the strike of the beds with which they are associated. The lenticular character is well shown in the Dunn, Columbia, and Great Western mines. In the Dunn mine the bodies overlap. In the Great Western mine in 1887 seven different ore bodies in an east-west line, separated by areas of barren rock, mostly slate, were being mined. In following these isolated ore bodies to

the east, at various places they are found to turn around a horse of rock. Their occurrence is illustrated by the horizontal section, fig. 14. Evidently the ore bodies accumulated in westward-pitching synclinal troughs, in which the hanging wall appears to the miners as a horse of rock.

[1]This information was furnished by Mr. C. T. Roberts, of Crystal Falls. It was not possible to obtain a specimen of the graphite for examination.

The ore bodies in general pitch to the west at varying angles corresponding to the pitches of the axes of the synclines in which they occur. The pitches of these folds in turn correspond to the westward pitch of the Crystal Falls synclinorium, of which the secondary synclines containing the ore bodies are a part. A typical example of the occurrence is shown in the Armenia mine ore body, which is found, according to Van Hise, "at the bottom and on the sides of a synclinal trough, pitching at an angle of about 45°."[1] The trend of the axis is to the south and west.

The dip of the ore bodies is always steep, and generally to the south, but varies in places to a few degrees north.

ORIGIN.

The fact that the important mines in the district are located in a synclinal basin and that they all possess an impervious footwall of black slate gives very clearly the reason for their existence and indicates their mode of origin. They are concentrates in synclinal troughs.

In the Marquette and Penokee-Gogebic districts the ore bodies are frequently found associated with dikes of dolerite (diabase), which have been altered to "diorite"-schists, and so-called soapstone or paint rock.[2] Only one such association is known for the Crystal Falls district. Wadsworth mentions having seen a dike in the Paint River mine.[3]

In the field notes of the Lake Superior survey for 1891, I find the statement made that "the strata of the ore formation, which here strikes nearly east and west, is cut by an eruptive dike which runs about northwest and southeast. This dike hades to the west, and forms with the hanging slates of the ore formation a trough pitching to the west at a very steep angle. In this trough is situated the ore body upon which the Paint River and the Monitor[4] mines are working." This ore body is stated to be about 100 feet wide, 300 feet long, and of unknown depth. When I was in the district, the mines were closed, or only shipping from stock piles, so that I had no opportunity of verifying this observation. From this statement it appears that in this particular case the ore is due to the presence of this dike, as it occurs in a pitching trough, formed by its junction with the impervious slate. These same relations are well known to be the cause of similar occurrences in the Lake Superior districts above mentioned.

[1]Iron ores of the Marquette district of Michigan, by C. R. Van Hise: Am. Jour. Sci., 3d series, Vol. XLIII, 1892, pp. 130.

[2]Merriam also mentions in his notes a dolerite dike found cutting the ferruginous rocks at the Glidden exploration. In this case it does not appear that an ore body was formed.

[3]Sketch of the geology of the iron, gold, and copper districts of Michigan, by M. E. Wadsworth: Rept. State Board of Geol. Survey for 1891-92, 1893, p. 108.

[4]Now known as Lamont mine.

The original rock from which the ores were formed was cherty iron carbonate, which in many places is found associated with the iron-bearing formation. The cherty carbonate shows the various stages of alteration from the compact cherty siderite to the banded ore and chert rocks which form the nuclei for the addition of the iron obtained from the higher extensions of the beds. Percolating waters have been the agents in this process of replacement and concentration. Consequently where the rocks have been most shattered, we find the water was especially active. Hence it is, also, that we find the deposits in this closely folded part of the Upper Huronian.

As to the origin of the cherty carbonate itself, we know nothing definite. Its association with the carbonaceous slates would indicate the agency of organic matter in its production, possibly in some such manner as is rather generally accepted for the formation of the Carboniferous carbonate ores. The Upper Huronian ores, as well as the Lower Huronian, are supposed to have been formed in this same way, and from the same kind of rock. Under the discussion of the Lower Huronian ores (p. 70) these points were discussed more in detail, and references given to the literature, and the reader is referred to that discussion for further details.

SIZE OF THE ORE BODIES.

No definite general statement can be made as to the size of the ore bodies, as this varies considerably. None of the bodies which are being worked, so far as I can learn, are less than 80 feet wide. In one of the old mines crosscuts disclosed a width of nearly 200 feet. This same ore body is reported to be at least one-fourth of a mile long.

METHODS OF MINING.

The first development of the iron ores of this district was by the stripping and open-cut method, very few resorting at once to under-ground work. Nearly two-thirds of the product of certain of the mines has been from open-pit work. When the open pits become too deep to be readily worked as such, shafts are sunk and the exploiting of the ore body is carried on under ground, at times both open-pit and under-ground work being carried on simultaneously. The Mastodon presented the unusual sight of an open pit extending down 200 feet, part of the workings still being roofed over by an enormous arch of rock. All work in the district is at present under ground.[1] As a rule, the under-ground work has not, thus far, been carried to very great depth, the two deepest mines being the Great Western and the Dunn, which are down, respectively, 700 and 720 feet. The others are down to depths varying from 100 to 450

feet, the lowest figures being, as a rule, for the youngest mines, the more important ones having nearly reached the 400-foot level or passed beyond it.

In the early mining days of the district an extensive system of timbering was resorted to, but gradually, as the cost of timber increased and this item became burdensome, careful attention was paid to this point, and, where practicable, the system of caving or the system of filling was introduced (Mastodon). At the present time most, if not all, of the important producers are mined with open stopes, pillars being left only when necessary. From this it would appear that the rocks had not been much broken, but it should be borne in mind that the ore deposits themselves are later than the folding, and in the process of their formation many of the cracks in the surrounding beds could have been filled with ore or other material and the rocks thus quite rigidly united again. That cementation has taken place is evident from an examination of almost any hand specimen or slide, where one may see veins of infiltrated quartz traversing them at various angles. The extremely wet character of the Great Western would seem to indicate that locally the rocks may still be very much fissured.

PROSPECTING.

Owing to the impossibility, with our present knowledge, of mapping the various beds of the Upper Huronian, it is not possible to give any directions with reference to the exact lines which should be followed in searching for ore. However, since the areas which are underlain by igneous rocks have been delimited, there is no longer any excuse for wasting time and money in prospecting in these unpromising portions of the district. Where indications point to considerable rock movements, and where the sideritic rocks are found associated with impervious slates, explorations are warranted.

[1]This was written in 1896. Since then a large part of the Mansfield ore body has been stripped, and this may be worked at present by open-cut methods.

PRODUCTION OF ORE FROM THE CRYSTAL FALLS AREA.

In the following table the first column contains the names of the mines or combinations of mines of the Crystal Falls area. These are arranged alphabetically for ease of reference, and not according to date of opening or amount of ore produced, as is so usually the case. In one case, that of the Claire mine, the mine was operated by the company operating the Youngstown, and its output accredited to that mine until 1891, when the two mines were separated. Following the name under which a mine is known at present, there is given in parentheses in chronological order the name or names by which the mines were formerly known. The second column gives the location of the mine. Following these data there are arranged in columns the yearly shipments from the time of the first opening to the closing of the mines, or to January 1, 1899. In many cases the ore body had been definitely located and considerable work done and ore accumulated upon stock piles several years before the first shipments were made, but it would be impossible to give the exact date of the opening of the mine unless we considered the year of first shipment as such. In a column following the yearly shipment the total shipment for each mine is given. This is followed by a column giving the year in which the maximum shipment was made, and by another giving the amount of this shipment. In the horizontal column at the foot of the page may be found the total shipments for each year and the total product of the district since its first exploitation. The figures for the district have been obtained either by correspondence with the mining companies or from the annual reports of the commissioner of mineral statistics of Michigan. Acknowledgments are due to certain of the companies which have, through their managers, been very obliging in furnishing information concerning the mines they operated.

From a comparison of the total shipment of the area for 1898 with the total shipment of the Menominee range 2,522,265 long tons and of the entire Lake Superior region 14,024,673 long tons for the year, it will be seen that the Crystal Falls area furnished 13 per cent of the total iron-ore shipment of the range and 2⅓ per cent of the region.[1]

[1]Total shipments for 1898 were obtained through Mr. John Birkinbine from the Iron Trade Review.

IRON-ORE SHIPMENTS OF THE WESTERN HALF OF THE CRYSTAL FALLS DISTRICT, GIVEN IN TONS OF 2,240 POUNDS.

Name of mine.	Location.	Operated by—	1882	1883	1884	1885	1886	1887	1888	1889
Armenia (Smith)	E. ½ SE. ¼ sec. 23, T. 43 N., R. 33 W.									47,775
Claire*	NE. ¼ SE. ¼ sec. 19, T. 43 N., R. 32 W.	Claire Mining Co								
Columbia (1. Union; 2. Sheldon & Schafer)	NW. ¼ NW. ¼ sec. 31, T. 43 N., R. 32 W.	Huron Iron Co.	15,940	4,334	6,774		14,282	2,337	10,936	11,385
Crystal Falls	Lot 3, sec. 20, T. 43 N., R. 32 W.		1,341							
Crystal Falls	SE. ¼ NE. ¼ sec. 21, T. 43 N., R. 32 W.	Corrigan, McKinney & Co.								
Delphic	NE. ¼ SW. ¼ sec. 24, T. 42 N., R. 33 W.			3,410	508	9,843	17,684	1,801		
Dunn	NW. ¼ NE. ¼ sec. 1, T. 42 N., R. 33 W.	Dunn Iron Mining Co						25,470	118,091	151,828
Great Western (Iron Star)	NE. ¼ SW. ¼ sec. 21, T. 43 N., R. 32 W.	Iron Star Co	587	22,825	20,722		25,725	23,240	21,861	38,451
Hemlock	NW. ¼ SW. ¼ sec. 4, T. 44 N., R. 33 W.	Pickands, Mather & Co.								
Hollister	NW. ¼ SW. ¼ sec. 13, T. 43 N., R. 32 W.									
Hope (1. Blaney; 2. Wauneta)	NE. ¼ SE. ¼ sec. 27, T. 43 N., R. 32 W.									
Lamont (Monitor)	Lot 6, NW. ¼ SE. ¼ sec. 20, T. 43 N., R. 32 W.	Lamont Iron Co							2,690	21,620
Lee Peck	W. ½ NE. ¼ sec. 26, T. 43 N., R. 32 W.									
Lincoln (Fairbanks)	W. ½ SW. ¼ sec. 21, T. 43 N., R. 32 W.	Lincoln Mining Co	8,131	453						
Manhattan (South Mastodon)	NE. ¼ SE. ¼ sec. 13, T. 42 N., R. 33 W.								2,722	4,006
Mansfield (Caledonia)†	NW. ¼ NW. ¼ sec. 29, T. 43 N., R. 31 W.	De Soto Mining Co								
Mastodon	SE. ¼ NE. ¼ sec. 13, T. 42 N., R. 33 W.	Mastodon Iron Co	3,477	18,577	18,020	11,737	41,640	49,115	51,293	63,086
Michigan	NE. ¼ NW. ¼ sec. 9, T. 44 N., R. 33 W.	Michigan Exploring Co								
Paint River	NE. ¼ SE. ¼ sec. 29, T. 43 N., R. 32 W.	Paint River Iron Co	6,615	5,972	11,652	2,378	13,933	10,240	12,566	32,760
Youngstown	NW. ¼ SW. ¼ sec. 20, T. 43 N., R. 32 W.	Illinois Steel Co	6,198	15,292	8,343		25,616	34,418	12,700	7,471
Total			42,189	70,864	66,019	23,953	138,902	146,621	232,799	378,322

Name of mine.	1890	1891	1892	1893	1894	1895	1896	1897	1898	Total shipment of individual mines and of district to date.	Year of maximum shipment.	Amount of shipment.	Name of mine.
Armenia (Smith)	26,649					2,045				76,469	1889	47,775	Armenia (Smith).
Claire*		55,000	57,351	9,612						121,963	1892	57,351	Claire.*
Columbia (1. Union; 2. Sheldon & Schafer)	60,133	70,770	57,682	22,426	10,300	70,867	87,202	24,623	14,199	484,190	1896	87,202	Columbia (1. Union; 2. Sheldon & Schafer).
Crystal Falls										1,341	1882	1,341	Crystal Falls.
Crystal Falls	3,975					14,387	44,526	95,210	128,233	286,331	1898	128,233	Crystal Falls.
Delphic										33,246	1886	17,684	Delphic.
Dunn	156,053	162,721	133,045	58,261		90,896	47,081	31,062	49,381	1,025,670	1891	162,721	Dunn.
Great Western (Iron Star)	71,719	62,464	87,487	661						375,742	1892	87,487	Great Western (Iron Star).
Hemlock		35,531	63,459	11,523		1,046	95,767	96,052	60,865	373,623	1897	96,052	Hemlock.
Hollister	2,020	1,057	1,021							4,098	1890	2,020	Hollister.
Hope (1. Blaney; 2. Wauneta)			15,543	2,275						17,818	1892	15,543	Hope (1. Blaney; 2. Wauneta).
Lamont (Monitor)	31,139	26,226	42,819	13,777	2,600					140,871	1892	42,819	Lamont (Monitor).
Lee Peck			2,844							2,844	1892	2,844	Lee Peck.
Lincoln (Fairbanks)		1,813	26,020	8,757						45,174	1892	26,020	Lincoln (Fairbanks).
Manhattan (South Mastodon)	1,476									8,204	1889	4,006	Manhattan (South Mastodon).
Mansfield (Caledonia)†	18,303	49,836	69,259	69,558				39,012	60,877	306,845	1893	69,558	Mansfield (Caledonia).†
Mastodon	66,559	45,370	9,150	23,485		23,781				425,290	1890	66,559	Mastodon.
Michigan				565		1,071		216		1,852	1895	1,071	Michigan.
Paint River	62,654	45,435	18,390							222,371	1890	62,654	Paint River.
Youngstown	44,460	3,705				13		661		158,899	1890	44,460	Youngstown.
Total	546,040	559,828	586,070	220,640	12,900	134,060	274,576	286,816	322,555	4,096,448			Total.

* Previous to 1891 Claire and Youngstown products were quoted together and credited to Youngstown, though they were about equally divided.
† Lower Huronian. Only productive Bessemer mine in Crystal Falls area.

MON XXXVI—face p. 186

CHAPTER VI.
THE INTRUSIVES.

Under this general head there is here included an extremely varied assortment of rocks exhibiting in common intrusive relations to sedimentary and igneous rocks. This division is here used merely because it simplifies the classification of the rocks of the district, and the term “intrusives” is not to be interpreted as synonymous with the “dike rocks” (ganggesteine) of some authors, a petrographical division which, in the opinion of the writer, is not warranted.

These intrusive rocks differ very materially in field occurrence, petrographically, and in point of age from the igneous rocks thus far described. In age much younger than the volcanics, they still bear a close resemblance to some of them; indeed, some forms are identical in character. Massive granular rocks are the common forms. Porphyritic varieties are very subordinate.

The rocks are all considered as intrusives into either the Lower or the Upper Huronian. In most cases the

intrusive relations may be said to be rather inferred than demonstrated, for the direct contacts have been observed in very few cases. However, where isolated sets of knobs of eruptive rocks are found in areas, the greater portion of which are underlain by sedimentaries, the natural inference is that they penetrate these sedimentaries. Where isolated sets of knobs are composed of the same kind of rock or show variations of the same type, they may be presumed to be connected. For the most part the dikes and bosses are too small to admit of indication upon the accompanying map. Wherever their size has warranted it, they have been represented, as in the case of the acid intrusives between the Paint and Michigamme rivers, and of the basic intrusives north of Crystal Falls.

ORDER OF TREATMENT.

For the sake of convenience and to avoid repetition, the age of the intrusives as a whole is first determined, and then follows a brief description of the effect of the folding of the district on the distribution of the eruptives.

The rocks described have been divided into those of acid, basic, and ultrabasic composition, and the usual order of discussion from the acid to the basic will be followed. In Section I rocks are described which are geologically disconnected. In Section II is a description of a series of rocks which constitute a geological unit, and are especially interesting from a petrogenetic standpoint. Here also the order of discussion is from the acid to the basic. The geographical distribution of the rock of each division is given, only those outcrops being accurately located which are of very large size or which for other reasons are of special interest from a stratigraphical or a penological standpoint.

After the petrographical description of each of the rocks a statement will be made of its field relation to the adjacent rocks, if its relations have been discovered. This will be followed by a brief account, in those rare cases in which a contact has been observed, of the metamorphic action which it has caused in the sediments through which it was forced.

AGE OF THE INTRUSIVES.

The intrusives have forced their way through the Lower and Upper Huronian sedementaries, but have never been found to penetrate the horizontal Lake Superior (Cambrian) sandstone. These facts alone are conclusive proof that their period of intrusion falls in the time which elapsed between the deposition of the Upper Huronian and that of the Cambrian.

In the discussion of the time of the folding of the Upper Huronian the conclusion was reached that this folding preceded the deposition of the Keweenawan series. If the intrusives to be described had existed at the time of folding, they must certainly have suffered from the orogenic movements. Examination of the exposures of the intrusives has not shown schistose masses, nor has detailed microscopical study disclosed the cataclastic textures which accompany powerful dynamic movements, except in one case, which is described on p. 194, and is presumed to be due to purely local movements. Such being the facts, the conclusion follows that the intrusives were introduced subsequent to the folding of the Upper Huronian, or are of Keweenawan or post-Keweenawan age.

A closer approximation to the age of the intrusives is not possible, unless we rely upon petrographical similarity. The dolerites of the Crystal Falls district are similar to those forming the flows and dikes of the Keweenawan on Keweenaw Point. They are also similar to the basic intrusives of the Marquette district, with which this is practically a geological unit, and likewise they agree petrographically with the dolerite dikes of the Penokee-Gogebic district. In both districts the late intrusives have been considered to be of Keweenawan age.[1] Rominger,[2] in his report for 1881 and 1884, calls attention in a general statement to the possible connection of the doleritic dikes penetrating the Michigan Huronian with the flows and dikes of the “Copper-bearing formation” (Keweenawan).

While correlation by means of petrographical similarity would not hold for widely separated areas, it seems to be well worth considering for areas which are so closely connected as are the iron districts of the Upper Peninsula of Michigan.

Judging from the evidence thus presented, the dolerites of the Crystal Falls area are probably contemporaneous with the intrusions of the Penokee-Gogebic and Marquette districts and with the volcanics of Keweenawan time.

RELATIONS OF FOLDING AND THE DISTRIBUTION OF THE INTRUSIVES.

In the preceding chapter, in the sections on folding of the Upper Huronian, p. 158, it was shown that the main folds of the district follow an approximately northwest-southeast course, and that upon these were superimposed minor folds approximately at right angles to these. The lines of weakness parallel to the axes of the main folds have been taken advantage of by certain of the intrusives, especially the dolerites.

A glance at the general map (Pl. III) shows that the dolerite dikes which have been traced for considerable distances—that is, are more than great knobs uncovered by erosion—have a northwest-southeast trend, in agreement with the general direction of the major folding of the district. The only apparent exception is that part of the great mass in T. 43 N., R. 81 W., which extends north and south along the Michigamme River; but this is really not an exception, since the folds of the Mansfield slates here run in the same direction.

[1] Mon. U. S. Geol. Survey, Vol. XIX, p. 349; Vol. XXVIII, p. 218.

[2] Geol. of Mich., Vol. V, cit., p. 6.

SECTION I.—UNRELATED INTRUSIVES.

CLASSIFICATION.

Under the above heading are included intrusive rocks which occur in such isolated outcrops that no definite relations can be shown to exist between them and other igneous rocks of similar or related characters.

The intrusives described under this heading comprise rocks of acid, basic, and ultrabasic composition, represented respectively by the granites, the dolerites and basalts, and the picrite-porphyries.

ACID INTRUSIVES.

The acid intrusive rocks may be divided into ordinary biotite-granite (granitite) with a micropegmatitic variety, and muscovite-biotite-granite and rhyolite-porphyry.

GEOGRAPHICAL DISTRIBUTION AND EXPOSURES OF GRANITES.

The biotite-granite proper does not occur in the district in large quantity. It is found in dikes penetrating the Upper Huronian rocks in secs. 15 and 22, T. 42 N., R. 31 W., and in dikes, cutting diorite intrusives in the Upper Huronian, in sec. 22, T. 42 N., R. 31 W.

The micropegmatitic variety of the biotite-granite is confined to an area underlain by the Lower Huronian rocks. It occurs at N. 750, W. 740, sec. 17, T. 43 N., R. 31 W., and N. 1750, W. 1580, sec. 29, T. 43 N., R. 31 W., in small quantities in isolated dikes, cutting the dolerites which penetrate the Lower Huronian series.

Owing to their small size, none of the above-mentioned exposures are represented on the maps.

The muscovite-biotite-granite forms large, bold, isolated knobs in secs, 19, 20, 29, and 30, T. 42 N., R, 31 W., between the Paint and Michigamme rivers. These knobs are so closely related petrographically that they are presumed to represent a large boss, and they are therefore represented as a unit on the geological map of the district, Pl. III. Other smaller areas of granite occur and are shown on the detail map, Pl. XVIII.

BIOTITE-GRANITE.

The biotite-granites vary in color from light reddish-brown to dark-gray and greenish rocks, and in grain from fine to coarse. The structure ordinarily is that of a normal granite. In some of them the micropegmatitic intergrowth of quartz and feldspar may be observed in small quantity. In others this forms the characteristic part of the rock, and these rocks may be properly termed micropegmatitic granites. In most of the sections the usual constituents in ordinary proportions occur.

In all the rocks the main mass of the quartz forms irregular grains, molded on the other constituents. Sometimes round areas of quartz are included in the feldspars. The quartz contains very commonly, and usually in great quantities, liquid inclusions with dancing as well as stationary bubbles.

The feldspar is nearly always of two kinds—orthoclase and plagioclase. Microcline was also observed, but in neglectable quantity. These feldspars in the great majority of slides show fairly good rectangular outlines, and in some cases these are strikingly well developed. In some slides the plagioclase is observed in rectangular crystals and the orthoclase is found in large irregular plates which are molded on the plagioclase, showing conclusively their relative age. The plagioclase is finely twinned according to the albite law, and also in some slides exhibits pericline twinning. A case was observed in which two crystals, one showing albite twinning, the other both albite and pericline twinning, were grown together so as to correspond to the Carlsbad twins of orthoclase. The plagioclase gives low extinction angles, which show it to be rather acid. The amount of plagioclase in some of the sections—for example, in those of the numerous small dikes cutting the schists near Norway portage in sec. 15, T. 42 N., R. 31 W., and the one cutting the gabbro at the SE. corner of sec. 22, T. 42 N., R. 31 W.-—is very large, denoting an increase in soda and lime and indicating a relationship to the diorites. The geological relations are not such, however, as to enable this connection to be shown in default of chemical analyses.

