freer from hematite dust than that in the jasper layer. Although there is usually a gradation from jasper to ore, nevertheless in some cases the ore layers are rather sharply separated from the jasper layers by a distinct line. Sometimes there may be a gradation on one side of an ore bed and a sharp contact with the neighboring siliceous bed on the other side. Again, a quartz vein may intervene between the two, in which case, of course, their separation is complete.

All the jaspilites, whether of the homogeneous or of the mottled kind, are without exception schistose. The elongation of the individual grains of the quartz mosaic, the trend of the ore laminæ, and the position of the long axes of the pebble-like masses in the few specimens exhibiting them, are all in the same direction, which is also parallel to the banding. Moreover, the tiny quartz veins that here and there ramify the siliceous bands usually tend to follow this same direction, and thus to accentuate the schistosity.

BRIER SLATE.

DISTRIBUTION.

The Brier slate lies immediately above the Traders member and is practically coextensive with it. Wherever the ground which is geologically just above the ore-bearing Traders member has been explored the Brier slates have been uncovered. Where its distribution has not been complicated by faulting and profound folding, the slates occupy a continuous belt about 200-400 feet across, lying between the Traders ore belt on one side and the Curry ore belt on the other. In a few places faulting has caused the slates to disappear from the surface, and in other places folding has increased their apparent thickness, but in those stretches in which the rocks have not been affected by disturbances other than those which produced the major folding of the entire sedimentary series the belt maintains a nearly uniform width.

Along the north side of the Huronian trough there are no natural exposures of the Brier slates, and explorations that have been made in the belt of country immediately south of the northern dolomite belt have nowhere encountered the slates except at the Loretto and the Appleton mines, in the extreme eastern end of the district. In sec. 14, T. 40 N., R. 30 W., pits have been opened up in an iron formation which is believed to belong in the Curry member. The Brier slates should be north of these, but drift hills cover the surface, and this drift has not been penetrated by exploring pits or shafts. Therefore nothing is known of the nature of the rocks intervening between the ore pits near the center of the section and the dolomite outcrops near its north quarter post. On the map (Pl. IX) this area is colored to indicate that the underlying formation is not known. The same conditions exist for the entire belt between the pits just referred to and the Loretto mine in sec. 7, T. 39 N., R. 28 W. If the Brier slate occurs along this border of the trough it is as a narrow strip in the area colored for "Formation not determinable" (see legend of map, Pl. IX).

At the Loretto and Appleton mines the Brier slate has been encountered in the underground workings, in diamond-drill holes, and in numerous pits (see pp. 404-406) scattered over the surface between the shafts of the two mines. East of the Appleton mine exposures of the Vulcan formation are unknown. Its presence in this area is indicated by the existence of a strong magnetic line (see p. 286), but whether one or all of its members are present under the drift is unknown.

The distribution of the Vulcan formation around the central dolomite belt has been described (pp. 286-287). At the Traders and Clifford pits of the Traders mine the Brier slate is exposed under the stripping just above the beds that have yielded the merchantable ore. It has been discovered again by drilling south of the Indiana mine between the ore-bearing Traders member, which has been exploited from the Indiana shaft, and a magnetic ore formation farther south. At the Forest mine, in the southwest quarter of sec, 25, T. 40 N., R. 30 W., several drill holes, located between the main iron formation in which the mine shaft is sunk and a second ore formation about 400 feet south of this shaft, penetrated a dark slate, the position of which corresponds to that of the Brier slate elsewhere. East of the Forest mine for some little distance the Algonkian beds are covered by the Lake Superior sandstone, hence the eastward extension of the Brier member can be followed no farther. But somewhere between the Forest mine and Iron Hill, where the Hanbury slates are approximately in contact with the Randville dolomite, it disappears entirely with the rest of the Vulcan beds.

The best exhibition of the Brier member is south of the belt of the Traders member lying on the south side of the southern dolomite belt. It is exposed for nearly the entire length of the district from Waucedah in the east to the Menominee River in the west. At Waucedah (Pl. XXXVI) it has been exposed for nearly a mile through the north portion of sec. 22, T. 39 N., R. 28 W., by ledges and a series of pits, the most numerous of the latter lying a short distance to the northwest of the Emmett mine. Between this point and the Sturgeon River, a distance of about 2 miles, no ledges of the Vulcan formation have been found, nor has any test pitting been done. A magnetic line passes through secs. 17 and 18, T. 39 N., R. 28 W., and gives evidence of the presence of the Vulcan formation beneath the sands that cover the rocks in this portion of the district. Since, however, the Brier slate is found both at Waucedah and on the west side of the Sturgeon River in sec. 13, T. 39 N., R. 29 W., there is no reason to suppose that it is not present in the stretch of country between these