The orthoclase is for the most part untwinned, or else shows simple Carlsbad twinning. In some sections the feldspars are quite fresh, but in others they are seen to be opaque, porcelain-like, and in still others the original feldspar material is almost entirely replaced by a mass of muscovite, with some little epidote-zoisite and biotite. The muscovite in these secondary aggregates gives excellent though small rectangular sections, showing its fine cleavage very distinctly. Well-determinable kaolin flakes were not found.

The mica is well represented by both biotite and muscovite. Both occur in very well developed crystals, the muscovite showing the most perfect development. The biotite has partly altered to chlorite, with a simultaneous production of rutile, sagenite, and sphene. Between the chlorite laminæ one frequently secs lenticular areas of secondary calcite. Quite commonly the sagenite is found included in these areas.

In only one specimen was hornblende observed. This was from a granite dike which cut the dolerite. The hornblende is of a noncompact variety, which upon the edges is finely fibrous. It corresponds exactly to that which is found in the adjacent dolerite.

The contact between the granite and dolerite appears irregular, as though the dolerite had been to some extent broken. As the contact is approached from the granite side the hornblende increases in quantity. It is thought probable that the hornblende in the granite along the contact is secondary after pyroxene, and that this pyroxene was obtained by the inclusion of fragments of the dolerite.

Accessory minerals are not present in large quantity.

Iron oxide is not present in great quantity, and when seen it is usually titaniferous, as rutile is found as an alteration product. In one case the hexagonal plates show the presence of ilmenite. Apatite is rare, as a rule, though occurring in some sections in considerable quantity. Zircon is scarce, as are also sphene and rutile. Epidote is rather common. In some cases it is seen in biotite surrounded by a pleochroic halo, and in such cases it is probably original. The secondary minerals, muscovite, biotite, chlorite, epidote, sphene, rutile, and calcite, show their usual characters. Calcite is abundant, and is more or less ferruginous. It is found in rhombohedra and also in irregular masses. In all cases its secondary origin is clear.

MICROPEGMATITES.

The micropegmatitic varieties of the biotite-granite show the same variations in color, from reddish to gray and greenish, and in grain from fine to medium, as do the biotite-granites proper. In general they may be described as biotite-granites in which the micropegmatitic intergrowth of quartz and feldspar instead of being subordinate preponderates. Many of the well-crystallized feldspars are surrounded by a border of micropegmatite, which varies from a narrow strip to a very wide border, usually in inverse ratio to the size of the feldspar nucleus. The feldspar in the intergrowth is continuous with that of the nucleus. A coarsely radial arrangement of the micropegmatitic intergrowth was frequently observed. Where the feldspars and quartz are predominantly porphyritic, and micropegmatite forms the groundmass, the rock grades over into the rhyolite-porphyries with micropegmatitic groundmass-—the inappropriately named granophyres of Rosenbusch.

The biotite of the micropegmatitic granites has partly altered to chlorite and sagenite. In some of these rocks the biotite is collected into large aggregates of imperfect individuals, which surround large pieces of iron ore. In some instances it is included in the plagioclase. The biotite flakes in the feldspar are sometimes so numerous as to conceal almost completely the feldspar substance. In one instance the feldspar of such a micropegmatitic intergrowth is completely replaced by biotite. These secondary biotite flakes surrounding the remaining more or less rounded quartz areas of the micropegmatite produce a rock which is strikingly like a mica-schist in places, although it is of unquestionably eruptive character.

Tourmaline is a rare accessory in these granites, a small smoke-brown crystal having been observed in one section. Titaniferous iron ore altering to leucoxene or sphene and rutile is found, as are also the common accessory minerals—apatite, rutile, and zircon. They contain also the same secondary minerals as the normal biotite-granite.

MUSCOVITE-BIOTITE-GRANITE.

These are medium-grained rocks, and, owing to the fact that the muscovite is more abundant than the biotite, have a light-gray color.

The muscovite is noticeably automorphic with respect to the biotite, though the biotite is also in well-developed automorphic plates. Plagioclase is present in these granites in very large quantity. It shows an excellent zonal development, with diminishing angle of extinction—that is, increasing acidity—from the center outward. The center of the individuals is nearly always extensively altered, while the outer zones are comparatively fresh. A maximum extinction angle of 15° against the twinning planes in the zone perpendicular to 010 was observed on an unaltered zone surrounding an altered core. This would indicate the feldspar to be perhaps as basic as labradorite at the center. The other essential minerals, quartz and orthoclase, occur in usual quantity and show nothing of especial interest. Sphene and apatite are the only accessory minerals present. An apatite crystal was observed which was included in quartz, and contained the brown apparently vitreous core so frequently seen in the apatites of basic rocks. Where included in biotite, it is surrounded by a pleochroic halo.

No analyses were obtained of these granites, but from the quantity and character of the feldspar as noted above, these rocks are thought to be closely related to dioritic rocks. Indeed, it is a question if they should not be classed as quartz-diorites.

RELATIONS OF GRANITES TO OTHER INTRUSIVES.

In two cases already mentioned granite dikes cut the diorites. Granite also cuts the gabbro, and dikes of granite were observed penetrating the dolerites, thus indicating that the granites are younger than these igneous rocks.

DYNAMIC ACTION IN GRANITES.

An examination of the granites with particular reference to pressure phenomena shows that they exhibit a great difference in this respect. Some show scarcely any traces of pressure, while others quite closely associated may have been affected thereby to such an extent that a more or less strongly wavy extinction of their mineral constituents is general. However, but a single instance of a supposed granite possessing an excellent cataclastic structure and imperfect schistosity was observed, and this rock was so extremely altered as to render doubtful a determination of its original character.

CONTACTS OF GRANITES AND SEDIMENTARIES.

The largest intrusive granite mass is found between the Paint and Michigamme rivers, in secs. 19, 20, 29, and 30, in T. 42 N., R 31 W. The granite is a muscovite-biotite-granite. The sedimentaries are micaceous graywackes, which have been described on p. 170. Let it suffice here to repeat that they have been much mashed and recrystallized, but that some of them still

show their fragmental origin. New biotite, muscovite, feldspar, and quartz have developed. Where most altered, they are mica-schists and mica-gneisses. These changes are presumed to be due, for the most part, to the orogenic forces which were active prior to the intrusion of the granite (p. 170). If such be the case, the granite began its metamorphic action upon a rock already greatly changed from its original condition.

EVIDENCE OF INTRUSION.

The intrusive character of this large mass of granite is indicated by its stratigraphical position, and is further confirmed by the mechanical effects produced by the intrusion of the granite upon the sedimentaries, by the contact effects produced in the sediments, and by the presence in the sedimentaries of granite dikes forming offshoots from the main mass.

The mechanical effects are well shown by the inclusion of sedimentary fragments and by the dislocation and folding of the beds. Inclusions are rather common and are usually of considerable size.

The dislocation and folding are beautifully shown at N. 1970, W. 570 paces, sec. 30, T. 42 N., R. 31 W. In general the layers in the graywacke, which are alternately rich and poor in mica, strike N. 15° to 30° W., but where the intrusives are, these layers are found to strike almost due north and south. At the above location the beds are folded into small, closely-compressed anticlines and synclines, which plunge to the east at an angle of about 80°. At this place the micaceous graywacke is broken into small pieces, which are thoroughly injected and cemented by the granite, thus forming a typical eruptive breccia. The granite cement is microgranitic, with comparatively little quartz and a small amount of chloritized mica. The fragments of micaceous graywacke in the breccia appear to be rather more feldspathic than usual, but otherwise seem not to have been much affected.

Owing to the altered condition of the sediments prior to the granite intrusion, and to the alternation of sediments of somewhat varying character, we can not expect to find such clearly outlined concentric zones surrounding the granite as in cases where the sediments are uniform. In one case a contact was observed between the granites and apparently the main mass of the sediments. Along this line of contact biotite and white mica have developed in great abundance. Mica is well known as one of the minerals produced in granite contacts, and it evidently here owes its abundance to the presence of the granite.

At a considerable distance from the nearest intrusive outcrop (2 miles) a mica-schist was observed which was characterized by numerous small but prominent nodules that stood out upon its weathered surface. The rock contains a considerable quantity of an apparently original chlorite in large automorphic plates. The nodules were produced by large individuals of staurolite. The staurolite has almost completely altered, remnants only of the original individuals remaining. These remaining grains show a very poor cleavage, and extinguish parallel to it. These include blebs of quartz and particles of iron oxide. They have the usual pleochroism for staurolite, varying from golden yellow for $\mathfrak{c}$ to yellowish white for $\mathfrak{a}$ and $\mathfrak{b}$. The alteration products in which the grains lie are fine scaly aggregates of minute leaves of muscovite, with here and there larger plates of the same mineral. A few grains of quartz and a small amount of iron oxide, possibly partly original, are found in the mass. This observation of the alteration of the staurolite to muscovite confirms the observations of Thürach[1] and Pichler.[2] A similar staurolitiferous mica-schist, occurring in the same locality, was described by C. E. Wright for the Wisconsin survey.[3] On these particular specimens the characteristic twins of staurolite may be observed macroscopically as well as in thin section. Wright has also described a garnetiferous mica-schist from this area of metamorphic schists.[4] Both of these schists contain prisms of bluish tourmaline in considerable quantity.

It appears highly probable that these staurolitiferous and garnetiferous schists owe their origin to the intrusion of the igneous rocks, though no well-marked contact zones could be outlined.

The exomorphic contact effect of the granite is more noticeable where a large body of the granite contains a sedimentary intrusion than elsewhere.

The determination of the sedimentary origin of the fragments included in the granite is based primarily upon the probability that in its passage through the sedimentary rocks which now surround it the granite included fragments of them.

[1]Thürach, Groth's Zeitschr., Vol. II, p. 423.

[2]A. Pichler, Beiträge zur Mineralogie Tirols, Neues Jahrb., 1871, p. 54.

[3]Geology of the Menominee iron region, by C. E. Wright: Geol. of Wisconsin, Vol. III, 1878; Part 8, p. 695.

[4]Loc. cit., p. 695.

In addition to this a well-defined banding is still present in these fragments. Though by no means conclusive evidence, this is considered as an indication of their having been originally deposited through the mediation of water. The sediments have been completely recrystallized into fine-grained mica-gneisses.

The sedimentary fragments included in the granite now show the following characters. They are composed of layers of two kinds. The one kind of layer is very fine grained, of gray color, and consists predominantly of biotite in fairly good automorphic plates, muscovite in small quantity—but in automorphic plates—even with respect to the biotite, feldspar, quartz, and iron oxide. The feldspar is in small equidimensional grains. Only one finely striated feldspar was observed, the greater part possibly being orthoclase. It shows in places a well-developed zonal structure, the zones conforming to the outlines of the grains. The zonal structure probably depends upon varying quantities of the soda and potash molecule. Quartz occurs in grains in very small quantity.

The second kind of layer which is seen in the fragments is much coarser grained than is the first, just described, and is very much darker. It is composed mainly of muscovite and biotite, in about equal quantities, feldspar, quartz, magnetite, and ilmenite, with some tourmaline. Both feldspar and quartz occur in grains, the former in small quantity. The biotite is in small plates less well developed than the muscovite, though mostly automorphic. It is partly bleached and has associated with it here and there some secondary epidote. The muscovite is in very large automorphic plates, some of them twinned according to Tschermak's law, and includes flakes of biotite and grains of quartz and feldspar. This gneiss contains also a large number of crystals of tourmaline, showing strong dichroism from light pinkish to dark grayish blue. Iron oxide is present, both as magnetite and as ilmenite. The quadratic individuals of the one and the hexagonal plates of the other at times are very well developed. No signs of pressure whatsoever are seen.

The muscovites evidently represent the last product of crystallization, as shown by their including all the minerals which had been previously formed. (Fig. *A*, Pl. XXXIV.) These muscovites are probably to be looked upon as the product of mineralizers, dependent upon the presence of the hot granite injection, to whose action may also be referred the presence of the tourmaline.

The line of contact between the granite and the sedimentary fragments, though somewhat irregular, is macroscopically very well defined by the difference in size of the mineral constituents of the two rocks. Here and there in the fragments there are seen thin masses of the granite which were injected along the planes of sedimentation, and also traverse cracks penetrating the sediments. On the granite side of such a contact there is a narrow zone very noticeably richer in large biotite flakes than the granite is ordinarily. No difference can be noticed on the sedimentary side of the contact. The microscopical examination of the contact emphasized the endogenous character of the metamorphic action. There is more biotite present than in the normal granite.

The feldspar in the normal granite has a decided tendency toward automorphic development. Where the feldspars of the granite touch the metamorphosed sediments they are partly rounded, and the mica plates developed in the sediments have in general a parallel structure around that side of the feldspar which is turned toward the fragments.

At another point the quartz of the granite, where it comes in contact with the sediments, has developed as an automorphic individual, and looks as though it were pressed into the fragment. The quartz crystal contains near its edge grains of feldspar and flakes of mica, thus making an imperfect narrow poikilitic zone. Beyond this zone there is the sedimentary rock proper, and there the mica plates lie parallel to the contours of the quartz. An illustration of such a contact is shown in figs. *A* and *B*, Pl. XXXV, as seen in ordinary light and also between crossed nicols.

It appears that the formation of the quartz and feldspar noted above caused the arrangement of the constituents of the gneiss parallel to their contours. It would thus seem probable that in this particular case the recrystallization of the original graywacke into the gneiss which we now find in its place followed and was chiefly the result of the intrusion of the granite.

BASIC INTRUSIVES.

The basic intrusives are represented by metadolerites and metabasalts. The dolerites are the most important, and will be treated in detail. Rocks very similar to the basalts have already been described at length under the Hemlock volcanics, and since they are found in comparatively few dikes they will be passed over with very brief mention.

METADOLERITE.[1]

GEOGRAPHICAL DISTRIBUTION.

The dolerites of the Crystal Falls district for the most part form high ridges extending in a northwest-southeast direction. Their principal occurrence is in the area immediately north, northeast, and east of Crystal Falls. Beginning in secs. 32 and 33, T. 43 N., R. 31 W., there extends a great intrusive mass, varying from a mile to a mile and a half in width, due north to sec. 6, T. 43 N., R. 31 W. There it bends to the northwest, and ends in sec. 3, T. 43 N., R. 32 W. The northwestern extension of this mass is much narrower, never exceeding a half mile, and at many places it is only a few hundred yards in width. In the northern part of T. 42 N., R. 31 W., are a number of knobs which are evidently connected below with these large masses, although the exposures are discontinuous.

A large dike begins in sec. 1, T. 42 N., R. 32 W., and extends for about 5 miles to the northwest into sec. 19, T. 44 N., R. 32 W. This averages about one-eighth of a mile in width, though in places it is three-fourths of a mile wide. Another dike begins in sec. 28, T. 44 N., R. 32 W., and runs for 3½ miles to the northwest into sec. 18, T. 44 N., R. 32 W., and, like the above, is narrow, being only about one-eighth of a mile in average width. A narrow dike less than one-eighth of a mile in width extends in a high ridge from in sec. 16, T. 43 N., R. 32 W., to the northwest for 3 miles and ends in sec. 7 of the same township and range. Numerous isolated knobs occur in T. 44 N., R. 32 W. A small boss is in sec. 24, T. 46 N., R. 33 W., and another at 1,600 paces N., 1,000 W., sec. 19, T. 47 N., R. 33 W.

[1] I use the name "dolerite" here merely to indicate the macrostructural difference between the rocks included under it and the fine-grained and aphanitic rocks of the same composition included under the basalts. It is also extended to include paleo as well as neo eruptives. As nearly all, if not all, the paleodolerites have undergone great alteration, the prefix meta—indicating alteration without reference to any specific kind—is very generally applicable.

PETROGRAPHICAL CHARACTERS.

Macroscopical.—The dolerites vary in color from greenish to dark olive-green and almost black. The weathered surface is usually of a very light color, rather a light gray, with frequently a reddish tinge. The texture is medium to coarse. Probably the most striking textural characteristic is the peculiar mottled appearance described as "luster-mottling" by Pumpelly,[1] to which the name poikilitic[2] has of late years been more generally applied. This texture is almost always brought out macroscopically on the weathered surfaces by the difference in the weathering of the feldspar and the augite or uralite, these being the prominent mineral constituents of the rock. This poikilitic texture is most common in the coarsest of the metadolerites. In such rocks the augite or uralite areas are of large size, quite commonly 2 centimeters in diameter, and show their mottled character very plainly to the naked eye.

In the medium-grained dolerites the ordinary ophitic texture is predominant, though in these rocks poikilitic areas may be seen. In fact, these poikilitic areas really possess an ophitic texture, according to the definition of that texture by A. Michel Lévy, for the feldspars are developed as laths and the pyroxene is the mesostasis in which the feldspars lie.[3] It is thus clear that, restricting the statement to these dolerites, the ophitic texture is at times included in the poikilitic, and that under such circumstances the two can not be considered as totally different and independent textures, but are, on the contrary, practically identical.

In one dike of dolerite the influence which the conditions of consolidation exert upon the texture is well shown. This dike is only 8 feet wide, but the center is developed as a dolerite, while along the edges where cooling was more rapid, the rock is a porphyritic basalt. The porphyritic texture is caused by the development of pyroxene and feldspar phenocrysts, which lie in a dense basaltic groundmass.

Microscopical.—The original minerals of which the rocks were composed were feldspar, quartz, pyroxene, olivine, biotite (?), apatite, and titano-magnetite. The minerals which are now present in the rocks are for the most part secondary. They are hornblende, muscovite, epidote-zoisite, chlorite, biotite, sphene, leucoxene, calcite, albite, quartz, and iron pyrite. Of these, hornblende is by far the most prominent constituent. A study of the isolated specimens of these rocks might result in their determination as uralitic dolerites, epidiorites, or even diorites, as it is impossible, without a sequence of changes, to determine whether the hornblende is original or secondary. Rare rocks contain quartz in sufficient quantity to warrant their designation as quartz-dolerites. However, they differ in no essential respects from the other dolerites. The quartz is in micropegmatitic intergrowth with feldspar, filling the angular interspaces of the rock. These intergrowths were evidently the last elements to crystallize.

[1] Metasomatic development of the copper-bearing rocks of Lake Superior, by Raphael Pumpelly: Proc. Am. Acad. Arts Sci., Vol. XIII, 1878, p. 260.

[2] On the use of the terms "poikilitic" and "micropoikilitic" in petrography, by G. H. Williams: Jour. Geol., Vol. 1, 1892, pp. 176-179.

[3] Structures et classification des roches éruptives, by A. Michel Lévy, Paris, 1890, p. 30.

The feldspar occurs in large automorphic lath-shaped crystals, which in most cases show polysynthetic twinning. In a few cases unstriated crystals were observed. Owing to the alteration of the feldspar, which has in most cases almost completely destroyed the striations, it has been impossible to make many accurate measurements. Measurements on the zone perpendicular to 010 gave equal extinction angles against twinning planes of 37° as maximum, showing the feldspar to be bytownite. The chief alteration products of the feldspar are epidote and zoisite. With these are usually associated more or less muscovite, some chlorite, and, more rarely, scales of biotite. Accompanying these alteration products one very frequently finds limpid spots of secondary albite or quartz. Some few of the feldspars are smoke-colored, and as the coloring appeared homogeneous even under the highest powers, it would seem to be due to some pigment in the mineral and not to minute inclusions.

Pyroxene is very rare, having been observed in only a few sections and in the majority of these is present merely as small remnants surrounded by its secondary product, uralite. The pyroxene possesses the usual characters of common augite. The augite is quite free from inclusions. Along the edge its alteration to the light-green hornblende, uralite, can be readily followed, and in one case an octagonal basal section of augite was observed which was completely occupied by uralite fibers.

The former presence of olivine is based upon very slight proof, viz, the existence in some of the pyroxene and uralite crystals of areas which are oval or round in shape and are occupied by pilite. The presence of this pilite in the altered augite might possibly be explained as an alteration product of the augite itself, but it is difficult to explain why pilite should develop in one part of the augite and secondary coarse hornblende in the other part. Moreover, the general characters of the rocks are such as to lead one to expect to find olivine present in some of them.

Biotite occurs in large irregular masses which are considered to be primary, as well as in the scales which occur within secondary products of the rock and are considered to be secondary. It is scattered throughout the rocks in irregular pieces, usually associated with iron oxide. Where fairly fresh, it is brown and shows its ordinary character. By weathering it becomes green, having still a high double refraction. By further weathering it passes into a nearly colorless mass that has the faintest tinge of green and scarcely polarizes light. Such masses are crossed by lines of hair-like crystals, some of which intersect one another at angles

of 60 degrees, extinguish parallel to their long directions, and show high single and double refraction. These are taken to be rutile. Other crystals, somewhat coarser, also lie irregularly in the biotite masses. They show the same intersections as the rutile. They are very faintly greenish, have a high single and double refraction, are positive in the long direction, and have a maximum extinction angle of 46 degrees. These characters were not sufficient to determine the mineral by, and no other characteristics could be observed.

Ilmenite and titano-magnetite are in irregular grains. These minerals are more or less altered to leucoxene or to sphene. Very frequently the alteration product incloses bands of the iron oxide, which intersect one another at angles of 60 degrees, pointing toward the hexagonal character of the ore. In one case a beautiful example of the alteration of such an ilmenite to rutile was observed. It is exactly similar to that described by Williams in the case of the greenstones of the Menominee district.[1] By low power the mass has a semimetallic luster, and, as it seems to be almost solid, has very much the general appearance of an ore, but by higher power it is resolved into a mass of small golden-brown crystals. These frequently intersect one another at angles approximating 60 degrees (120°), similar to the fine needles in sagenite.

The hornblende is mainly in large xenomorphic plates inclosing the automorphic feldspars. This is the variety of hornblende known as uralite and is all presumed to be of a secondary nature. In no case does it possess the compact nature of original hornblende, but is always more or less fibrous, its fibrous nature being best seen along the edges, and less clearly shown, though still observable, where the sections are thicker. It varies from scarcely colored needles to those which are strongly pleochroic. The pleochroism varies from yellowish for $\mathfrak{a}$ to yellowish or olive green for $\mathfrak{b}$, and in many cases to a dark bluish-green for $\mathfrak{c}$. In a few cases much of the hornblende has frequently a darker shade in the center than at the border, although of the same color.

[1] A letter to Neues Jahrbuch,Vol. II, 1887, p. 263. The greenstone-schist areas of the Menominee and Marquette regions of Michigan. Bull. U. S. Geol. Survey, No. 62, 1890, p. 99.

A somewhat different variety of hornblende is observed occupying round to oval areas in the dolerites. This is in tangled aggregates of needles, with which some chlorite is associated. This hornblende is automorphic in prismatic zone, ragged at the ends. These aggregates seem to be very coarse pilitic pseudomorphs after olivine. The areas occupied by these aggregates are similar in appearance to the pseudoamygdules described by Pumpelly as occurring in the Keweenawan lavas.

The hornblende is largely altered to masses of chlorite and epidote, usually with the production of some calcite, and to this is due the present extremely chloritic and epidotic characters of many of the badly altered specimens.

The secondary minerals, chlorite and epidote-zoisite, possess their usual characters. The chlorite is present in very large quantity, and next to it the epidote-zoisite is most common. These two minerals make up a large proportion of the rock. In one case porphyritic scalenohedra of calcite were found in a medium-grained dolerite, the occurrence in every way being similar to that described in the volcanics of the same region.

None of the original minerals of these intrusive greenstones give evidence of having been severely mashed; consequently we may safely conclude that they have not participated in the orogenic movements in pre-Keweenawan time which have universally affected the older rocks of the Crystal Falls district.

RELATIONS TO ADJACENT ROCKS.

Relations to Lower Huronian Mansfield slates.—The relation of the dolerites to the Mansfield slate is quite clearly shown along the line of contact between them. This extends from sec. 7 S. to sec. 32, T. 43 N., R. 31 W., on the east side of the Michigamme River, near Mansfield. The presence of numerous large inclusions of the slate in the dolerite and the occurrence of contact rocks in the slate plainly show that the dolerites are younger than the slate. Another piece of evidence pointing to this same relation was found in sec. 28, T. 44 N., R. 32 W. Here was found an angular inclusion of sedimentary rock in a dolerite. The rock now possesses the characters of a spilosite, and was evidently brought up from below by these intrusives. No slate is exposed near this point, but it is presumed to underlie this area, although below the exposed volcanics.

Relations to Lower Huronian Hemlock volcanics.—The dolerite ridges which occur in the area underlain by the Hemlock volcanics are surrounded on all sides by rocks of related petrographical character. The number of localities at which the relations between the two may be observed are very few, but their relations where seen are clear. For instance, in secs. 18 and 30, T. 44 N., R. 32 W., the coarse intrusives break through the volcanics. In sec. 27, T. 46 N., R. 33 W., a boss of the dolerite occurs in the midst of schistose volcanic tuffs. The volcanics surrounding the intrusives exhibit symptoms of more or less violent dynamometamorphic action, whereas the dolerites in no case show any evidence, microscopically or macroscopically, of having undergone the metamorphism from which the volcanics have suffered. The dolerites are thus clearly younger than the effusives of the district.

Relations to Upper Huronian.—Only a few isolated dolerite outcrops have been found in the area underlain by the Upper Huronian. The most conspicuous outcrops are the large dike in secs. 7, 8, and 9, T. 43 N., R. 32 W., and the knobs in Ts. 42 N. and 43 N., R. 31 W. These last are practically continuous with the great dike which penetrates the Lower Huronian along the Michigamme River immediately to the north. One isolated knob has also been found in the extreme northwestern part of the district in sec. 19, T. 47 N., R.

33 W. Although in none of these areas have the dolerites been found in contact with the Upper Huronian, as it has been shown by the stratigraphy that these areas are underlain by the Upper Huronian sediments, the statement seems warranted that the dolerites are intrusive through them.

Relations to other intrusives.—-In one place a dolerite is intruded by a dolerite of later age, and it is highly probable that there are many more similar cases never observed. The dolerites are cut by small granite dikes at several places east of Mansfield.

CONTACT METAMORPHISM OF MANSFIELD SLATES BY THE DOLERITE.[1]

The contacts between the dolerites and the sedimentaries are very rarely observable. For the most part where the sedimentaries are altered by contact action they are surrounded on all sides by the dolerites, being in fact inclusions, but without the immediate contacts exposed. Such inclusions are rather numerous on the east side of the Michigamme River, from sec. 29 N. to sec. 8, T. 43 N., R. 31 W., near the boundary line between the Mansfield slates and the dolerites.

[1]A contribution to the study of contact metamorphism, by J. Morgan Clements: Am. Jour. Sci., 4th series, Vol. VII, 1899, pp. 81-91.

The Mansfield slates are uniformly rather fine grained, and the contact products are also fine-grained rocks, which still show in some cases the fine banding of the original slates. They are very dense “hornstone”-like rocks, have a splintery and at times almost conchoidal fracture, and vary in color from light to very dark gray and greenish. The weathered surfaces in almost all cases are covered by a thin white to light-yellowish crust. This weathering brings out very clearly the banded and spotted character of some of the rocks.

The mineralogical components are quartz, feldspar, biotite, chlorite, white mica, actinolite, rutile, epidote, sphene, and iron oxide. Quartz is in very minute grains. Much of the feldspar shows fine striations, but owing to the minute size of the grains their exact characters are not determinable with the microscope, although from the very high percentage of soda shown by analysis to be present in the rocks the conclusion is drawn that they are grains of albite.

Biotite is present in small quantity in some of the contact products. This production of secondary biotite has been noted as rare for “diabase” contacts.[1] Plates of chlorite and white mica and needles of actinolite, the latter of much larger size than the individuals of the other minerals mentioned, lie scattered through the fine-grained mass of feldspar and quartz. Usually they are gathered together in bunches and sheaf-like or radial aggregates, but they occur at places in isolated individuals. Scattered through the slates is unmistakable rutile in coarse crystals with pyramidal ends. In only one case are the crystals very fine, and in that case they approach closely the appearance of needles in the clay slates (Thonschiefernadeln). These needles are commonly aggregated into tangled and roughly radial growths. The needles show very pretty knee- and heart-shaped twins.

[1]Mikroskopische Physiographie, by H. Rosenbusch, Stuttgart, 1896, Vol. II, p. 244.

Various combinations of the minerals occur, and the structures which accompany the combinations likewise vary. As a result of these variations there are found the different types of contact products described as spilosites, desmosites, and adinoles.[1] The general characters of the minerals being the same, I shall describe the structure which characterizes the rocks.

SPILOSITES.

The ordinary spilosites are distinctly mottled in hand specimens and show clearly to the naked eye in thin section the oval spots which characterize them. These oval areas are commonly 4 millimeters long, and in rare cases even longer. They are frequently connected, forming chains. The spots are appreciably darker than the mass in which they lie, and are composed of chlorite, quartz, feldspar, and rutile, with a small amount of muscovite, the chlorite being the chief mineral. The surrounding mass consists essentially of muscovite, quartz, and feldspar, with rutile crystals and flakes of hematite, and with a very slight amount of chlorite. The different proportions of chlorite and muscovite seem to cause the difference between the spots and the groundmass (fig. A, Pl. XXXVII). In some of the spilosites we find a few flakes of biotite and needles of actinolite; however, these are always very subordinate in quantity to the chlorite.

In the ordinary form described these spots consist essentially of bisilicates. Others also have been noted in which these spots are white and lie in the fine-grained dark mass composing the greater part of the slides. Thus far it seems only one instance of the occurrence of such a variety of the spilosites has been described. This is by Van Werveke, to whose description reference is made by Zirkel[2] and Rosenbusch.[3] These white spots are composed essentially of albite feldspar, with only a minor amount of chlorite and epidote. The feldspar grains are much larger than those which take part in the constitution of the mass surrounding the spots. This mass is made up of quartz and feldspar, chlorite, epidote, and some sphene, with sheaves of actinolite scattered through it, and in one section clumps of biotite were observed mixed with the chlorite, though in very subordinate quantity (figs. *A* and *B*, Pl. XXXVI).

[1]Über den spilosit and desmosit Zincken’s, by Lossen: Zeitsehr. Dentsck. Geol. Gesell., Vol. XXIV, 1872, p. 701.

Dureli diabas veränderte Schiefer im Gebiet der Saar and Mosel, by Van Werveke: Leonard’s Jahrb., Vol. II, 1884, p. 225.

An interesting contact rock, with note on contact metamorphism, by W. M. Hutchings: Geol. Mag., Vol. II, pp. 122, 163.

Numerous other references may be found in Chemische Geologie, by Roth, Bd. Ill, and in petrographical works of Zirkel and Rosenbusch.

[2]Zirkel, Pet., Vol. II, p. 719.

[3]Rosenbusch, Vol. II, 3d ed., p. 1177.

Differing slightly from the ordinary spilosite is one in which the spots are of microscopical size, and consist of ragged bunches of chlorite and aggregates of sphene and epidote, with some flakes of biotite, which lie in a quartz-feldspar mass. The photomicrograph, fig. *B* of Pl. XXXVII, illustrates the appearance of the rock. As these spots increase in number they approach each other and unite, forming streamers, which in their turn unite and form bands (photomicrograph, fig. *A*, Pl. XXXVIII,). The spilosites or spotted contact products thus pass over into the desmosites or banded contact products.

Analyses of spilosites.—Analyses of two of the spilosites (Nos. I and II) were made by Dr. H. N. Stokes in the laboratory of the United States Geological Survey, and are here appended. With them there is given an analysis (No. III) by E. Kayser of a spilosite from the Harz Mountains.

Analyses of spilosites.

	I (32827).	II (32861).	III.
SiO_2	57.77	52.51	55.56
TiO_2	.92	1.70	.....
Al_2O_3	19.35	19.00	18.15
Cr_2O_3	None.	None.	.....
Fe_2O_3	1.29	3.31	5.08
FeO	3.37	7.19	7.04
MnO	Trace.	Trace.	.51
CaO	1.71	1.55	1.40
BaO	None.	Trace.	.....
SrO	Trace.	Trace.	.....
MgO	4.35	3.29	3.17
Na_2O	8.22	6.72	4.20
K_2O	.22	.70	2.25
Li_2O	None.	Trace.	.....
CO_2	None.	None.	.10
P_2O_5	.04	.15	.....
H_2O at 110°	.18	.34	2.79
H_2O at 110° +	2.34	3.26	
S and SO_3	None.	None.	.....
Cl	None.	None.	.....
F	None.	Trace.	.....
Total	99.76	99.72	100.25

DESMOSITES.

Under the desmosites are included contact products composed of the same mineral constituents as the spilosites, but which show a distinctly banded structure. As shown in the discussion of the spilosites, the two must be very closely related and grade into each other.

E. Kayser, from Roth's Chem. Geol., Vol. III, 1890, p. 143, No. IV.

ADINOLES.

Chlorite has been the chief dark mineral in the contact products thus far mentioned, with actinolite as an accessory. In the adinoles actinolite is the characteristic constituent. The mineral constituents in the adinoles are, as a rule, more uniformly distributed than is the case with the spilosites; however, the spots are composed essentially of actinolite. The actinolite is in sheaf-like growths. These actinolite sheaves lie in an exceedingly fine grained mass of quartz and albite, with some flakes of chlorite and grains of epidote. The groundmass is formed of such minute mineral constituents that no conclusive test could be obtained for the determination of the limpid grains, and their nature has been concluded from the analyses. The rock is rendered rather dark by minute black specks disseminated through it. In places these are collected in irregular or lenticular heaps. They seem to be carbonaceous matter.

Analyses of adinoles.—The following is an analysis (No. I) by Mr. George Steiger, of the United States Geological Survey, of one of the typical adinoles from this district. With this there are given for comparison two adinole analyses (Nos. II and III) by E. Kayser.[1]

Analyses of adinoles.

	I (32465).	II.	III.
SiO_2	74.16	75.25	72.63
TiO_2	.37	.....	.....
Al_2O_3	11.85	11.80	15.81
Fe_2O_3	.82	Trace.	.....
FeO	1.66	1.76	.74
MnO	.06	.....	.....
CaO	2.10	.32	1.02
BaO	None.	.....	.....
MgO	2.10	1.57	1.21
K_2O	.15	.61	.75
Na_2O	6.57	7.54	8.33
H_2O at 100° −	.05	.81	.61
H_2O at 100° +	.52		
P_2O_5	.08	.....	.....
CO_2	.09	.....	.....
FeS_2	.....	.49	.....
C	.18	.....	.....
Total	100.76	100.15	101.10

[1]E. Kayser, Zirkel, Vol. II, p. 721, Analyses III and VI.

There is still a kind of contact rock in which actinolite is the chief dark mineral, and in which the actinolite, though in clumps, is mainly collected in bands. This corresponds to the desmosites in structure, though differing from them in mineralogical composition.

These chlorite and actinolite contact rocks may be expected to grade into each other, and such a gradation is shown in one specimen, in which actinolite and chlorite are present in about equal quantity. The actinolite occurs in crystals and sheaves, forming the spots, whereas the main mass of the slide surrounding the spots is formed of chlorite as the metasilicate associated with feldspar, quartz, and some epidote.

It would be of great interest to determine which of the contact products, the desmosites, the spilosites, or the adinoles, represent the greatest amount of metamorphism, as shown by the relations to the intruding mass. Unfortunately, the records of the specimens do not enable me to determine this, although for other contact zones in other regions it has already been determined that the adinoles are next to the contact, while the spilosites (and desmosites) are intermediate between them and the clay slates.

COMPARISON OF THE ANALYSES OF THE NORMAL MANSFIELD CLAY SLATES AND THE CONTACT PRODUCTS.

In a series of analyses designed to illustrate the chemical changes which accompany the increasing metamorphism of a rock, it is of great importance that the various phases, from the unmetamorphosed to the most metamorphosed form of the rock, be represented. Moreover, the order of succession from the unmetamorphosed to the most metamorphosed form of

the rock should be definitely known. In the present case certain pha es of the metamorphosed rocks are represented, but it has been impossible, owing to poor exposures, to determine in this locality the order of succession. This has, however, been done so satisfactorily by Lossen and others, and the characters of each facies in the progression have been so well described, that I have no hesitation, after a microscopical study of the thin sections of the specimens analyzed, in presenting the series of analyses in the following table as illustrative of the changes which have taken place in a clay slate, in the contact zone of dolerite, in its passage to spilosite and adinole. The analyses are given in the order of approach to the dolerite as determined by the character of the rocks. No. 1 is the unmetamorphosed form of clay slate; Nos. 2 and 3 are the intermediate phase, and No. 4 is the most metamorphosed phase.

Comparison of analyses of clay slate, spilosites, and adinole.

	1.	2.	3.	4.
SiO_2	60.28	52.51	57.77	74.16
TiO_2	.69	1.70	.92	.37
Al_2O_3	22.61	19.00	19.35	11.85
Cr_2O_3	.....	None.	None.	.....
Fe_2O_3	2.53	3.31	1.29	.82
FeO	.45	7.19	3.37	1.66
MnO	Trace.	Trace.	Trace.	.06
CaO	.13	1.55	1.71	2.10
BaO	.04	Trace.	None.	None.
SrO	.....	Trace.	Trace.	.....
MgO	1.35	3.29	4.35	2.10
K_2O	5.73	.70	.22	.15
Na_2O	.54	6.72	8.22	6.57
Li_2O	.....	Trace.	None.	.....
H_2O at 100°−	.60	×.34	×.18	.05
H_2O at 100°+	3.62	+3.26	+2.34	.52
P_2O_5	.03	.15	.04	.08
CO_2	None.	None.	None.	.09
C	.97	.....	.....	.18
S and SO_3	.....	None.	None.	.....
Cl	.....	None.	None.	.....
F	.....	Trace.	None.	.....
Total	99.57	99.72	99.76	100.76

×H_2O at 110°.
+H_2O above 110°.
No. 1=Clay slate (Sp. 32497). Sec. 17, T. 43 N., R. 31 W., 450 N., 1620 W.; George Steiger.
No. 2=Spilosite (Sp. 32861). Sec. 7, T. 43 N., R. 31 W., 750 N., 1380 W.; H. N. Stokes.
No. 3=Spilosite (Sp. 32827). Sec. 7, T. 43 N., R. 31 W., 250 N., 325 W.; H. N. Stokes.
No. 4=Adinole (Sp. 32465). Sec. 8, T. 43 N., R. 31 W., 500 N., 475 W.; George Steiger.

In these analyses the usual Increase of silica as the dolerite is approached is at once noticeable, and hand in hand with it goes the diminution in percentage of alumina and iron oxides. The content of water and carbonaceous matter also suffers a diminution. The most noteworthy difference between the clay slate and the contact rocks is shown in the relations of potassa and soda. This is well brought out in an examination of analyses Nos. 1 and 2. It will be seen that there is only about one-eighth as much potassa in the contact rocks as in the normal clay slate; while, on the contrary, about 12 times as much soda as there was in the slate has been added to the contact rock. This causes a reversal of the relations of the soda and potassa, so that, whereas in the clay slate there is present 10 times as much potassa as soda, we find in the contact rock taken as a sample very nearly 10 times as much soda as potassa. The very considerable change in chemical composition, especially in the amount of silica and soda, seems to lend great weight to the supposition that in such contacts an actual transfer of material (soda-silicate) takes place from the basic intrusive to the slate. This idea is upheld by Roth,[1] Zirkel,[2] and others. W. Maynard Hutchings[3] advocates this view, and has described some interesting products as a result of the contact of the Whin Sill which still further support it.

NO ENDOMORPHIC EFFECTS OF DOLERITE INTRUSION.

Although the exomorphic contact effects of the dolerite intrusion were so obvious, no evidence is found that the dolerite itself suffered any change consequent upon its intrusion.

METABASALT.

Basalt has been described at length under the volcanics, where it plays an exceedingly important role. Basalt as a dike has been found in only two places, and therefore very little remains to be added.

The two basalt dikes occur within a very short distance of each other, in secs. 15 and 16, T. 42 N., R. 31 W., and are found penetrating the crystalline schists of the Upper Huronian. Their relations to the other intrusive rocks of the same region are not known. They are probably of the same age as the dolerites, of which they should most likely be considered offshoots.

These dikes are a porphyritic basalt. The phenocrysts were of augite, olivine, and labradorite. They were in a very fine groundmass of feldspar, augite, and iron oxide. However, the former existence of the augite and olivine phenocrysts is determinable only by means of their outlines. They are in very small quantity and are entirely altered to pilite. The feldspar phenocrysts are in coarse, heavy crystals and are remarkably fresh. The groundmass is very fine grained, and ranges from an exceedingly fine micro ophitic texture to the pilotaxitic texture. The feldspars in it are in small lath-shaped individuals, and, like the phenocrysts, are fresh. The augite of the groundmass is to a great extent altered to uralite, and the iron ores to sphene.

[1]Chem. Geol., by J. Roth, Berlin, 1890, Vol. III, p. 145.

[2]Lehrbuch der Petrographie, by F. Zirkel, Vol. II, 1894, p„ 722.

[3]Notes on the composition of clay slates, etc., and on some points in their contact metamorphism, by W. Maynard Hutchings: Geol. Mag., Vol. I, Dec. 4, 1894, p. 75. Chem. Geol., Vol. III, p. 145. An interesting contact rock, with notes on contact metamorphism, by W. Maynard Hutchings: Geol. Mag., Vol. II, 1895, pp. 122-131, 163-169.

One of the dikes is about 5 feet wide. In the center it is a moderately fine-grained rock; on the edges it is a dense aphanitic basalt. Even in thin section the gradation from the rock with microophitic groundmass to the one with a dense pilotaxitic groundmass is well shown. A dike of larger size might readily have cooled sufficiently slowly to have crystallized at its center as a dolerite.

ULTRA-BASIC INTRUSIVES.

Under this head are the descriptions of the picrite-porphyries (porphyritic limburgites).

PICRITE-PORPHYRY (PORPHYRITIC LIMBURGITE).

GEOGRAPHICAL DISTRIBUTION AND EXPOSURES.

The picrite-porphyries occur in isolated outcrops of comparatively small size in secs. 9, 22, and 27, T. 44 N., R. 32 W., in the area supposed to be underlain by the Lower Huronian Hemlock volcanics. They are surrounded by outcrops of the altered poikilitic dolerites, but the exposures are not such as to allow their relations to be determined. Their occurrence points to an intrusive character. It is on account of their field occurrence alone that we feel justified in describing them here under the general heading for this chapter, "Intrusives," instead of under the volcanics with the basalts, their proper place from a strict petrographical standpoint.

PETROGRAPHICAL CHARACTERS.

The picrite-porphyries are medium-grained rocks, which vary in color from gray to dark green and almost black. In general they have a porphyritic character. This is, however, not so well marked in the gray as in the darker-colored rocks. The gray ones have a spotted appearance. The spots are gray in color, fibrous, very rarely larger than 3 or 4 millimeters in length, and lie in a finely fibrous, dark-green matrix. In the dark rocks the porphyrinic crystals reach a length of 1 centimeter, and are bluish to black, with silky luster. They lie in a fine-grained, more or less fibrous, green groundmass. In one of the dark rocks the magnetite is very noticeable. The crystals project from the weathered surface and the rock is strongly polar-magnetic.

The rocks originally consisted largely of olivine, pyroxene, hornblende, biotite, magnetite, and ilmenite. They now contain also, in considerable quantity, a chloritic product which seems to have been derived from the alteration of an original vitreous base. All of the specimens are exceedingly altered. The original mineral constituents have to a great extent been determined from their form, which in some cases has been preserved by the products of alteration, and by certain structures in the pseudomorphs. The minerals now composing the rock are original hornblende, biotite, apatite, magnetite, and ilmenite, with secondary amphibole, serpentine, chlorite, calcite, sphene, and rutile.

The two kinds of rocks, the gray and the dark-colored ones, were evidently derived from rocks of essentially the same composition. They have undergone different processes of alteration, and upon this depends the difference in color. As the study of these picrites is chiefly one of the alteration products of the minerals which composed them, it seems best to describe separately the two rocks showing the different products of alteration.

GRAY TREMOLITIZED PICRITE-PORPHYRY.

Ill the gray rocks the spots which are macroscopically observed are found under the microscope to consist of an aggregate of minerals. Examination of these aggregates shows them to be entirely secondary. A careful study of these aggregates shows them to consist of amphibole, magnetite, ilmenite, and serpentine, the first being predominant. No trace of the original minerals remains. The aggregates are the same in all of the crystals, and the only clue to the original mineral is the form of the pseudomorphs and certain structures in the aggregates. By means of the form the phenocrysts are readily divisible into three kinds. The first kind has a long prismatic habit, with pyramidal faces meeting at rather an acute angle. The iron oxide is arranged along certain lines, giving the characteristic mesh structure of serpentinized olivine. The second kind is a short, thick prism, for the most part with rounded ends, in some cases the pyramidal faces meeting in a rather obtuse angle. The iron oxide in some of these cases marks an imperfect parting perpendicular to the long direction of the prism. These are supposed to be pseudomorphs after a pyroxene. The third kind consists of round and irregular grains or plates, some of which may be referred to pyroxene, others to olivine.

The amphibole is in small needles. It has a very faint greenish tinge. In cross section it shows marked prismatic development. The character of the needles is pins in the long direction. The maximum angle found between $\mathfrak{c}$: c is 18 degrees. The needles appear to be tremolite containing some iron, and thus approaching actinolite in composition. Usually the needles have no regular arrangement, but in some of the pseudomorphs with rectangular outlines there is a parallel arrangement of such a number of the needles parallel to the long axis of the pseudomorphs as to give to the pseudomorph a distinctly uniform polarization effect.

Isolated crystals of magnetite and brownish transparent plates of ilmenite are scattered among the actinolite needles. By far the greater part of the iron oxide is collected in aggregates of small crystals and irregular grains. The formation and arrangement of these aggregates has in some cases taken place along fracture and cleavage planes of the original minerals, and thus in the pseudomorphs we see the mesh structure of olivine and transverse parting of pyroxene clearly brought out. In other cases the iron oxide is in irregular masses collected at the center or outlining the periphery of the pseudomorphs or scattered in small masses through them.

Between the tremolite needles and the iron oxide is a small quantity of minute fibers. They have a greenish tinge and low double refraction. Their extinction is parallel to the long c axis, which is also the axis of least elasticity. They are believed to be serpentine fibers. No definite arrangement of these fibers could be discerned over the greater part of the pseudomorphs, but in one crystal, on the edge of the section, where it is especially thin, the arrangement of these needles perpendicular to the long direction of the iron aggregates outlining the meshes is unmistakable. Calcite is in considerable quantity in some of the pseudomorphs. It is highly probable that it owes its origin to the alteration of the

original mineral, though some of the calcium went into the amphibole.

Besides the above-described pseudomorphs after olivine and pyroxene, a few large prismatic and irregularly bounded areas were found among the phenocrysts, which now consist chiefly of chlorite, with grains of calcite, titanite, magnetite, and minute plates of ilmenite scattered through them. It is clear that the chlorite is derived from a hornblende, as shown by the presence of ragged remnants of hornblende which possesses uniform orientation throughout each area. This hornblende shows weak pleochroism in the light-yellow to greenish tones of actinolite, although its character is more that of the compact hornblende. In one case its secondary nature was shown by the presence of a small irregular area of brown hornblende lying in a mass of the green. The two have the same orientation. In this case the chlorite is apparently a tertiary product, the original mineral being the brown hornblende, from which was formed the light-green variety, which in its turn alters to the chlorite.

Between the various pseudomorphs are irregular plates of compact, dark-brown hornblende, plates of biotite, large crystals of magnetite, and rough branching aggregates of ilmenite. These, while molded on the phenocrysts, themselves lie in the chloritic mass already mentioned, which also often completely surrounds the phenocrysts, and which is probably an altered vitreous base.

The pieces of brown hornblende which remain unaltered show moderately strong pleochroism, reddish brown for $\mathfrak{c}$ and $\mathfrak{b}$ and light brownish yellow for $\mathfrak{a}$. $\mathfrak{c}=\mathfrak{b}>\mathfrak{a}$. This hornblende contains Inclusions of iron oxide and has all the appearance of an original mineral. By alteration it passes through a compact greenish amphibole to a much lighter colored, reedy, actinolitic variety of amphibole. In the secondary amphibole occur certain golden-brown grains with high single and double refraction, which are supposed to be rutile formed from the hornblende, and also some brown transparent plates of ilmenite. The orientation of the secondary hornblende is the same as the original. No further alteration of this amphibole was observed, but it is believed that the prismatic crystals altered to chlorite, calcite, and magnetite, as described above, are the extreme cases of alteration of an automorphic form of a brown hornblende very similar to the part described.

The biotite between the phenocrysts is in ragged areas either surrounding iron oxide or associated with it or with the hornblende. It is very pleochroic, the absorption parallel to the basal cleavage being so strong as to render the section opaque. Perpendicular thereto the color is a dark chocolate brown. The mica does not show its usual bright polarization colors in sections cut parallel to crystallographic c. This may be due in some measure to the very strong absorption. In some cases the biotite is seen to have a strong blue to violet metallic luster in incident light. The biotite has partly altered to chlorite. The alteration proceeds along the basal cleavage. As this alteration progresses there is a lightening of the color of the biotite, and, as a consequence of this the whole cause of the metallic luster and the partial cause of the color of the biotite is disclosed. In the lighter biotite one by careful examination can see innumerable small plates of a brown or smoky color. At first sight they remind one strongly of the inclusions so common in many hypersthenes. Closer examination only emphasizes this resemblance, and they are believed to be micaceous ilmenite plates. These inclusions were studied by means of an oil immersion objective giving a magnification of about 1,250, and were found to have mainly a roundish or hexagonal outline. In addition to these, some plates of long, irregular form were observed. These are all isotropic and non-pleochroic. These minute plates lie parallel to the biotite lamellæ. The consequence of this is that in sections parallel to c one secs, for the most part, only short black streaks—the edges of the plates—whereas in the basal sections of the biotite one can determine the irregular or rounded contours of the plates. The plates are too small to allow the metallic luster to be seen on an isolated one. En masse they produce a very decided blue metallic shimmer, as seen in some of the biotite fragments.

Numerous apatite crystals occur. They are usually clear white, but one crystal was seen showing a dichroism from faintest brownish for rays perpendicular to crystallographic c to light smoky brown for rays parallel thereto. This crystal contains a core of brown glass.

Some of the iron oxide is in roughly rectangular masses, and appears to be magnetite. This is associated with an iron oxide, which occurs in opaque, ragged masses formed of long, irregular, and knotty stringers. These at places are parallel to one another and at other places cut one another at various angles, and at still other places meet at a common center, forming an opaque mass of varying dimensions, but usually small. Now and then one of the large magnetite masses constitutes a center from which extend the knotty, irregular stringers. The general appearance of these ragged masses is that described by German petrographers as *zerhackt*.

When these stringers pierce the section at an oblique angle, the ends are translucent, with a brown color, becoming more opaque as the section gets thicker. Such masses have all the appearance of ilmenite, and are believed to be that mineral. Similar ilmenite stringers are included in the chlorite, which results from the alteration of the biotite.

The chlorite in the paramorphs after biotite shows extremely low blue polarization color, and the characteristic pleochroism—yellowish, tinged with red, when the rays vibrate perpendicular to the cleavage, and green when parallel thereto. Apatite needles included in the biotite are unaltered in the secondary chlorite.

Some of the minute octahedral crystals in the amphibole pseudomorphs after olivine appear to be slightly pellucid, with a brown color. If so, they might be referred to

picotite, but there is doubt of the correctness of the observation, in view of the high power used, the oil immersion lens, and the fact that the search was for picotite. Close search was also made for perovskite, but none could be found, unless the transparent crystals very doubtfully referred to picotite are really perovskite.

Forming the matrix in which the pseudomorphs after hornblende, olivine, and pyroxene of these rocks lie, and frequently surrounding isolated crystals, one secs an aggregate composed chiefly of a fine felt of chlorite fibers. This alteration product contains a few apparently original apatite needles, some secondary grains of magnetite, and crystals of amphibole which are colorless or else show but the faintest tinge of green, and are larger than the amphibole crystals in the pseudomorphs. It is a secondary amphibole very poor in iron, probably highly calcareous, and approaching tremolite in composition. This chlorite aggregate shows no indication whatever of crystal forms. It seems to be the product of a homogeneous mass, such as would result from the decomposition of a vitreous base. Such a base the aggregate is presumed to represent, although no trace whatever of the glass has been observed in the rock, nor in view of the altered condition of the rock could such a glass be reasonably expected to still remain.

DARK SERPENTINIZED PICRITE-PORPHYRY.

The second variety of the picrite-porphyries is very dark greenish-black, and represents the results of a slightly different process of alteration from that by which the gray forms just described were produced. These dark picrite-porphyries show a very much better developed porphyrinic structure than do the gray ones. This is due to the fact that the olivines in these rocks were well developed and reached a length of a centimeter. The olivines are completely altered, serpentine, pilite, and magnetite, being the products which form the pseudomorphs. The characteristic mesh structure of altered olivine is well brought out by the serpentine and iron ore. In the centers of the meshes there remain small masses of a felt of tremolite needles (pilite). This alteration of the olivine corresponds to that first described by Lewis,[1] and more recently by Professor Bonney and Miss Raisin,[2] from a rock—kimberlite—-very similar to the picrite-porphyries here described. He writes as follows: “It frequently happens that while serpentinization begins at the outside of a crystal, fibrous tremolite begins growing within, finally forming a mass of asbestiform fibers surrounded by a zone of green serpentine.”

The minerals which composed these black picrite-porphyries were the same as those constituting the gray ones. These minerals were olivine, pyroxene, hornblende, biotite, magnetite, and ilmenite. They were cemented by a glass matrix. The glass is completely altered. All of the minerals are represented by pseudomorphs. Remnants of the original hornblende and biotite alone are preserved.

The contours of the original pyroxene crystals are filled with pilite, serpentine, and magnetite. The serpentine is present in greater quantity in these pyroxene pseudomorphs than it was in the pyroxene pseudomorphs in the gray picrite-porphyries. The alteration of the hornblende results in the production of an aggregate of chlorite inclosing grains of calcite, some sphene, and iron oxide, similar to that in the gray picrite-porphyries. The biotite, magnetite, and ilmenite also show those characters which have been described for the same minerals in the first-described picrite-porphyries.

Between all of the foregoing minerals we find a fine felty chlorite mass containing grains and dendritic masses of iron ore and a few needles of tremolite. This corresponds to the material forming the cement for the minerals in the gray porphyries, and, like that, is believed to represent an original vitreous matrix.

[1]On a diamondiferous peridotite and the genesis of the diamond, by H. C. Lewis: Geol. Mag., 3d ser., Vol. IV, 1887, p. 22.

Papers and notes on the genesis and matrix of the diamond, by the late Henry Carvill Lewis, edited by Prof. T. G. Bonney, London, 1897, p. 14.

[2]Notes on the diamond-bearing rock of Kimberly, South Africa, Part II, by Prof. T. G. Bonney and Miss C. A. Raisin: Geol. Mag., 4th series, Vol. II, 1895, p. 496.

In one of the dark picrite-porphyries the magnetite is present in large quantity and is very noticeable, crystals of it standing out upon the weathered surface. This rock did not affect the magnetic needle very powerfully, though it was expected that it would do so. However, another one of these porphyries. In which, by the way, the iron content Is relatively low, is unique, in that it is very strongly polar magnetic, and in this, as well as its probable original mineralogical composition, may be compared with the polar magnetic wehrlite from the Frankenstein, Hesse-Darmstadt, Germany.[1] The German rock shows tremolite scattered through the serpentine resulting from the olivine. It is a coarse, evenly granular rock, differing in this respect from the Crystal Falls rocks which are porphyritic.

An analysis (No. 1) of the polar magnetic serpentinized picrite-porphyry, in which great abundance of olivine was originally present, is here given, and there is placed with it for comparison an analysis (No. 2) of a very similar rock described by Darton and Kemp,[2] from New York. Both analyses were made by Dr. H. N. Stokes, United States Geological Survey. In No. 1 Ba, Sr, Li, CI, S, and SO_3 were not looked for.

Analyses of picrite-porphyry.

	1.	2.
SiO_2	37.36	36.80
TiO_2	.79	1.26
Al_2O_3	4.76	4.16
Cr_2O_3	.62	.20
Fe_2O_3	6.61	.....
FeO	6.12	8.33
MnO	Trace.	.13
NiO	.04	.09
CaO	1.19	8.63
BaO	.....	.12
SrO	.....	Trace.
MgO	31.11	25.98
K_2O	Trace.	2.48
Na_2O		.17
P_2O_5	.06	.47
CO_2	None.	2.95
SO_3	.....	.06
S	.....	.95
H_2O at 110°	.65	.51
H_2O above 110°	10.37	6.93
		100.22
Less O=S	.....	.47
Total	99.68	99.75

[1]Der magnetstein von Frankenstein an der Bergstrasse, by Andreae und König: Abhandl. der Senkenberg. naturf. Gesell., Frankfort a Main, 1888, pp. 59-79.

Cf. Above article; p. 66, footnote, for references to other occurrences of tremolite associated with serpentine.

[2]Newly discovered dike at Dewitt, near Syracuse, New York, by N. H. Darton and J. F. Kemp: Am. Jour. Sci., Vol. XLIX, 1895, p. 461.

CLASSIFICATION.

These rocks just described, from their mineralogical composition, if we admit the presence of a vitreous base, would belong with the picrite-porphyrites of Rosenbusch.[1] This designation does not seem, however, to be appropriate, as he states[2] that he uses the term "porphyrite" only for certain textural phases of rocks containing lime-soda feldspar. He has evidently extended that definition so as to be able to use it for these picrites, considering that the glass possesses the necessary ingredients for the formation of such lime-soda feldspar, provided the conditions under which it cooled had been favorable for the feldspar development.

The porphyritic texture of these Crystal Falls picrites and the presence of a vitreous base[3] show them to be closely related to rocks of effusive character. Those which they most closely resemble among the younger basaltic lavas are the porphyritic forms of the limburgites (magma basalts).

One of the best-known rocks with which this may be closely compared, as far as association is concerned, is the rock first described by H. Carville Lewis as a saxonite-porphyry,[4] later called kimberlite. This was described by him as volcanic, and as associated with dolerites and melaphyres. He described it as a basic lava.[5] Other occurrences of very closely related basic rocks having a vitreous base have been described from the United States by Diller, Williams, Merrill, Branner and Brackett, Kemp, and Darton and Kemp.[6]

[1]Microscopische Physiographic, by H. Rosenbusch: 3d ed., Stuttgart, Vol. II, 1896, p. 1191.

[2]Op. cit., p. 436.

[3]Should the vitreous base be considered as not having been present and the rocks be put among the peridotites, then they would correspond very closely to the wehrlite described on p. 254.

[4]Papers and notes, cit., p. 50.

[5]The genesis of the diamond, by H. C. Lewis: Science, Vol. VIII, 1886, p. 345.

On a diamondiferous peridotite and the genesis of the diamond, by H. C. Lewis: Geol. Mag., 3d series, Vol. IV, 1887, p. 22.

[6]Dikes of peridotite cutting the carboniferous rocks of Kentucky, by J. S. Diller: Science, 1885, p. 65; Notes on the peridotite of Elliot County, Kentucky, by J. S. Diller: Am. Jour. Sci., Vol. XXXII, 1886, p. 188: Bull. U. S. Geol. Survey, No. 38, 1887.

The serpentine (peridotite) occurring in the Onondaga salt group, at Syracuse, New York, by G. H. Williams: Am. Jour. Sci., Vol. XXXIV, 1887, p. 137; Proc. Geol. Soc. Am., Vol. I, 1889, p. 533; Perowskit in serpentin von Syracuse, New York, by G. H. Williams: Neues Jahrb. Vol. II, 1887, p. 263.

On a peridotite from Little Deer Isle, in Penobscot Bay, Maine, by G. P. Merrill: Proc. U. S. Nat. Mus., 1888, p. 191.

The peridotite of Pike County, Arkansas, by J. C. Brainier and R.N Brackett: Am. Jour. Sci., Vol. XXXVIII, 1889, p. 50.

Peridotite dikes in the Portage sandstone of Ithaca, New York, by J. F. Kemp: Am. Jour. Sci., Vol. XLII, 1891, p. 410.

A newly-discovered dike at Dewitt, near Syracuse, New York, by N. H. Darton and J. F. Kemp: Am. Jour. Sci., Vol. XLIX, 1895, p. 456.

The rock described by F. L. Ransome as a fourchite should perhaps also be compared with these rocks, representing as it probably does the olivine-free form of the limburgite (augitite). Geology of Angel Island, by F. L. Ransome: Bull. Geol. Dept. Univ. of California, Vol. 1, 1894, p. 200.

Hatch[1] has also described a very similar pre-Tertiary rock from England as a limburgite. Kemp[2] emphasizes the resemblance of the Dewitt dike to limburgite, and states that it should be called limburgite.[3] If we attempt to extend the use of the term "limburgite" to include the pre-Tertiary vitreous basalts, we shall have to include under it the rocks heretofore designated as picrite and picrite-porphyrite. Rosenbusch has now put the picrites and picrite-porphyrites with the effusive rocks, and if of these two sets of terms there is one to be discarded, it should be the name "limburgite." It seems preferable under the rules of priority to retain the name "picrite." It would then seem very suitable to apply to these pre-Tertiary porphyritic limburgites Hussak's old term, "picrite-porphyry," using the term "porphyry" simply with a textural significance.[4]

SECTION II.—A STUDY OF A ROCK SERIES RANGING FROM ROCKS OF INTERMEDIATE ACIDITY THROUGH THOSE OF BASIC COMPOSITION TO ULTRA-BASIC KINDS.

Beginning near the town of Crystal Falls, in isolated knobs, and extending southeast toward the Michigamme River, where the exposures are larger and better connected, there is found a series of rocks whose characters are of such interest petrogenetically as to warrant a detail description of them.

These rocks are all intrusive in character, with few exceptions are medium to coarse grained, and, while the granitic texture is predominant, there are certain facies in which the texture is porphyritic and even parallel. They have been only slightly affected by dynamic action, and these cases are purely local. Analyses show them to vary in chemical composition from those of intermediate acidity to those of ultra-basic character.

[1]The Lower Carboniferous volcanic rocks of East Lowthian (Carlton Hills), by F. Hatch: Trans. Royal Acad. Edinburgh, Vol. XXXVII, 1892, p. 115.

[2]Op. cit., p.460.

[3]Taking plutonic rocks as practically the granitoid, and volcanic as the porphyritic, the Dewitt rock is a basaltic dike of the same composition and texture as limburgite, and should be called limburgite, even if it is not a surface flow." (Loc. cit., p. 460.)

[4]I believe E. Hussak was the first to use this term for a somewhat similar rock. Pikrit-phorphyr von Steierdorf im Banat, by E. Hussak: Verhandl. K.-k. geol. Reichsanstalt, 1881, pp. 258-262.

The prevailing rocks are, on the one hand, diorites of intermediate acidity ranging to more acid rocks, tonalites, quartz-mica-diorites, and granite (plagioclastic), and, on the other, hornblende gabbros, gabbros, norites, and, lastly, peridotites of varying mineralogical character. These rocks thus resemble in their variations those Scottish plutonic rocks so well described by Messrs. Dakyns and Teall.[1]

The rapid changes in mineralogical composition and texture in a single rock, and the changes from one kind to another through intermediate facies, show very clearly the intimate relationship of these rocks to one another, and warrant the assumption that they all belong to a geologic unit, a conclusion reached a number of years since by Williams for a somewhat similar series, the Cortlandt series, from New York.

Granite is present as a local facies of the diorite. However, it is very subordinate in quantity and not altogether typical, and as no analysis has been obtained, its position is still more or less doubtful.

In the following pages only those kinds of rocks of which analyses have been obtained will be included in the final discussion. Others will be described in detail or merely mentioned, as representing facies of the main types, according to their penological interest. The rock types of which analyses have been made are as follows: Diorite, gabbro, norite, and peridotite.

DIORITE.

NOMENCLATURE.

Diorite, according to the generally accepted definition, is a granular rock consisting essentially of hornblende, which must be primary, and a soda-lime feldspar.[2] The term has been used in a different sense by many writers on the Lake Superior and other regions. It has been used to comprise rocks which contain hornblende and plagioclase as preponderating constituents, it is true, but in which the hornblende is secondary, therein differing from a true diorite. These so-called diorites have been regarded as derived from an original dolerite (diabase) by uralitization of the pyroxene. By some writers these rocks have been classed with the epidiorites, thus recognizing their secondary nature, but by this name, epidiorite, unfortunately implying a false relationship.

1On the plutonic rocks of Garabal Hill and Meall Breac, by J. R. Dakyns, esq., M. A., and J. J. H. Teall, esq., M. A., F. R. S., F. G. S.: Quart. Jour. Geol. Soc., Vol. XLVIII, 1892, pp. 104-121.

[2]Lerhbuch der Petrographic, by F. Zirkel, Leipzig, Vol. II, 1894, p. 465.

In this paper, following Brögger, I restrict the name to the granitic rocks of intermediate acidity, in which the feldspar is plagioclase and the bisilicate constituent is mica or primary hornblende. The feldspar is a lime-soda plagioclase.[1]

DISTRIBUTION AND EXPOSURES.

The distribution of the diorite is limited to a few localities, all of which are in the area underlain by Upper Huronian sedimentaries. The most typical occurrences, and those showing greatest variations, form knobs beginning near Crystal Falls and continuing to the south and southeast. Especially large outcrops form the hills in secs. 19 and 20, T. 43 N., R. 31 W. The smaller occurrences are not indicated on the map. These diorite exposures are always good, so far as getting fairly fresh specimens are concerned, but their contacts with other rocks are almost invariably deeply covered with drift; hence their relations in many cases are doubtful.

PETROGRAPHICAL CHARACTERS.

The diorites are holocrystalline rocks of medium to coarse grain. In texture they show some variation from those which are granitic to those in which the texture is imperfectly ophitic. The color is, on the whole, moderately light gray or reddish, but at times when the dark minerals become more prominent in the basic facies, especially where we get basic schlieren, the rock is very dark gray or greenish brown.

The important mineral constituents are feldspar, quartz, biotite, and hornblende. The accessory minerals are epidote, apatite, zircon, sphene, and iron oxides. The secondary minerals, white and brown mica, chlorite, biotite, epidote-zoisite, calcite, and rutile are also present.

Feldspar.—Plagioclase feldspar, orthoclase, and microcline occur together. The plagioclase is found in individuals which are fairly automorphic. In the ophitic

textured diorites, the plagioclase is the best developed of all the essential constituents. In the granular rocks the degree of automorphism is highest where orthoclase and quartz are present in the largest quantity, and diminishes as these diminish, when the plagioclase individuals begin to interfere with one another's development. For the most part the plagioclase gives rather thin sections, though they can hardly be correctly called lath-shaped. No other form of plagioclase, showing a uniformly better or poorer development, or any other difference in character indicating the presence of two kinds of lime-soda feldspar, was observed.

[1]Die Eruptivgesteine des Kristianiagebietes. I. Die Gesteine dor Grorudit-Tinguait-Serie, by W. C. Brögger, 1894, No. 4, p. 93. II. Die Eruptionsfolge der triadischen Eruptivgesteiue bed Predazzo in Südtyrol, 1895, No. 7, p. 35. Videnskabsselskabets Skrifter, I Matheniatisknaturv. Klasse.

The plagioclase sections almost invariably show polysynthetic twinning according to the albite law, with twinning lamellæ which vary from very thin to moderately thick plates, the thinner being the more common form. Very common is the combination of the albite and Carlsbad twinning laws in one individual. Less commonly we find individuals twinned according to the pericline as well as the albite law, and sometimes a Carlsbad twin is made up of individuals twinned according to the albite and pericline laws.

In determining the character of the feldspar, the Lévy method was followed.[1] A great number of measurements made on the zone perpendicular to 010 gave equal extinction angles, varying chiefly around 15 degrees, but running as a maximum to 19 degrees. From this it appears that the plagioclase is andesine, probably a somewhat basic kind. That these andesines vary slightly in composition is shown by a very slight but noticeable zonal structure, the more basic character of the center of the individuals being most admirably brought out by the more advanced condition of alteration of the center as compared with the periphery.

The andesine is for the most part very much altered, to such an extent that in many sections the boundaries of the twinning lamellæ are so blurred that measurements are rendered impossible. Muscovite, which appears in minute rectangular sections showing good cleavage, is the chief secondary product from the feldspar, with epidote-zoisite next in importance. Calcite and biotite are present, but in comparatively small quantities. In some cases muscovite almost replaces the feldspar; in others epidote-zoisite does so. In such a case one secs in the center of the feldspar only a mass of secondary mineral. As the examination is carried from the center toward the outside, the original feldspar material is distinguished as a thin film between the secondary minerals. This increases in mass until we reach the outside narrow rim of practically unaltered feldspar.

Orthoclase.—This is present in large quantity in irregular plates which form a part of the mesostasis for the plagioclase and bisilicates. Less commonly we find it in micropegmatitic intergrowth with the quartz. It is invariably more or less decomposed, and shows innumerable minute dark specks scattered through it. The quantity of orthoclase varies in these dioritic rocks considerably; at times it almost equals or even exceeds the plagioclase, when the rocks approach the granites, and at times it sinks to a few large plates in each section, when the rocks are a normal diorite.

[1]Étude sur la determination des feldspaths, by A, Michel Lévy, Paris, 1894.

Microcline.—This mineral is not abundant. It is in individuals which frequently, though not in all cases, are automorphic with respect to the orthoclase and quartz. It is remarkably fresh.

Quartz.—Quartz, at times, is an essential constituent, and again it diminishes in amount until it is present only in a few grains, or even disappears altogether. Like the orthoclase, it is completely xenomorphic, and with the orthoclase constitutes the mesostasis. Undulatory extinction in the quartz gives indication of slight pressure.

Biotite.—The original biotite in the granular dioritic rocks is automorphic with respect to all minerals but the hornblende. In the ophitic forms it has a development about equal to that of the hornblende. It shows a dark rich chocolate-brown or greenish-brown color for $\mathfrak{b}$ and $\mathfrak{c}$, and a light yellowish-brown for $\mathfrak{a}$. The biotite includes small epidote crystals with pleochroic courts and some grains of spliene. Both of these are original. The biotite is almost invariably more or less altered, bleaching in some cases to a very light colored mica with exceedingly high polarization colors. This bleaching follows along the laminæ of the biotite and results in giving sections parallel to the vertical axis a banded appearance resembling parallel intergrowths of muscovite and biotite laminæ. More commonly it alters to chlorite, rutile (often present as sagenite), sphene, epidote-zoisite, and calcite. There is also a distinct banding of the biotite and the chlorite in places. In the alteration of the biotite we very commonly find lenses of calcite produced between the laminæ. In some cases the epidote-zoisite is clearly a product of the alteration of the biotite, for in many cases it is found in the rectangular shape of the biotite section, and in other instances in spaces between the feldspars in the ophitic rocks, which in fresher specimens are found to be occupied by the biotite. Moreover, in the epidote-zoisite are minute grains of sphene similar to those contained in the original biotite.

Where it is present as a secondary product, it occurs with the muscovite and is xenomorphic with respect to it. The green tone is absent from the secondary biotite.

Hornblende.—The hornblende ill the diorites shows a most excellent development in the prism zone; very much less well developed are the terminating planes. The color varies from dirty green to a reddish-brown. The brown hornblende occupies the center of the crystals, while the green occupies the outside, the green agreeing perfectly, optically, with the brown. A zonal structure is indicated by the difference in the character of

the hornblende, though the zones are not sharply delimited, but grade into one another. In a few cases the greenish hornblende grades into one which is almost colorless. The pleochroism is as follows: Brown hornblende: $\mathfrak{a}$, light yellow or light reddish-yellow; $\mathfrak{b}$, light reddish-brown; $\mathfrak{c}$, darker reddish-brown. Green hornblende: $\mathfrak{a}$, light yellow; $\mathfrak{b}$, bright green; $\mathfrak{c}$, dull or olive green. This green hornblende is clearly original and not to be considered as a secondary product after the brown hornblende. Both kinds are free from inclusions.

Accessory minerals.—The epidote is observed very frequently inclosed in the altered biotite, and is surrounded by pleochroic halos. In such cases it is considered a primary constituent. The accessory minerals, apatite, sphene, and zircon, show none other than their usual characters. Titaniferous magnetite is present in the diorites in very small quantity.

According to the relative proportion of the important minerals just described—plagioclase, orthoclase, quartz, hornblende, and biotite—composing the diorites, we get the following varieties: Mica-diorite, quartz-mica-diorite, quartz-diorite, and tonalite. These grade into one another, as stated above; and, as will be shown later, certain of them grade into granites. On account of these variations these dioritic rocks are especially interesting.

DESCRIPTION OF INTERESTING VARIATIONS.

SEC. 15, T. 42 N., R. 31 W.

A dike of rock 4 feet wide, occurring at 425 paces N., 1050 W., sec. 15, T. 42 N , R. 31 W., near Norway portage, shows the following mineralogical variation. A specimen taken from the center of the dike shows the rock to be there a typical fine-grained granitite with little or no plagioclase. (Photomicrograph, fig. *A*, Pl. XXXIX.) Along the sides the dike rock is a mica-diorite consisting of mica and plagioclase without any quartz. Measurements on zone perpendicular to 010 gave equal extinction angles with a maximum of 15 degrees. Only one kind of plagioclase is distinguishable by its mode of development, and this is rich in CaO, as shown by its alteration products. The feldspar ranges at most from albite to andesine. No chemical analysis has been obtained of either the granitite or the mica-diorite phase, but the mineralogical composition is sufficiently marked to show conclusively that we have here a gradation from a granitic to a dioritic rock rich in CaO. The idea has been suggested by Johnston-Lavis[1] that in some cases the variation in chemical composition of intrusive rocks, especially where this variation is one between the center and the periphery of an intrusive mass, may be due to resorption by the intrusive of parts of the rock intruded. The sharp line of demarcation which exists between the dike and the intruded hornblende-gabbro in the occurrence described above seems to preclude the possibility of a fusion and mingling of the two rocks.

ACROSS RIVER FROM CRYSTAL FALLS.

Near Crystal Falls, just across the river from the town, are a number of small knobs of granite grading into quartz-mica-diorite. They are medium-grained rocks, reddish to gray in color. They take a very fine polish and are well adapted to ornamental stonework, as is shown by the columns made from them which are used in the court-house at Crystal Falls. When examined under the microscope, the rocks are found to consist of automorphic biotite and plagioclase, with xenomorphic orthoclase and quartz, these last forming the cement. Some of the slides show beautiful micropegmatitic intergrowths of quartz and feldspar. The amount of quartz, plagioclase, and orthoclase varies so that, depending upon the specimen examined, one would call the rocks forming the knobs granite or quartz-mica-diorite. Most commonly the rock is a plagioclase-bearing granite. No analysis has been obtained of the granite, but it is confidently believed that the chemical composition would sustain the microscopical diagnosis. Within the granite there are found lenticular schlieren of considerably darker color than the main mass, in which the plagioclase is the preponderant feldspathic constituent. The rock of these lenses is essentially a quartz-mica-diorite.

[1]The basic eruptive rocks of Gran (Norway) and their interpretation; a criticism by H. J. Johnston-Lavis: Geol. Mag., 4th ser., Vol. I, 1894, p. 252.

The causes of variation in the composition of igneous rocks, by H. J. Johnston-Lavis: Natural Science, Vol. IV, 1894, pp. 134-140.

These knobs are cut by a number of small dikes from a fraction of an inch to 3 inches in width. In all of these dikes the rock shows the same characters. It is very light gray to pink in color, and aphanitic.

An examination under the microscope enables the separation of each dike into a very compact fine-grained saalband and a somewhat coarser-grained porphyritic central portion. In the central part of the dike phenocrysts of quartz, feldspar, and biotite lie in a very fine groundmass of quartz and feldspar. The texture of this groundmass is microgranitic. The saalband is composed of the microgranitic groundmass without the phenocrysts. The quartz phenocrysts show the usual characters. The feldspar phenocrysts are in most cases so completely replaced by a muscovite aggregate as to preclude any exact determination of their original character. In some cases indistinct remains of polysynthetic twinning are seen. Even when the main mass of the feldspar phenocrysts is entirely altered, there is a narrow zone of very fresh feldspar material surrounding it. Twinning in the center is also continuous through this zone. Moreover, this zone itself shows a very noticeable zonal structure by the change in extinction angle observed in passing from the inner to the outer portion. This less altered zone of feldspar contains numerous inclusions of quartz from the groundmass. The character of the feldspar phenocrysts could not be determined, but the presumption is that they are of the same character as the feldspar in the

coarser main mass—that is, andesine—with a more acid feldspar, possibly oligoclase, surrounding them. The further presumption is then warranted that the feldspar of the groundmass agrees with this outer feldspar zone in character—that it is also oligoclase, or at least is more acid than the phenocrysts. Automorphic biotite plates are now represented by chlorite pseudomorphs, with here and there some secondary epidote.

The groundmass consists chiefly of quartz and feldspar, but contains disseminated through it many minute plates of white mica and a few crystals of zircon. The feldspar of the groundmass is too small to permit of its accurate determination. A plagioclase feldspar in sections indicating an approach to automorphism was observed. Its character as oligoclase (?), or at least a feldspar of a more acid character than that of the centers of the phenocrysts, is surmised for reasons given above. Microcline in sections showing characteristic twinning and in more or less rectangular outlines was observed in considerable quantity. An untwinned feldspar was determined as orthoclase by the difference shown by its refractive index and that of the twinned plagioclase. Quartz was also recognized in this way in the groundmass. The quartz and orthoclase form the cement for the other constituents. The muscovite in the groundmass is presumably secondary, as is that in the phenocrysts. (Figs. *A* and *B*, Pl. XL.)

The rock is here inserted as showing an exceedingly fine grained porphyritic form of the quartz-mica-diorite. It may compare to this mica-diorite as does the tonalite-porphyrite of Becke[1] to the tonalite described by him, and one might call it a quartz-mica-diorite-porphyry.

No analysis of this rock has thus far been obtainable. Possibly its chemical composition may indicate it to be more closely allied to the true granites than is believed to be the case, judging from its mineralogical composition and its association with the rocks on the border line between granites and diorites.

SOUTHEAST OF CRYSTAL FALLS.

Southeast of Crystal Falls, in sec, 16, northwest of Lake Tobin, and extending southwest into sec. 28, T. 42 N., R. 32 W., is a range of hills upon which are numerous exposures of a uniformly medium-grained rock. The main mass of the knobs is of tonalite, which shows several facies. A miarolitic texture is very common in this massif. The cavities are now filled with calcite, quartz, and epidote-zoisite alone or together. This last mineral occurs in single large individuals or in tufts of individuals, which radiate from one side of the cavity. In one case a cavity incompletely filled by such a tuft has been completely filled by a later infiltration of quartz. The color of the rock varies from light pink to very dark greenish gray. The areas of the lighter-colored rocks may be seen extending in finger-like projections into the darker-colored phases. There are, however, no sharp lines between these varieties, but a gradual passage from the lighter to the darker rock. These different phases evidently belong to a single rock mass. Under the microscope, however, important variations in the textural and mineralogical character of the rock masses are seen. The main mass of the rock is granular tonalite. The essential constituents are plagioclase, orthoclase, quartz, hornblende, and mica. The most common association of minerals is hornblende and mica in automorphic crystals, with plagioclase somewhat less well developed. Between these there is found the quartz, with some accessory orthoclase, and microcline as the last products of crystallization. In some cases these two minerals are present in micropegmatitic intergrowths. A textural variation, which the fades mentioned below also undergo, is from a granular to an imperfectly ophitic texture. In such cases the order of crystallization of the hornblende-mica and plagioclase is reversed, the plagioclase being most automorphic in the ophitic varieties.

[1]Petrograpkische studien am Tonalit der Rieserferner, by F. Becke: Tschermaks mineral. Mittheil., Vol. XIII, 1892, p. 435.

The rock resembles the tonalite described by Becke from the Rieserferner.[1] It also closely resembles some slides of the typical Adamello tonalite with which I have been able to compare it. The chief difference between them is that the plagioclase and hornblende have a better crystallographic development in the Crystal Falls rocks than in the Adamello tonalite, and that the accessory allanite of the Adamello rock is wanting in the Crystal Falls tonalite, though the normal epidote may represent it. The hornblende also differs slightly from that of the Adamello rock in that it is not throughout reddish brown. The central portion of some of the crystals shows this color, but the outer portion is a dirty green, even grading into an almost white hornblende.

The tonalite grades, by diminution of biotite, with corresponding increase of hornblende, into a quartz-diorite, and by diminution or disappearance of the hornblende and increase of the biotite into a quartz-mica-diorite.

Hornblende never occurs alone in the rocks, whereas biotite may occur as the only bisilicate constituent. It is a very common thing to find in the diorites rounded basic segregations consisting chiefly of mica with hornblende subordinate and just a little accessory feldspar. When the orthoclase and quartz diminish, we get the mica-diorites. Orthoclase is always present in all of these dioritic rocks. In certain facies orthoclase and quartz are very abundant and the plagioclase is correspondingly diminished. Such rocks are clearly plagioclase-bearing granites, and represent gradations between the ordinary tonalite and granite, and point to close relationship of this occurrence with the occurrences nearer Crystal Falls already described, in which the granitic facies predominates and the dioritic facies is subordinate.

[1]Petrographische studien am Tonalit der Rieserfemer, by F. Becke: Tschermaks mineral. Mitt-heil., Vol. XIII, 1892, pp. 364-379.

Similar gradations have been noted by Becke in the tonalite from the Rieserferner.[1] The diorite massif of the Crystal Falls district seems to correspond very closely to

the granodiorite masses of Becke, Turner, and Lindgren,[2] which on the one hand grade into the granitites and on the other into the diorites.

ANALYSIS OF DIORITE.

It has not been found possible thus far to obtain analyses of all these varieties. The more acid facies of the diorites seem in their mineralogical composition to show very clearly their gradations toward the tonalites and granites. This being the case, it was deemed of more importance to study the relations of the more basic dioritic facies in order to determine the relationship of these rocks to those of the more basic gabbro and peridotite families which are found in association with them. To this end an analysis of one of the mica-diorites was obtained.

This rock contains the dark constituents, biotite and hornblende, in large quantity, and of these the mica predominates. Plagioclase predominates among the white silicates, with orthoclase and quartz very subordinate. The mica is considerably altered, but on the whole the rock is fairly fresh. Fig. *B*, Pl. XXXIX, is a photomicrograph of the rock and shows its general characters. The following analysis was made by Dr. H. N. Stokes, in the laboratory of the United States Geological Survey:

Analysis of diorite.

	Per cent.		Per cent.
SiO_2	58.51	K_2O	4.08
TiO_2	.72	Na_2O	3.11
Al_2O_3	16.32	H_2O at 100°	.23
Fe_2O_3	2.11	H_2O above 100°	2.00
FeO	4.43	P_2O_5	.30
MnO	Trace.	Co_2	None.
CaO	3.92	Total	99.17
MgO	3.73		

[1]Petrographische studien am Tonalit der Rieserferner, by F. Becke: Tschermaks mineral. Mittheil., Vol. XIII, 1892, pp. 379-464.

[2]The granodiorite of California appears from Lindgren's description (Granitic rocks of California, by W. Lindgren: Am. Jour. Sci., 4tb series, Vol. III, 1897, p. 308; where can be found references to mention and descriptions of granodiorite) to correspond very closely to tonalite, though Turner uses the name as synonymous with quartz-mica-diorite (Geology of the Sierra Nevada, by H. W. Turner: Seventeenth Ann. Rept. U. S. Geol. Survey, Part I, 1896, pp. 636, 724).

The altered character of the rock is readily seen in the large content of water. It is, nevertheless, not so marked as to render the analysis useless for purposes of determination.

The character of the plagioclase feldspar is clearly indicated by the relatively high percentage of lime. This high content in lime and the large amount of alkalies present, 7.18 per cent, clearly show its relationship to the diorite family. The content in potash feldspar and the possible derivation of the rock from a granitic magma is shown by the high content in potash. Possibly a considerable amount of the potash, with the greater part of the magnesia, should be deducted for the biotite which is so abundant.

This rock is one which it is somewhat difficult to place definitely in the existing division of rock families. The large amount of lime and the relatively low percentage of alkalies prevent the placing of the rock with the syenites. On the whole it approaches close to the monzonite group according to the chemical composition of the group given by Brögger. But it differs from this in that the lime (3.92 per cent) is too low to bring the rock within his limits (4.52 to 10.12 per cent).[1] However, if we consider the total of the alkaline earths (7.65 per cent) in the rock under discussion, we find that it comes well within Brögger's range (6.05 to 17.52 per cent) for a total of magnesia and lime. Moreover, the alkali total (7.19 per cent) is about right to warrant its classification in the monzonite group as a representative of the type of biotite-monzonite.

On comparing the analysis with that of true normal diorites. we find that the relative proportions of the alkalies are abnormal. The lime content is also too low for rocks of this character, and the magnesia is too high.

The above considerations seem to make clear the relationship of the rock to the monzonites and diorites. However, it is so intimately associated with and so evidently but a facies of the tonalite which is the dominant type where this rock occurs, that it is considered to be more closely related to the lime-soda feldspar rocks, in which the orthoclase is but accessory, than to the monzonite family of orthoclase-plagioclase rocks. It is therefore considered to be a mica-diorite.

[1]Op. cit., Part II, p. 51.

GABBRO AND NORITE.

PETROGRAPHICAL CHARACTERS.

The gabbros and norites are holocrystalline rocks of moderately fine to coarse grain. They show a considerable variation in texture. Some, the finest-grained forms, possess a very good parallel texture (Pl. XLII, figs. *A* and *B*); others are noticeably porphyritic. A few have poikilitic textures (Pl. XLI, figs. *A* and *B*); less common is an approach to the ophitic texture of the dolerites. Most common of all the rocks are the hypidiomorphic granular ones (Pl. XLIV, fig. *A*, and Pl. XLIII, fig. *A*).

The rocks vary from a light grayish-green color for some of the coarse-grained ones, through darker greenish colored rocks to those of a dark brownish or greenish-black color for the finest-grained forms.

The important original mineral constituents are feldspar, mica, hornblende, pyroxene, and olivine. Apatite, sphene, zircon, rutile, octahedrite (anatase), brookite (?), and iron oxide occur as accessory minerals. White and brown mica, chlorite, hornblende, talc, serpentine, sphene, rutile, and calcite occur as secondary minerals.

Feldspar.—Both plagioclase and orthoclase are present in the gabbros and norites. Plagioclase is by far the most important. It occurs normally in the coarse-grained

kinds of rock as broad tabular individuals. In the finer-grained, especially the porphyritic and poikilitic facies, the feldspar sections assume a broad, lath-shaped character. The sections show the characteristic polysynthetic twinning. Twins, according to the albite, pericline, and Carlsbad laws, are present, usually the albite and Carlsbad or the albite and pericline being combined; in some cases all three occur together. Twinning lamellæ vary in breadth, but on the whole are moderately narrow. Measurements made on the zone normal to 010 give equal extinction angles against the twinning plane, which reach a maximum of 34 degrees. The feldspar is evidently labradorite. A zonal structure is noticeable, and is especially shown by the alteration being more advanced in the centers of the individuals. It is possible that the labradorite is accompanied by a small amount of more acid feldspar, andesine in zonal growth with it. The alteration of the feldspar results in the production of the same secondary products formed from the slightly more acid feldspar of the diorites, mica (both muscovite and biotite), epidote-zoisite, and calcite. The plagioclase shows very beautifully the effects of dynamic action in local granulation of the peripheries of the individual. Such lines of granulated feldspar can be followed through the sections, probably indicating shearing planes. Inclusions are common. Some stout rutile crystals were observed in the feldspar. In some cases minute hair-like needles, which in a few instances were of a size sufficient to admit of their ready determination as rutile, were also found penetrating the plagioclase. Crystals of apatite and iron ores are also commonly included in it. There have also been found in a few cases minute hexagonal plates, which are translucent, with brown color, and are presumably micaceous ilmenite.

Mention of the presence of orthoclase in these rocks is made with considerable doubt. Here and there a few plates of untwinned feldspar, showing a character somewhat different from that of the plagioclase plates, were observed. As will be seen, the possibility of its presence is indicated by the potash shown in the analysis.

Biotite.—The biotite in the coarsely granular rock is in irregular plates. They are frequently included in and attached to the outside of the hornblende. Its period of crystallization thus overlaps that of the hornblende, though on the whole being contemporaneous with it. In the fine-grained rocks biotite is better developed than the hornblende, and is apparently for the most part older than it. In color it varies from a rich reddish brown for rays vibrating parallel to the cleavage to a light yellow for those perpendicular thereto. It includes crystals of zircon and apatite, which are surrounded by pleochroic halos.

Hornblende.—In most of the sections hornblende is the most striking component. It is present in the gabbros in three different varieties. The most prominent kind is a reddish-brown hornblende, which has a dirty green hornblende commonly associated with it and frequently intergrown with it zonally. This hornblende occurs without the green, but the green is invariably associated with the brown. The two are optically continuous in the intergrowths. It is possible, though not susceptible of proof, that the green is the result of the incipient alteration of the brown. The second kind is compact, strongly pleochroic, common green hornblende, and the third is a noncompact, reedy variety of light-green hornblende. The first two kinds of hornblende are presumed to be primary. The third variety is secondary, but secondary after the original hornblende, thus not affecting the character of the rock.

The first variety, the reddish-brown hornblende, occurs in the gabbros in anhedra. A zonal structure is marked by brown hornblende occupying the centers of the crystals and by dull green hornblende, which agrees optically with the brown, occupying the outsides. The brown hornblende is somewhat lighter colored than basaltic hornblende. The pleochroism is strong in the following colors: Brown hornblende: $\mathfrak{a}$, light yellow or red, with tinge of green; $\mathfrak{b}$, red brown; $\mathfrak{c}$, same or darker red brown, exceptionally yellowish-brown; $\mathfrak{c} \geqslant \mathfrak{b} > \mathfrak{a}$. Green hornblende: $\mathfrak{a}$, greenish-yellow; $\mathfrak{b}$, yellowish- or brownish-green; $\mathfrak{c}$, dull olive green, frequently with bluish tinge; $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$.

This hornblende, with respect to its rather exceptional pleochroism and its general characters, seems to agree very well with that described by van Horn from very similar rocks from Italy, and, like that, is probably a very basic hornblende.[1] Twinning parallel to 100, $\infty \mathbb{P} \infty$, is very common. An imperfect parting parallel to the orthopinacoid 100, $\infty \mathbb{P} \infty$, was also observed in some cases. It is also indicated by the platy inclusions which lie in this plane. In some of the sections where the green hornblende is not intergrown with the brown the green kind shows very commonly a system of fine striations parallel to the positive orthodome 101, $\mathbb{P} \infty$. In rare cases the brown hornblende is intergrown with almost colorless hornblende, one end of a crystal being brown, the other faintly yellowish. Irregular mottled intergrowths of the two were also found.

The normal brown-green hornblende is rendered poikilitic in some specimens by a few rounded grains of perfectly fresh pyroxene, and also by plagioclase crystals which it includes. This same kind of hornblende is frequently rendered very dark by the number of exceedingly small inclusions which it contains, and in this, and also in its reddish-brown color, resembles so strongly many hypersthenes as to be readily mistaken for them upon cursory examination. These inclusions are of several kinds, all distributed throughout the same individuals. It is impossible in studying them to get any optical tests, except that of extinction, owing to the minute size of the inclusions and to the fact that where large enough for examination the tests were vitiated by the presence of the hornblende.

[1]Petrographische Untersuchungen über die noritischen Gesteine der Unigegend von Ivrea in Oberitalien, by F. R. van Horn: Tschermaks mineral Mittheil. Vol. XVII, 1897, Part V, p. 409.

Of these inclusions some are readily distinguishable as rutile. Some of the larger of the crystals reach a length of 0.045 mm. and a thickness of 0.0125 mm. Numbers of them show the characteristic heart-shaped and geniculated twins of rutile, so that there is no doubt as to the determination. Associated with the rutile are other crystals 0.019 mm. long, which show the typical pointed pyramidal development of octahedrite (anatase). Still others show a flat tabular development somewhat similar to that of brookite, though these could not be positively determined as that mineral. The hexagonal plates of clove-brown color so frequent in hornblende and also in hypersthene occur also in this hornblende. They are believed to be micaceous ilmenite. The thin plates are translucent, thicker ones are less so, and those which are still thicker are opaque and metallic. The thin plates appear when on edge as fine, hairlike streaks. The thick ones appear in the same position as more or less rectangular bars or rods. Often these small plates are associated with masses of iron oxide, also included in the hornblende. This iron ore occurs in the plates and bars characteristic for ilmenite. These ilmenite masses are translucent only on the edges, where the slide has cut the mass in such a manner as to give an exceedingly thin section of the ore. At such places the ore is translucent with the same brown color as the thin plates. Another rare variety of the inclusions occurs in round grains of rich green color, and may possibly be a spinel.

In those sections in which both original brown and original green hornblende occur the inclusions are confined to the brown kind. Where the brown kind is surrounded by the green hornblende the inclusions gradually diminish in quantity as we approach the green zone. With this goes also, hand in hand, a lightening of the color of the including mineral (brown hornblende), and there is thus an imperceptible change from the brown to the green hornblende. Where the green hornblende occurs alone it is frequently as full of inclusions as is the brown hornblende of other sections. Individuals of the same sections differ from one another with respect to the quantity of the inclusions, some being crowded with them, while others are practically free from them.

This brown hornblende, on alteration, breaks up into aggregates of epidote-zoisite and light-green chlorite.

The second kind of hornblende is the perfectly fresh, compact, common dark-green kind, with pleochroism varying from yellow for $\mathfrak{a}$, to yellowish-green for $\mathfrak{b}$, and to bluish-green for $\mathfrak{c}$; $\mathfrak{c}>\mathfrak{b}>\mathfrak{a}$. This is found in very few cases. It appears in every instance to be a primary constituent.

The third kind of hornblende may be primary, although the evidence obtainable points to its secondary nature. It has a light-green color, and when examined for pleochroism exhibits a scarcely noticeable change. This hornblende differs very much from the other two hornblendes described, in that it is not compact, but occurs in aggregates of coarse reedlike (schilfaehnliche) individuals. Such aggregates do not at all resemble uralite. The individuals are far too coarse and wedge put at short distances within the aggregates. The aggregates occupy irregularly shaped areas. The aggregates consequently have a coarse patchy polarization. They are frequently surrounded by ragged pieces of biotite, just as are the plates of compact hornblende. Moreover, they occur in rocks which show pressure effects, and are best developed in those in which such effects are most marked. The aggregates rather frequently occur with irregular pieces of the greenish or brown compact interposition-bearing hornblende bordering the aggregates or in the midst of them. The light-green reedy hornblende never contains such interpositions, but does have associated with it fairly large grains of rutile, which may perhaps be considered as having been derived from the various titanium-bearing microlites in the original brown hornblende. The general appearance of these aggregates and their association with the original hornblende seem to point toward their secondary origin from the latter through the effects of pressure.

Pyroxene.—The pyroxene comprises both a monoclinic and an orthorhombic kind. These are the first of the bisilicates to crystallize in these gabbros. The monoclinic kind is of two varieties. The first is in colorless to faint-pink grains included in large plates of original brown hornblende. These grains have a well-developed prismatic cleavage. One basal section shows very nicely the characteristic pyroxene cleavage. The extinction measured against the prismatic cleavage reached as high as 50 degrees. This pyroxene is presumed to be augite. It never shows diallagic parting. In other sections the monoclinic pyroxene is a clear white to faintest green malacolite or diopside. This is in roundish grains included in the original green hornblende, which it equals in quantity.

The orthorhombic pyroxene occurs in individuals which show fairly good prismatic development, but with rounded terminal faces. The prismatic cleavage is very well developed. A transverse parting is also common. The pyroxene is usually colorless, but in some cases a scarcely noticeable pleochroism was observed, varying from a faint-greenish tinge for rays vibrating parallel to $\mathfrak{c}$, to a yellow for those parallel to $\mathfrak{a}$ and $\mathfrak{b}$. It contains small, dark, streak-like intrusions, some of which under exceptionally favorable conditions are transparent, with a faint-greenish tinge. The exit of the bisectrix in basal sections, as well as the parallel extinction, renders it easily distinguishable from the monoclinic pyroxene. The optical angle could not be measured, but was clearly very large, as the hyperbolas passed completely out of the field of view. The orthorhombic pyroxene is evidently enstatite or bronzite, and the pleochroism clearly points to its position near bronzite. A few crystals of rutile and also some of the ilmenite plates, so common in hypersthene, were found occurring in the

bronzite. The ilmenite plates are in rather rare irregular patches in the crystals.

In many cases along the cleavage lines or around the edges of the crystals or along the transverse parting planes are narrow zones of a secondary yellowish-green, finely fibrous, serpentinous mineral. Beyond these zones is a pure white aggregate of secondary talc scales (Fig. *B*, Pl. XXXVIII). Among these scales are a few minute rutile crystals, and also a few black ferruginous specks, these products being probably derived from the inclusions in the bronzite, and the ferruginous material possibly to some extent from the mineral itself. In some cases, instead of the intermediate serpentine zone, the rather rare occurrence is observed of the passage of the bronzite directly into the talc aggregate.

Olivine.—The determination of the original presence of olivine in the gabbroic rocks is based upon very slight evidence. In some of the sections containing augite almost every individual of this augite has near its center a rounded, very rarely irregular area of yellowish-green fibrous serpentine. These areas are sharply delimited from the surrounding pyroxene, and the conclusion seems warranted that it resulted from the alteration of some mineral included in the pyroxene. The only bisilicate found in the rocks of the district which crystallized before the pyroxene is olivine. In the peridotite, to be described in the next section, this is usually surrounded by monoclinic or orthorhombic pyroxene. This altered mineral is not important in quantity.

Iron oxide.—Ilmenite and titaniferous magnetite occur in some of the rocks in considerable quantity. Both alter to sphene and rutile.

Apatite.—Among the accessory minerals apatite is perhaps the most common, and, as usual, one of the very earliest minerals to crystallize. It is contained in all the essential constituents, and in biotite is surrounded by pleochroic halos. In some cases it has even crystallized before sphene. It is noticeable in some sections that great numbers of apatite crystals are arranged along lines representing sections of planes between the plagioclase plates, thus practically outlining the feldspar individuals.

Sphene.—In many cases in these gabbros sphene is found contained in some of the freshest rocks as an original accessory constituent. It is present in largest quantity in the very finest-grained gabbros, which show a parallel texture. In these rocks sphene in some cases surrounds an iron ore, which, to judge from the rod-like sections which are so common, is ilmenite. One might be led to think that the sphene was secondary in such cases, but the iron ore is perfectly fresh, and, considering that in the same thin section crystals of apatite are also surrounded by sphene, it seems clear that we may consider such sphene as original. It thus appears that a portion of the titanium oxide combined with the iron oxide first, forming the titanic iron ore. This was followed by the crystallization of the calcium-titanium compound, thus giving the sphene. In these rocks sphene is not in crystals, but in grains. These grains are arranged in long chains lying between the other mineral constituents and with the long direction of the individual grains, as well as of the lines of grains, parallel to the long directions of the other constituents of the rock.

Zircon and rutile.—Zircon is in very small quantity. Rutile shows its usual characters. It is most commonly associated with the octahedrite (anatase) and brookite (?) as inclusion in the hornblende. The iron oxide is chiefly present as ilmenite, with some titanic magnetite.

The secondary minerals have already been mentioned and their characters described under the description of the minerals from which they are derived.

DESCRIPTION OF INTERESTING KINDS OF GABBRO.

The minerals described above as the leading essential constituents of the rocks to be described may be combined in varying quantities. According to these combinations a number of different mineralogical types of rock may be produced. The wide range in mineral composition of the gabbroic rocks is equaled, if not surpassed, by similar variations noted by Fairbanks in certain rocks from Point Morrito, California.[1] It may cause the further description to be more readily understood if we preface it by the statement that all of these types, however, are simple facies of a single magma. The important phases which will be described are, in the order of their importance, hornblende-gabbro, consisting essentially of hornblende and labradorite; gabbro, consisting of monoclinic pyroxene and labradorite, and bronzite-norite, consisting essentially of bronzite and labradorite. The various mineralogical types exhibit very interesting ranges in texture in certain cases, to which attention will be called.

HORNBLENDE-GABBRO IN SEC. 15, T. 42 N., R. 31 W.

A hornblende-gabbro forms a large knob in sec. 15, T. 42 N., R. 31 W., just at the foot of the Norway Rapids, on the west bank of the Michigamme River. This exposure shows very prettily a change in texture. The change in texture is also accompanied by a slight mineralogical change. The knob is composed partly of a fine-grained granular, but more largely of a coarse-grained porphyritic, gabbro. The fine-grained portion is a pure gabbro composed of plagioclase and brown hornblende, with very little brown mica. No quartz was observed, nor was any orthoclase definitely determined. The plagioclase is in fairly well-developed automorphic plates. The hornblende is the brown variety, with numerous minute inclusions, which has already been described, and is not always so well developed as is the plagioclase. In places it plays rather more the role of a cement. This relation of the two minerals results in forming an imperfect ophitic texture in places, though on

the whole the two minerals are about equally developed, and produce a granular structure. (Fig. *A*, Pl. XLIV.)

[1]The geology of Point Sal, by H. W. Fairbanks: Bull. Dept. Geol., Univ. California, Vol. II, 1896, p. 56 et seq.

The coarse-grained porphyritic gabbro forming the greater part of the knob consists of plagioclase, hornblende, biotite, and iron oxide, with a very small amount of pyroxene. The hornblende occurs in phenocrysts which have irregular rounded shapes instead of being well crystallized. Some of the largest phenocrysts have a diameter of slightly less than 1 centimeter. They are poikilitic, rendered so by inclusions of lath-shaped plagioclase and rounded grains of pyroxene. (Photomicrograph, fig. *A*, Pl. XLI.) This porphyritic hornblende is a dark reddish-brown variety containing such great numbers of minute inclusions as to be opaque in many places, which grades over into, and is in many places in optical continuity with, a dirty green hornblende. This green hornblende is in anhedra and forms the cement for the feldspar, and the two together the groundmass for the brown hornblende phenocrysts. The plagioclase is most commonly in broad, well-developed crystals, which frequently give quadratic sections. Some few grains of a pink monoclinic pyroxene are included by the hornblende.

SECS. 15, 22, 28, AND 29, T. 42 N., R. 31 W.

Exposures of a hornblende-gabbro with interesting facies associated with it occur in the southeastern corner of sec. 15, at the southeastern corner of sec. 22, extending east and west through the northern part of sec. 28, at the southeastern corner of sec. 28, and on the west bank of the Michigamme River in sec. 29, T. 42 N., R. 31 W., at the location N. 100, W. 1,250 paces. This is medium to coarse grained and of a gray color from a short distance. Examined at moderately close quarters, one distinguishes very readily a milky white feldspar and a black or dark-green hornblende in about equal quantities. The microscopical examination adds to these two minerals in a very subordinate quantity biotite, pyroxene, and orthoclase. The labradorite plagioclase is in medium-broad, irregular plates, though at times approaching a very distinctly lath-shaped form. The orthoclase is present in a few rare individuals in the form of irregular plates. The hornblende constituent is in irregular plates and varies in character. It may be the brown or the green variety already described, or the two together in separate individuals, or even the brown grading into the green. This green is original and not the alteration product of the brown. Biotite is the normal reddish-brown kind in irregular plates. The pyroxene is usually absent from the sections of these rocks, but when present it is very rare, and occurs in small irregular grains not uncommonly intergrown with the hornblende and evidently older than the hornblende. It is light green in color, with a scarcely noticeable pleochroism. Its monoclinic character was readily determinable; but a more exact determination was not made. It does not, however, show diallagic parting, and is diagnosed as possibly diopside.

The feldspar shows the best development of the accessory minerals. It can rarely, however, be said to be automorphic. The texture is, on the whole, granular.

From a mineralogical study of the rocks alone, one would unhesitatingly place them with the diorites, especially if those facies were seen in which the pyroxenic constituent was wanting.

The following analysis (Sp. 23354), obtained from Mr. George Steiger, of the United States Geological Survey, shows the chemical composition of one of these rocks:

Analysis of hornblende-gabbro.

	Per cent.		Per cent.
SiO_2	49.80	K_2O	.61
TiO_2	.79	Na_2O	2.22
Al_2O_3	19.96	H_2O 100°−	.13
Fe_2O_3	6.32	H_2O 100°+	1.71
FeO	.49	P_2O_5	.07
MnO		CO_2	.15
CaO	11.33	Total	100.63
MgO	7.05		

An examination of the analysis shows that the microscopical determination of the rock as a diorite would be incorrect if we accept, as has been done in the preceding pages, Brögger's characterization of the diorite and gabbro families.[1]

The rock analyzed is hornblende-gabbro, as shown by the relatively high content in the characteristic alkaline earths, especially magnesia, which usually appears in inverse proportion to the silica, and in the low percentage of alkalies.

[1]Op. cit., Part II, pp. 35, 39.

HORNBLENDE-GABBRO DIKES.

One of the exposures of the above-described hornblende-gabbro—the one on the west bank of the Michigamme River in section 29—is very interesting on account of at least two different series of dikes which cut it. The coarse-grained hornblende-gabbro forms the main mass of the knob. The dike rocks may be divided into the fine-grained hornblende-gabbro forming the earliest dikes and the coarse-grained bronzite-norite forming the latest dike.

Some of the specimens of the fine-grained rock are massive, but the greater portion possess a distinctly parallel texture. These are distinctly micaceous. The rock of the dikes has in general very much the macroscopical appearance of a biotite-mica-schist. The dikes are very narrow, never more than 18 inches wide. The larger ones send off branches, and in places inclose angular pieces of the coarse diorite. Thus the relation of this fine-grained rock to the main gabbro mass is perfectly clear, though in places it so closely resembles, macroscopically, pieces of mica-schist that in spite of the branching of these dikes, indicating their intrusive nature, they were supposed by one observer to be curiously shaped stringers of the mica-schists included in the main mass of the gabbro.

The notes do not indicate from just what portions of the dike the specimens were taken; hence it is impossible to state positively that the more schistose parts are nearest the edges and the more granular portions nearer the center, as one would naturally expect. However, in all but one of the specimens which show a contact between the dikes and gabbro which they penetrate, the rock nearest the contact shows a parallel structure. Hence it may be stated that in some cases the edges of the dikes are the more schistose portions. The one specimen referred to above is granular and much finer grained along the contact than farther from it.

The microscope shows the rock of these dikes to be a gabbro differing little in character from the main mass. The plagioclase is well developed in rectangular, more or less lath-shaped crystals. Mica of a rich brown color is rather more abundant than usual, and is in about equal quantity with the hornblende. The hornblende is brown or of a dirty greenish color, containing the inclusions mentioned in the detail descriptions of the minerals of the gabbros. Some irregular grains of a light-green augite (diopside) were observed in the sections. Orthoclase (?) in grains is present simply as an accessory. Ilmenite occurs in irregular masses in rod-shaped pieces. Sphene is present in original grains and also as a secondary product after ilmenite. Apatite occurs and is sometimes included in the sphene.

The most striking feature of the rock is its textural variation. Some of the sections show very good granular texture; others have a fair ophitic texture; the most common is a striking parallel texture which macroscopically gives to the rock a schistose appearance. This may be seen even in the same section with the ophitic texture, the two grading into each other. The parallel texture is occasioned by the arrangement in a common direction of the long diameters of nearly all of the minerals (figs. *A* and *B*, Pl. XLII). The grains of sphene often lie in long trains agreeing with this general parallelism. One's first idea would probably be that the texture was due to the cause which has produced parallel structures in most other ancient rocks—pressure. However, it can not be referred to this, as the minerals— with some individual exceptions—show slight or no pressure effects. Apparently the only explanation borne out by the facts in this case is that we have to do with a fluidal texture, produced by the movement in the magma consequent upon its injection along the fissures in the gabbro, the parallelism of the minerals agreeing with the bounding sides of the fissure.

BRONZITE-NORITE DIKE.

The main hornblende-gabbro and the fine-grained dikes just described are cut by a dike, about 3 feet wide, of coarse rock which resembles that forming the main mass of the knobs in every way except that it contains a very much altered orthorhombic pyroxene (bronzite) in greater quantity than the hornblende. The rock is a very pure kind of bronzite-norite (fig. *B*, Pl. XLIV). The following analysis (No. 1, Sp. 23755), by Mr. George Steiger, shows the gabbro affinities of the rock. The high percentage of magnesia gives a clear indication of the important role played by the bronzite in the composition of the rock.

With the analysis of the bronzite-norite there is placed for comparison an analysis (No. 2) of a norite from Ivrea, Italy, which is essentially the same as the above in mineralogical as well as chemical composition. In the Italian rock hypersthene, instead of bronzite, is the chief pyroxenic constituent.[1]

[1]Petrographische Untersuckungen über die noritischen Gesteine der Umgegend von Ivrea in Oberitalien; by F. R. van Horn: Tschermaks mineral, Mittheil., Vol. XVII, 1897, Part V, p. 404.

Analyses of norites.

	1.	2.
SiO_2	48.23	49.95
TiO_2	1.00	.69
Al_2O_3	18.26	19.17
Fe_2O_3	1.26	4.72
FeO	6.10	6.71
MnO	.....	Trace.
CaO	9.39	9.61
MgO	10.84	5.03
K_2O	.73	.74
Na_2O	1.34	3.13
H_2O 100° —	.26	.09
H_2O 100° +	2.00	
P_2O_5	.07	Trace.
CO_2	.43	.....
Total	99.91	99.84

SEC. 29, T. 42 N., R. 31 W., 1,200 N., 200 W.

On the east bank of the Michigamme River at 1,200 paces N., 200 W., sec. 29, T. 42 N., R. 31 W., there is an outcrop which shows even better than the occurrence just described the variation in mineralogical character and the relative ages of these varieties. At this place there is a knob composed of hornblende-gabbro essentially like the general type described as typical for this district. This knob is cut by a rock which is coarser in grain and a trifle darker than the variety which it intrudes. Examined under the microscope, it is seen to differ from the normal phase also in mineralogical composition, and resembles rather closely in this respect the porphyritic variety described on p 240. Like that, the hornblende is reddish-brown, containing a large number of inclusions and grading over into the green hornblende. This hornblende includes rounded grains of a white to pinkish monoclinic pyroxene in sufficient quantity to be characteristic. The pyroxene is never automorphic, as one would perhaps expect to find it, though it was evidently one of the first minerals to crystallize. Contained in the pyroxene individuals are rounded areas of yellowish-green serpentine. These areas are sharply outlined from the pyroxene and do not appear to be the result of its alteration; consequently the conclusion is reached that the serpentine results from the alteration of a mineral older than the pyroxene. Most probably this mineral was olivine, though no positive

statement to that effect can be made. This pyroxene rock also contains an exceedingly large quantity of apatite. No analysis was obtained of this facies, but the microscopical characters enable us to place it as a gabbro (possibly olivine-bearing) and to consider it, like the bronzite-norite, as a facies of the predominant hornblende-gabbro.

This same exposure of gabbro is cut by a coarse peridotite (wehrlite), a description of which will be found on p. 253. In this peridotite there is found a narrow strip of rock, about 2 inches wide, which is presumed to be either an inclusion or a very narrow dike in the peridotite. The exposure does not admit of its relations being determined more accurately. The presumption is that it is a dike. Whether an inclusion or a dike, it is younger than the massive hornblende-gabbro forming the main exposure. In this respect it corresponds to the gabbro just described (p. 243) as cutting the normal gabbro.

This dike rock is macroscopically a fine-grained, granular, dark-gray rock. The microscope shows it to be very fresh, porphyritic in texture, and composed of phenocrysts of bronzite lying in a finely granular ground-mass of plagioclase, hornblende, and orthorhombic and monoclinic pyroxene. No quartz whatever was found associated with these minerals. The plagioclase is the usual kind, labradorite. Some unstriated feldspar, possibly orthoclase, was also observed, though in very small quantity. The bronzite is in narrow prisms which reach a length of 1.23 mm. Commonly they have well-developed transverse partings. It is worthy of note that a few of the crystals contain the brownish platy inclusions so common in hypersthene. There is, however, no relation between the color and pleochroism of the mineral substance and these brownish plates. The bronzite is very clear, with weak color, showing a scarcely distinguishable greenish tinge for the rays vibrating parallel to $\mathfrak{c}$, with yellowish for the rays parallel to $\mathfrak{a}$ and $\mathfrak{b}$. In one case the bronzite was seen altering to a greenish-yellow fibrous aggregate of serpentine. In the groundmass this same orthorhombic pyroxene is represented by irregular grains. The hornblende is the usual reddish-brown kind, but differs from that seen in the other gabbros of this district in that it contains ilmenite inclusions only, without any rutile or anatase. It is in anhedra. A faint-greenish pyroxene occurs in irregular xenomorphic individuals, forming a somewhat smaller proportion of the groundmass than does the hornblende, but is more abundant than the bronzite of the groundmass. Sphene is present in considerable quantity, and likewise ilmenite (fig. *A*, Pl. XLV).

This rock stands between the hornblende-gabbros and the norites. In texture it might be compared with the norite-porphyrite (enstatite-porphyrite of Rosenbusch) with holocrystalline groundmass. But it differs essentially from this rock in the presence of a large quantity of hornblende. This hornblende connects it with the hornblende-gabbros, from which its content of pyroxene, both orthorhombic and monoclinic, tends to separate it. Owing to its obvious relation to the bronzite-norites, which, like it, occur as differentiation facies of and dikes in the hornblende-gabbro, I shall call it a "bronzite-norite-porphyry," using the term "porphyry" purely in a textural sense.

The rocks may be compared, in their variation, to those described by G. H. Williams from Maryland,[1] by Chester from Delaware,[2] and by Fairbanks from California.[3] A series of basic rocks similar in many respects to those of Crystal Falls has also recently been described in two interesting papers by Van Horn[4] and Schaefer.[5]

DYNAMICALLY ALTERED GABBRO.

Near the junction of secs. 26, 27, 33, 34, T. 43 N., R. 31 W., there is a large gabbro mass which shows marked evidence of dynamic action, and may well be cited as an example of a metamorphosed gabbro, or, perhaps more clearly, as a rock intermediate between a hornblende-gabbro and a hornblende-gneiss. None of the gabbros thus far described show any evidence of having taken part in very extensive orogenic movements. The minerals of but few of them show more than the common phenomenon of slight wavy extinction. Hence it is clear that their intrusion took place after the occurrence of the mountain-building movements to which the intruded rocks have been subjected. It is not believed that the mass referred to in this description is an exception to the general rule, but that its metamorphosed condition is referable to local causes, such as have produced the shearing planes to which allusion has been made (p. 234). It may perhaps occur near or along some minor fault plane, though no indications of a fault have been observed.

[1]The gabbros and associated hornblende rocks occurring near Baltimore, by G. H. Williams: Bull. U. S. Geol. Survey No. 28, 1886; Outline of geology of Maryland, Baltimore, 1893, p. 39.

[2]The gabbros and associated rocks in Delaware, by F. D. Chester: Bull. U. S. Geol. Survey No. 59, 1890.

[3]The geology of Point Sal, by H. W. Fairbanks: Bull. Dep. Univ., California, Vol. XI, 1896, p. 56 et seq.

[4]Petrographische Untersuchungen über die noritischen Gesteine der Umgegend von Ivrea im Oberitalien, by F. R. van Horn: Tschermaks mineral., Mittheil., Vol. XVII, 1897, Part V, pp. 391-420.

[5]Der basische Gesteinzug von Ivrea im Gebiet des Mastallone-Thals, by R. W. Schaefer: Tschermaks mineral., Mittheil., Vol. XVII, 1898, Part VI, pp. 495-517.

The outcrop is composed in part of massive gabbro and in part of the metamorphosed kind. The gabbro in its typical massive form (fig. *A*, Pl. XLIII) is a medium to coarse grained granular rock, composed essentially of plagioclase and dirty brown-green compact hornblende, the latter being quite full of the inclusions mentioned above as commonly occurring in the hornblende of the rocks in this region. In the metamorphosed rock the grain is much finer, the rock possesses imperfect schistosity, and the color is a lighter green than in the original. The component minerals are chiefly hornblende and feldspar, with some quartz, chlorite, epidote, calcite, and rutile. The hornblende has a light-green color. It occurs mainly in aggregates of small irregular grains. In some cases these surround an angular nucleus of dirty

brown-green original hornblende containing the same inclusions and in every way similar to that of the coarse-grained uncrushed rock. The light-green hornblende contains none of these minute inclusions and only here and there grains of rutile, which, if the diagnosis of the interpositions as titanium minerals is correct, may possibly be considered as having been derived from them. This hornblende is believed to be secondary. It is produced by a process of mechanical breaking down of the original hornblende, accompanied by recrystallization. The process is somewhat similar to the crushing of ordinary plagioclase and the production of a more acidic variety. As may be seen from the photomicrograph (fig. *B*, Pl. XLIII) of a section, the feldspar exhibits signs of intense crushing. The twinning lamellæ are strongly bent, and the pieces possess wavy extinction. Many, in fact most, of the feldspars are fractured. Wherever these fractures occur the feldspar along the edges of the fractured portions has been altered, producing secondary epidote, muscovite, plagioclase feldspar, and quartz; the last, however, in small quantity. The biotite has been crushed. This has partly altered to chlorite, and the latter contains many grains of epidote. Some granular calcite and considerable iron pyrites are also found in the altered rocks. These secondary products are easily distinguished from the original minerals by the total absence in them of wavy extinction. The effect of the crushing upon the texture has been to render it more or less schistose, the resulting rock resembling in its mineralogical character, and in texture, an ordinary hornblende-gneiss, or, when quartz is present in but small quantity, a plagioclase amphibolite.

RELATIVE AGES OF GABBROS.

An attempt to determine the relations of the varieties described resulted in the establishment of the following order of intrusion: The typical coarse-grained hornblende-gabbro was the first formed, and seems to be the most widely distributed. This was then intruded by dikes of gabbro, which contain both monoclinic pyroxene and hornblende in association and represent a gradation to the normal gabbro. These hornblende-gabbros and normal gabbros were then cut by the dikes of bronzite-norite and bronzite-norite-porphyry.

PERIDOTITES.

Until recently all of the ultrabasic rocks were included by most petrographers under the family name of peridotite. In the last edition of his Mikroskopische Physiographic, Rosenhusch has separated these rocks into the plutonic rocks and the volcanic rocks. The term “peridotite” is restricted to the first, and the last are called the “picrites.” The characteristic differences between these two types are very clearly shown in the specimens from the Crystal Falls district which I have had the opportunity of studying. The rocks here described agree with Rosenbusch’s narrower definition of the peridotites.[1]

DISTRIBUTION, EXPOSURES, AND RELATIONS.

The peridotite dikes were all found near the Michigamme River, in secs. 29 and 22, T. 42 N., R. 31 W. Typical wehrlite with very little green amphibole is found on the east bank of the Michigamme river, near the center of sec. 22, T. 42 N., R. 31 W. It shows no relations to the other rocks. The amphibole-peridotite, exhibiting marked variations to wehrlite and olivine-gabbro, forms an outcrop on the east bank of the Michigamme River in the NE. ¼ sec. 29, T. 42 N., R. 31 W. This dike cuts the gabbro. A rock to be described last, connecting the diorites, gabbros, and peridotites, was taken from near the northeast corner of sec. 22, T. 42, R. 31, where it is found cutting the gabbro.

[1]Op. cit., p. 343.

PETROGRAPHICAL CHARACTERS.

The peridotites are very dark green to black coarse-grained rocks, showing in almost all cases a granular texture. In one case an excellent poikilitic texture was observed, and in another the same texture in a very imperfect condition was seen. The almost total absence of any pressure phenomena in these rocks excludes the idea of their having been subjected to any powerful dynamic action. The chief mineral constituents, arranged in order of relative amounts, are pyroxene (monoclinic and orthorhombic), olivine, hornblende, and biotite. The following minerals also occur associated with these: Feldspar, apatite, green and brown spinel, and iron oxide.

Pyroxene —There is present in these rocks both orthorhombic and mono-clinic pyroxene. The orthorhombic has a yellowish tinge, and contains a few tabular inclusions. Only a few grains of this pyroxene were found, but upon one section a figure was obtained and the positive character of the mineral was determined. It appears to be bronzite. The bronzite grains are found included in the hornblende. Its relations to other minerals are not shown in any of the thin sections.

The monoclinic pyroxene, though one of the earliest minerals to crystallize, is likewise in xenomorphic individuals, many of them twinned, some polysynthetically. It is usually of a light yellowish color, and is then nonpleochroic; in some sections, however, it is sufficiently colored to show pleochroism from light yellowish to brownish. It includes a number of the clove-brown tabular interpositions like those in the hornblende, and these at times give the pieces a decided violet tinge. Less commonly than the tabular interpositions one observes green needles and laths, more rarely rounded grains or plates of larger size and having a brownish-green color. They are so minute as to defy positive determination, but are presumed to be hornblende microlites. The orthopinacoidal parting is in some cases well developed in the augite. This diallagic augite is in large quantity, and though usually included in the hornblende, nevertheless includes both hornblende and biotite in a few ragged plates. Such sections are

probably those which have passed through the outer edges of the augite crystals.

Olivine.—This is present most commonly in round anhedra, and is usually almost entirely altered to yellowish-green serpentine fibers. When the olivine is completely altered, the mesh structure affords a ready means of recognizing the original mineral, especially when taken in conjunction with grains of a rich-green isotropic mineral, and also octahedra and grains brown in color, probably spinels, which are found included in the pseudomorphs.

Hornblende.—The most of the hornblende in the peridotites is a brown variety showing strong pleochroism. $\mathfrak{a}$ is light cream-yellow, $\mathfrak{c}$ is yellowish brown, and $\mathfrak{b}$ is reddish brown; $\mathfrak{b}>\mathfrak{c}>\mathfrak{a}$. Patton[1] has already called attention to the pleochroism of the hornblende, which "is exceptional, inasmuch as the brownest color is that of rays of light vibrating parallel to the orthodiagonal axis." The brown hornblende is accompanied by a very small quantity of green hornblende. Moreover, the brown hornblende grades over into a light green, the two being in perfect crystalline continuity. In rare cases this brown hornblende is also intergrown with a light-green pyroxene in such way as to give a mottled polarization effect. The pinacoidal cleavage of the hornblende continues through the pyroxene, and the extinction angle of the hornblende against this cleavage is 19 degrees, while that of the pyroxene runs up to 34 degrees. The hornblende includes numerous anhedra of pyroxene, somewhat fewer grains of olivine, and, less commonly, ragged pieces of biotite, giving it a poikilitic character. It is also very full of opaque metallic or brownish translucent plates of ilmenite. In some individuals minute clear microlites, similar to those described above in the hornblende of certain gabbros, are noticed in small quantity. These are irregularly distributed in the hornblende, giving the crystals a patchy appearance. In respect to its color and these inclusions, this hornblende, as noted by Patton, bears a rather striking resemblance to hypersthene on superficial examination.[2] Iron ore in large masses is fairly frequent as an inclusion, and it is very commonly noticeable that where such inclusions occur the zone of hornblende immediately surrounding them is free from the platy inclusions mentioned above. Such a clear zone is also observed at times surrounding the inclusions of biotite and olivine, but never in case of pyroxene. Where these clear zones surround the included biotite or olivine, these two minerals have associated with them numerous small grains of ore, which probably represent the iron that would have been incorporated in the surrounding hornblende but for some selective influence exerted by the olivine and biotite.

[1]Microscopic study of some Michigan rocks, by H. V. Patton: Rept. State Board of Geol. Surv. for 1891-92, 1893; p. 186.

[2]Loc. cit., p. 186.

Biotite.—This mineral is present in flakes of very irregular outline. The pleochroism varies from cream color to yellowish red or brown. Although one of the last minerals to crystallize, its crystallization began before that of the pyroxene or hornblende had entirely finished. Hence we find flakes of it included in these minerals, but near the edges of the crystals. The biotite itself is almost free from inclusions, containing only a little hematite and magnetite. It alters to a brilliant green, strongly pleochroic, chloritic mineral.

Feldspar.—This is present in specimens from two outcrops, and in these hardly reaches the rank of an essential constituent. It was the last mineral to crystallize, and is consequently in anhedra, forming the mesostasis. All of the feldspar sections were tested, but no determinative measurements could be made. It is probably very basic.

Apatite.—Apatite is present in small quantity. It exhibits its usual characters.

Spinel.—There is a spinel found in round grains which are included in the olivine (serpentine). It is green in color, and is possibly pleonaste. A second spinel, probably picotite, occurs in small brown grains and octahedra in the olivine.

Calcite.—This mineral, derived partly, if not wholly, from the altering minerals, is found in lenses between the biotite lamellæ and in minute veins which traverse the slide.

Iron ores.—Iron ore is represented by hematite, magnetite, and pyrite. The hematite is in blood-red transparent flakes inclosed in the biotite. Magnetite is included by all of the chief minerals, and is in irregular masses without good crystal development. The iron pyrite is found in good crystals, though not in large quantity, and is scattered here and there through the slides.

PERIDOTITE VARIETIES.

The relative proportions of the minerals described above differ very much, and we have different kinds of rocks corresponding to these mineralogical variations. These kinds are not sharply separated, but are seen under the microscope to grade into one another.

The purest form of peridotite is wehrlite, which is composed essentially of olivine and augite. When, besides these minerals, hornblende is present in large quantities, the rocks belong to the amphibole-peridotite type. In some specimens biotite is almost in sufficient abundance to warrant the naming of them biotite-peridotite. Again, in other specimens feldspar is present in considerable quantity and the rock approaches an olivine-gabbro or olivine-hornblende-gabbro.

WEHRLITE.

This is represented by a coarse-grained rock which is mottled and has a dark-green color. (Specimen 23763, from sec. 22, T. 42 N., R. 31 W., N. 1,500, W. 900 paces.) Under the microscope the mottling is seen to be due to the association of very dark greenish-black

serpentine pseudo-morphs after olivine with a light-colored augite.

Olivine and augite were present in about equal quantities. They are in anhedra, and therefore must have crystallized at about the same time. The olivine is, with very few exceptions, completely altered to serpentine. Augite has a very poor development. Between the olivine and augite are small quantities of irregular plates of biotite. A few small irregular pieces of a very light colored greenish hornblende were observed. They are intergrown with the pyroxene and give it an imperfect poikilitic texture.

This wehrlite is unquestionably the same as specimen 1247 of the Geological Survey of Wisconsin, described by Dr. A. Wichmann as serpentine, consisting chiefly[1] of serpentine with some unaltered olivine and augite.

AMPHIBOLE-PERIDOTITE.

This variety of peridotite was obtained from the outcrop N. 1,260, W. 200 paces from the southeast corner of sec. 29, T. 42 N., R. 31 W., on the east bank of the Michigamme River. The rock is very coarse grained, and possesses poikilitic texture. It is composed of hornblende, pyroxene, olivine, biotite, and iron oxide. The hornblende equals in quantity all of the other constituents. Some of the hornblende individuals measure 3 cm. in length, and include all of the other constituents except the biotite. The pyroxene and olivine seem to have crystallized at about the same time, as they never include each other. They are both, however, included in the hornblende, which with the biotite forms, as it were, the mesostasis. Biotite is present in this specimen in very small quantity, and is essentially the same kind as that above described (p. 252), except that it shows a trifle higher absorption parallel to the cleavage and becomes a yellowish-red. The rock is very fresh and shows scarcely any traces of alteration. This is partly due to the erosive action of the Michigamme River having removed the weathered crust, thus making fresh specimens obtainable.

[1]Microscopical observations of the iron bearing (Huronian) rocks from the region south of Lake Superior, by Dr. Arthur Wichmann, Leipzig, 1876: Geol. of Wisconsin, Vol. III, 1880, p. 619.

This rock, from the description just given, would be classified as an amphibole-peridotite, with accessory diallage, bronzite, and biotite. It approaches Williams's cortlandtite. In some specimens the biotite is present in very large quantity, though hardly in sufficient quantity to warrant the designation of any of the rocks as biotite-peridotite.

GRADATIONS OF AMPHIBOLE-PERIDOTITE TO WEHRLITE AND OLIVINE-GABBRO.

There were taken from the same exposure whence the above-described amphibole-peridotite came some specimens which macroscopically can not be distinguished from those of the amphibole-peridotite except in that they are a trifle finer grained. Examined under the microscope, however, we find differences. In some the hornblende is very much reduced in quantity, and varies from the brown kind just described to a light-greenish color, the two being in optical continuity, and the augite and olivine are increased in quantity. These are good types of a wehrlite. In some of the wehrlites there is a variable percentage of feldspar. In certain cases it reaches an amount which would almost warrant the classing of the rock as an olivine-gabbro. Patton described a rock from the same outcrop in which the hornblende still predominated, but in which there was also a certain amount of plagioclase.[1] He called it a hornblende-picrite.[2] According to the terminology here used, if the plagioclase is to be neglected, it would be an amphibole-peridotite.

The thin sections of the feldspathic phase of this rock seem to show that it approaches more closely to a gabbro—that is, to be more feldspathic than the one described by Patton. They certainly contain far less hornblende than his, judging from his description, and more feldspar. The constituents are the same in the two rocks, and with some few modifications his description would answer.

[1]Mikroscopische Physiographie, by H. Rosenbusch; 3d ed., Stuttgart, Vol. II, 1896, p. 352.

[2]Op. cit., p. 186.

Augite is the chief constituent, and following it, in order of importance, come olivine, hornblende, biotite, and feldspar. The diallagic augite is more automorphic (see fig. *B*, Pl. XLV) as the feldspar increases in quantity. It is the only one of the minerals which shows any marked degree of automorphism. The augite present in the sections which I have studied has a light-brownish color, differing from that described by Patton, which is green to colorless. The augite contains the inclusions occurring in hypersthene, as well as the green (hornblende?) ones already described. It is invariably surrounded by a narrow rim of light-brown hornblende, and includes in places on the edges irregular patches of the same brownish hornblende.

J. Romberg describes the augite in Argentinian gabbros,[1] both with and without olivine, as being almost always surrounded by a rim of green hornblende. In one case, however—that of the olivine gabbro from the island of Martin Garcia, in the La Plata River[2]—both brown and green hornblende is present around the augite. The brown hornblende forms part of the periphery of a crystal; the green the remaining portion. Of the green hornblende some is fibrous, and is considered by Romberg to be certainly secondary.

The olivine possesses its usual properties. It is in annedra, with the exception of three or four individuals, which show a fair degree of automorphism. The olivine includes rounded grains of a brown spinel, and is traversed by anastomosing veins of the iron oxide. It shows the usual alteration to serpentine, and the iron oxide is the result of this serpentinization. The olivine is of exceptional interest on account of the fact that it is surrounded by certain zones where it is close to the

feldspar (figs. *A* and *B*, Pl. XLVI). The characters of zones observed in sections from this same locality, and which are almost, if not quite, identical with these which I shall proceed to describe, have already been described by Patton.[3] There are two of these zones. An inner one is composed of a mineral which is probably an orthorhombic pyroxene. It was so determined by Patton in

[1]Untersuchungen an Diorit-Gabbro-und Amphibolitgesteinen aus dem Gebiete der Argentinianen Republik, by J. Romberg: Neues Jahrbuch für Mineral., BB. IX, 1894, pp. 320-321.

[2]Op. cit., p. 322.

[3]Op. cit., p. 168.

the specimens collected and studied by him. I can obtain no positive proof for or against this statement. If it is an orthorhombic pyroxene, it agrees with the inner zones of related occurrences which have been described by Tornebohm, G. H. Williams, Adams,[1] Romberg,[2] and others. This zone is at any rate composed of a colorless, compact mineral, with high single and moderately high double refraction. Its single refraction is nearly equal to that of olivine. The mineral, as a rule, extinguishes parallel to the lines of cleavage. In a few instances the line of extinction made a scarcely noticeable angle with the cleavage. It is separated from the olivine by a sharp line. At times this inner zone seems to disappear, and at others becomes considerably broader than the average. The width is usually about 0.02 mm., though it becomes at times 0.08 mm.

Outside of this pyroxene zone there is a very much broader zone of light-green hornblende. This is compact, and is in optical continuity with the ordinary brown hornblende, which is the dominant hornblende in the rock. This, in its compact nature and in its relation to the compact brown hornblende of the rest of the slide, differs from the short fibrous actinolite zone ordinarily described as taking part in such “reaction rims.” This hornblende zone reaches an extreme width of 0.15 mm. The outer edge of this zone is penetrated by tubular ramifying growths of a colorless mineral, which usually extend inward, perpendicular to the periphery, and which appear to be continuous with the feldspar. This portion of the hornblende rim is about 0.05 mm. wide. No such intergrowth of feldspar with the brown hornblende was found, nor have I been able to find elsewhere any description of such an outside zone.[3] However, Romberg describes the interesting occurrence in an olivine-gabbro from the Argentine Republic of zones around the hornblende which are very much like those above described, except that the pseudopodia-like growths, as he describes them, consist of a dark-green spinel instead of a clear white feldspar, as in the Michigan rock.

[1]Uber das Norian oder Ober-Laurentian von Canada, by F. D. Adams: Neues, Jahrbuch für Mineral, BB. VIII, 1893, p. 466, where references to observations made previous to 1893 may be found.

[2]Op. cit., p. 322.

[3]Op. cit., p. 323.

In some cases, where the olivine and augite are in juxtaposition, the inner orthorhombic pyroxene zone completely surrounds the olivine. The outer hornblende zone, however, surrounds both the augite and the olivine with its orthorhombic pyroxene zone. Where it is in contact with the augite it is the brown variety of hornblende, but is in optical continuity with the green, which is the kind around the olivine and the orthorhombic pyroxene.

Of the remaining mineral constituents brown hornblende is the next one in importance. It has in it patches of inclusions, previously described as occurring in the hornblende of these ultrabasic rocks. It includes also the augite and olivine. This brown hornblende is comparatively rarely found in large plates, but usually as a rim of varying width around the augite and olivine, as already described. Where it occurs in large plates it is in that part of the section which is free from feldspar, and more closely resembles the amphibole-peridotite phase.

The biotite has a cream to light yellowish-brown color, and occurs in irregular plates. The plagioclase feldspar is in irregular broad plates, and forms the mesostasis. The feldspar contains, in not very large quantity, small microlites, which by very high power are translucent and show a greenish tinge. They are supposed to be hornblende microlites.

PROCESS OF CRYSTALLIZATION.

From the relations described as existing between the various minerals it seems that the following stages may be outlined in the progress of the consolidation of this rock. From the coarse even-grained character, and from the fact that neither a fine-grained groundmass nor glass is present, the conclusion seems to be warranted that it crystallized under high pressure and must have, of course, at some time been under very high temperature also.

The augite and olivine were the first and chief silicate constituents to form, and crystallized out of the magma at approximately the same time. The magma soon reached a condition unfavorable for further production of olivine, probably on account of increasing acidity. Immediately around the olivine there was formed, at this stage for a short while, the orthorhombic pyroxene. The monoclinic pyroxene continued to grow during the formation of this orthorhombic variety. Finally, however, the condition was reached when, in place of the monoclinic and orthorhombic pyroxenes, the crystallization of hornblende began.

It is not known what the conditions were which caused the formation of the hornblende subsequent to and in such intimate association with the pyroxene which it surrounds in zonal growth. An explanation of such occurrences has been attempted by Becke in a recent article,[1] in which the conclusion is reached that the formation of the hornblende and pyroxene depends upon changes in temperature and pressure. His explanation

is based upon the facts of occurrence of pyroxene and hornblende in plutonic and effusive rocks, and also upon the well-known fact that under high temperature and atmospheric pressure they can not exist, but when fused recrystallize as pyroxene; and in addition to this, upon the experiments of Von Chrustschoff,[2] who has obtained hornblende at a temperature of 550 C. with the presence of water, under which conditions a high pressure must be developed. However, attention should be called to the fact that his explanation does not take into account other important factors which certainly influence the crystallization of minerals—for example, the chemical composition of the magma and the fusing point and specific gravity of the minerals.

Whatever the factors are which determine its crystallization, the fact is that hornblende began to crystallize from this peridotite magma in the place of pyroxene.

The biotite appears to have been formed at the same time with the hornblende. The production of these two minerals, hornblende and biotite, then continued until the remaining magma had reached the composition of basic feldspar, which then crystallized and now forms the mesostasis.

A zone of orthorhombic pyroxene, succeeded by one of hornblende, has been described as surrounding the olivine in this peridotite. The term *reaction rim* has been applied to similar zones by various observers, but it seems to me that this term is inapplicable to such zones. It is not probable in such a case as this that there is a reaction between the magma and the olivine. Moreover, the zones should not be compared to the *resorption rims* found so commonly in certain effusive rocks, where from the fusion of the hornblende crystals pyroxene has been produced.

Such a zonal growth around the olivine seems to me comparable to such a case as that described by Washington,[3] where colorless diopside phenocrysts are surrounded by a narrow border of yellowish-green augite, which corresponds to the small augites in the groundmass, or to those cases which are so common in plutonic rocks—even in this rock described—where hornblende is found surrounding the pyroxene.

[1]Gesteine der Columbretes; Anhang: Einiges über die Beziehung von Pyroxen und Amphibol in Gesteinen, by F. Becke: Tschermaks mineral. Mittheil,, Vol. XVI, 1896, pp. 327-336.

[2]Bull. Acad. imp. sci. St.-Pétersbourg, 1890, p. 13. Cf. Becke, Op. cit., p. 337.

[3]Italian petrological sketches; 4. The Rocca Monfina region, by H. S. Washington: Jour. Geol., Vol. V, 1897, p. 254.

A general explanation which would account for the successive crystallization of hornblende and pyroxene in this rock should be applicable to such a zonal growth as occurs around the olivine, takings into consideration, of course, the probability that a factor of slight importance in the one case may be the controlling factor in the other. Such occurrences seem clearly to indicate a change in the chemical composition of the magma as the chief factor in the crystallization of the different minerals, in the pressure, in the temperature, and also in other factors, either one alone or more of these combined.

ANALYSIS OF PERIDOTITE.

The peridotite just described was analyzed by Dr. H. N. Stokes of the United States Geological Survey, and his results are here given (No. 1):

Analysis of peridotite.

	1 (23353).	2 (22981).
SiO_2	44.99	37.36
TiO_2	.97	.79
Al_2O_3	5.91	4.76
Cr_2O_3	.25	.62
Fe_2O_3	3.42	6.61
FeO	8.30	6.12
MnO	Trace.	Trace.
NiO	.....	.04
CaO	8.79	1.19
MgO	21.02	31.11
K_2O	.74	Trace.
Na_2O	.91	
H_2O at 110°	.63	.65
H_2O above 110°	3.19	10.37
P_2O_5	.05	.06
CO_2	Trace (?).	None.
Total	99.17	99.68

It will be seen from the analysis that the silica is somewhat too high for the typical peridotites. This same fact is also emphasized by the tendency manifested in some facies of the peridotite for feldspar to develop, and thus for transitions to norite and gabbro to be produced.

With this analysis of the peridotite there is placed for comparison the analysis (No. 2) by Dr. H. N. Stokes of the picrite-porphyry already described. The close resemblance chemically becomes at once manifest, although the latter is more nearly a typical peridotite in composition. It can not be denied that possibly this picrite is but a further differentiation product of the same magma to which the peridotites belong, although its occurrence is so remote from these that it is impossible to connect them in the field.

PERIDOTITE FROM SEC. 22, T. 42 N., R. 31 W., N. 1,990, W. 150.

Just west of the northeastern corner of sec. 22, T. 42 N., R. 31 W., there is a bold outcrop of hornblende gabbro, which is cut by a dike, about 10 feet wide, of a very massive, coarse, granular black peridotite. Microscopically one can readily distinguish in the peridotite flakes of biotite, poikilitic plates of hornblende, and a smaller amount of white feldspar. Under the microscope the constituents are, in order of importance: Hornblende, augite, feldspar, biotite, bronzite, olivine, magnetite, and quartz.[1]

Hornblende.—This is the rich brown kind, full of inclusions, grading into the green variety which was described on p. 234 as occurring in the gabbros of this district. It is present in anhedra inclosing biotite, pyroxene, and olivine.

Pyroxene.—This is represented by monoclinic and orthorhombic varieties. The monoclinic pyroxene, augite, is most abundant, and is in light-yellow to pink-colored anhedra, except where it touches the feldspar; there the augite is automorphic, and is surrounded by a narrow border of light-brown hornblende.

The orthorhombic pyroxene is present in a few anhedra, which are colorless or have a faint cream tint. It is presumed to be bronzite.

Feldspar.—This fills the interspaces between the other constituents, and occurs in grains which are polysynthetically twinned after the albite law. Measurements gave a symmetrical extinction of 32 each side of the twinning plane on zone ⊥010. I therefore conclude the feldspar to be labradorite.

[1]Only one section has been prepared from this specimen, and it may not give a correct idea of the true proportion of these minerals in the rock mass. In the macroscopical examination of the hand specimen the biotite seemed to he subordinate only to the hornblende.

Biotite.—This is the ordinary yellow to brownish kind, and is in irregular plates. It shows its usual characters and is included in the hornblende.

Magnetite.—This mineral occurs in crystals and grains, included in all the other constituents.

Quartz.—A few grains of quartz were found associated with the feldspar. The presence of dihexahedral liquid inclusions easily gave a clew to the orientation of the grains.

The rock composed of the above-described minerals offers a good illustration of that gradation which is one of the fundamental laws of nature and is nowhere better exemplified than in the rocks. On the one hand, from its texture and from the presence of the dominant hornblende, with the small quantity of quartz, this rock may perhaps be considered to be closely related to the diorites. On the other hand, the presence of the pyroxene and olivine seems to point toward its connection with a gabbro.

Its geological occurrence points most satisfactorily toward its correspondence in age and its intimate relationship to the peridotites of the district. The predominance of the bisilicates indicates it to be of very basic character, and for these reasons I have called it "peridotite," although I have not succeeded in getting an analysis to prove its ultrabasic nature.

RELATIONS OF PERIDOTITES TO OTHER ROCKS.

The peridotites occur in such small quantity that general conclusions concerning their relations to other rocks occurring in their vicinity are scarcely warranted. However, from the fact that they are so intimately associated with the gabbro—cutting it in two cases where the contact was observed—and from the fact that among the peridotites themselves certain phases approach in mineralogical composition certain of the gabbros (see p. 254), it seems advisable to conclude that they represent ultrabasic differentiation products of the same magma from which the gabbro types were derived. The inappreciable differences in grain between the portion of the rock nearest the contact between these basic rocks and the gabbros and those farther away can be explained by supposing their intrusion to have taken place while the main mass of the gabbro retained considerable heat and thus prevented their rapid cooling.

AGE OF PERIDOTITES.

The only statement which can be made concerning the age of the peridotite dikes is that they are younger than some of the gabbros, and that, not having suffered the deformation of the pre-Keweenawan orogenic movements, they are Keweenawan or post-Keweenawan.

GENERAL OBSERVATIONS ON THE ABOVE SERIES.

TEXTURAL CHARACTERS OF THE SERIES.

There are represented in the above series rocks with moderately fine grain as well as those of very coarse grain. They vary from those with parallel texture, through those with porphyrinic, poikilitic, and ophitic texture, to those with granular texture. There is, however, throughout a clear preponderance of the medium to coarse granular rocks. The rocks are evidently not of effusive character, though some possess the textures prevalent in effusive rocks.

The order of crystallization of the minerals in the rocks of granular texture, excluding the iron ores and the accessory minerals, is as follows. The order in the imperfectly ophitic and porphyritic rocks is not considered, as those are rather exceptional occurrences.

In the lists those minerals are hyphenated of which it has not been possible to determine accurately the order of crystallization. It seems that either they were formed at the same time or, in some cases, their formation has overlapped. In such cases the one placed first is the one presumed to have begun its crystallization first.

Diorite.	Gabbro and hornblende-gabbro.	Bronzite-norite.	Peridotite.
Hornblende.	Olivine.	Bronzite.	Olivine.
Biotite.	Monoclinic pyroxene.	Monoclinic pyroxene.	Orthorhombic pyroxene.
Plagioclase.	Biotite-hornblende.	Biotite-hornblende.	Monoclinic pyroxene.
Microcline.	Plagioclase.	Plagioclase.	Biotite-hornblende.
Orthoclase-quartz.			Plagioclase.

For the entire series the order may be arranged as follows: Olivine, bronzite, monoelinic pyroxene, mica-hornblende, plagioclase, orthoclase, quartz. This is the same order that is exhibited by the most basic rock represented in the series, the peridotite, so far as this rock contains the minerals.

The order of crystallization of the minerals throughout the series is due to their relative solubility in the eruptive magma. Among various factors affecting solubility the fusion point of the chemical compounds constituting the different minerals, the temperature of the magmas, and the pressure under which the minerals crystallized, are important. The porphyritic and the ophitic textured rock facies, having crystallized under different conditions of pressure and of temperature from those under which the granular rocks were formed, show, as is to be expected, a different order of crystallization of minerals.

CHEMICAL COMPOSITION OF THE SERIES.

In the following tables there are reproduced the analyses which have been obtained of the various types. They are arranged according to diminishing acidity. Nos. 1 and 4 were analyzed by Dr. H. N. Stokes, Nos. 2 and 3 by Mr. George Steiger, both of the United States Geological Survey:

TABLE I.—*Analyses of Crystal Falls rocks.*

	1 (26023).	2 (23354).	3 (23755).	4 (23353).
SiO_2	58.51	49.80	48.23	44.99
TiO_2	.72	.79	1.00	.97
Al_2O_3	16.32	19.96	18.26	5.91
Cr_2O_3	None.	.....	.....	.25
Fe_2O_3	2.11	6.32	1.26	3.42
FeO	4.43	.49	6.10	8.30
MnO	Trace.	.....	.....	Trace.
NiO	None.	.....	.....	None.
CaO	3.92	11.33	9.39	8.79
MgO	3.73	7.05	10.84	21.02
K_2O	4.08	.61	.73	.74
Na_2O	3.11	2.22	1.34	.91
H_2O at 110°	.23	100°— .13	100°— .26	110° .63
H_2O above 110°	2.00	100°+1.71	100°+2.00	110°+3.19
P_2O_5	.30	.07	.07	.05
CO_2	None.	.15	.43	Trace. (?)
Total	99.46	100.63	99.91	99.17

(1) Mica-diorite (quartzitic); (2) Hornblende-gabbro; (3) Norite; (4) Peridotite (wehrlite).

TABLE II.—*Percentages of chief oxides reduced to 100.*

	1.	2.	3.	4.
SiO_2	60.36	50.52	49.64	47.33
TiO_2	.75	.80	1.03	1.02
Al_2O_3	16.83	20.25	18.79	6.22
Fe_2O_3	2.17	6.41	1.30	3.60
FeO	4.57	.50	6.28	8.73
CaO	4.04	11.50	9.67	9.25
MgO	3.85	7.15	11.16	22.11
K_2O	4.21	.62	.75	.78
Na_2O	3.21	2.25	1.38	.96

TABLE III.—*Atomic proportions of metals.*

Si	55.85	46.53	45.27	42.48
Ti	.53	.56	.71	.70
Al	18.41	22.03	29.26	6.60
Fe	5.08	.834	5.70	9.02
Ca	4.04	11.42	9.51	8.98
Mg	5.32	9.85	15.22	29.67
K	4.99	.74	.88	.91
Na	5.78	4.04	2.45	1.67

The analyses show that all of the rocks contain a moderately large amount of water. Nevertheless, they are sufficiently well preserved to warrant a discussion of their analyses for classification purposes. This is especially true of No. 4, which is remarkably fresh for so basic a rock.

The chief rock-making oxides in the above analyses appear in Table II reduced to 100. The molecular proportion of these oxides was then obtained. From these data the atomic proportions of the metals were derived, and are given in Table III. These calculations were kindly made for me by Mr. V. H. Bassett, assistant in the chemical laboratory of the University of Wisconsin.

If we examine Table II we see that, in passing from the more acid to the basic end of the series, in correspondence with this decrease in silica the alumina increases rapidly, then decreases until it reaches the extreme basic rock, when it drops suddenly to 6.22 per cent. The analyses also show an increase in iron, which is best brought out in Table III. The alkalies decrease with diminishing silica, whereas the MgO, which for rocks of this character is very characteristic, shows a decided increase. Within the gabbro-norite-peridotite series (Nos. 2, 8, and 4) the lime shows a constant diminution corresponding to the increasing magnesian character of the rocks. The potash increases as the soda shows a decrease.

The rocks represented by the analyses are believed to belong to a series ranging from a diorite on the one hand, through hornblende-gabbro and norite, to peridotite on the other. It should be borne in mind that the diorite is somewhat exceptional, representing a gradation toward the orthoclase rocks. On the acid side of the series the microscope also shows variations to tonalitic and even granitic rocks very rich in quartz and orthoclase, consequently much more acid in character than the diorite represented in the analysis.

It is a difficult matter to estimate quantitatively the amount of the one or the other kind of rock present in the Crystal Falls district. We are thus prevented from drawing from the predominance of the one kind or the other the conclusion that those represented in the minority are the results of the differentiation of a magma most nearly resembling in its original constitution that which predominates. Moreover, since the analyzed rock types were not selected as representatives of the extremes of the process of differentiation, it would not be wise to endeavor to give the mean composition of the parent magma from the analyses of the differentiation products which have been presented. The main thesis, however, is established that the separation of a magma into the various products described has taken place, as is indicated by the relations in the field, and as has been shown by the microscopical and chemical analyses.

RELATIVE AGES OF ROCKS OF THE SERIES.

Study of the relative periods of eruption of the various rocks results in the determination of the hornblende-gabbro as the rock which first reached its present position. It was followed in the acid part of the series by the diorite, which in one place cuts it. The diorite is cut by the diorite-porphyry.

Along the basic series the order has been determined as hornblende-gabbro, gabbro, bronzite-norite, peridotite.

In general the forces of differentiation seem to have been active in two directions, tending toward increasing acidity and increasing basicity of the products of differentiation, thus agreeing with the law of succession of igneous rocks as propounded by Iddings.[1]

[1]The origin of igneous rocks, by J. P. Iddings: Bull. Philos. Soc. Wash., Vol. XII, 1892, p. 195.

PLATE XIX.

FIG. *A*.

(Sp. No. 32756. Without analyzer, x 90.)

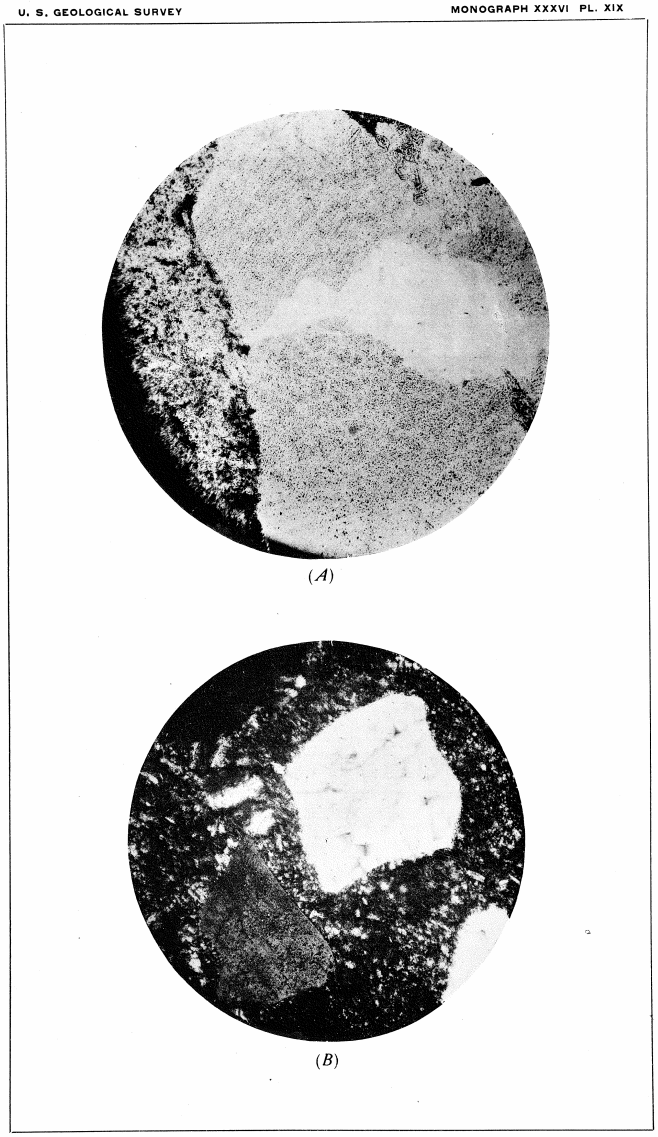
Photomicrograph of fractured quartz phenocryst from a rhyolite-porphyry. It includes numberless liquid inclusions, which diminish in quantity as the distance from the plane of fracture is increased, thus indicating their close connection with the fracturing of the quartz. The fracture in the quartz phenocryst continued into the groundmass, as may be seen on the left-hand side of the figure. It has been healed with secondary quartz. (Described, p. 82.)

FIG. *B*.

(Sp. No. 32914. With analyzer, x 47.)

Photomicrograph of a section of rhyolite-porphyry, designed to show the rhombohedral parting, which is very common in many of the quartz phenocrysts. (Described, p. 82.)

U. S. GEOLOGICAL SURVEY MONOGRAPH XXXVI PL. XIX



(*A*) INCLUSIONS IN A FRACTURED QUARTZ PHENOCRYST.
(*B*) RHOMBOHEDRAL PARTING IN A QUARTZ PHENOCRYST.

PLATE XX.

FIG. *A*.

(Sp. No. 32119. With analyzer, x 90.)

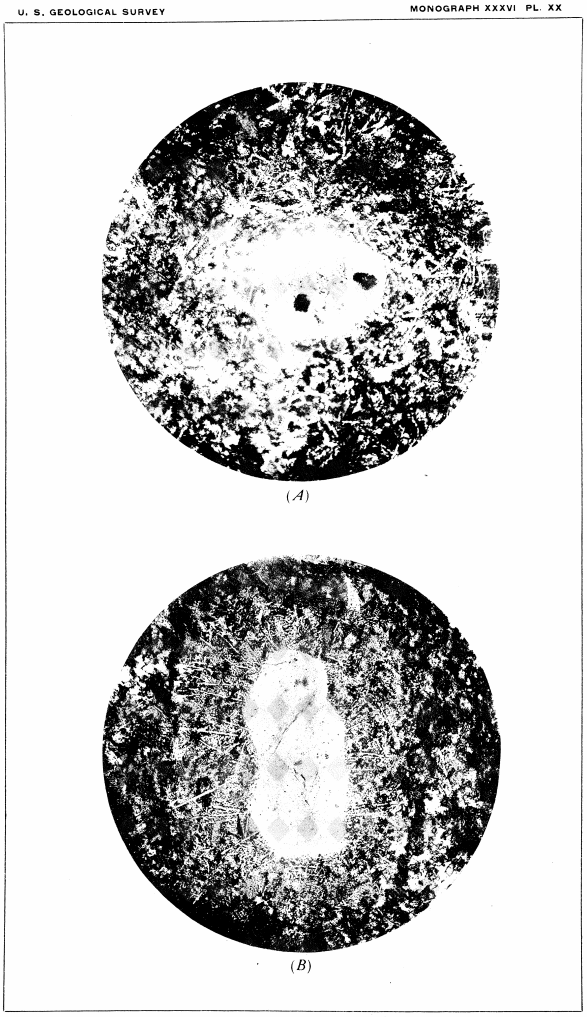
Micropoikilitic rhyolite-porphyry, showing the peculiar texture of the zones which invariahly surround the quartz phenocrysts in sections in which the texture occurs. The same texture prevails in the groundmass. The irregular white areas which are continuous with the quartz phenocrysts and are connected with each other represent quartz. Disconnected dark and light areas between the quartz stringers are feldspar grains. These do not possess uniform orientation; hence the texture is not micropegmatitic. (Described, p„ 84.)

FIG. *B*.

(Sp. No. 32137. With analyzer, x 90.)

Photomicrograph of micropoikilitic rhyolite-porphyry. In this rhyolite-porphyry the micropoikilitic texture is much finer than that represented in Fig. A, and the quartz in the zones shows a tendency toward spherulitic development. Owing to the extreme fineness of grain it is difficult to distinguish the quartz and feldspar in many cases. The greater part of the light areas shown in the photomicrograph are quartz. The dark areas between the quartz, and also some of the lighter areas, represent irregular pieces of feldspar. (Described, p. 84.)

U. S. GEOLOGICAL SURVEY MONOGRAPH XXXVI PL. XX



MICROPOIKILITIC RHYOLITE-PORPHYRY.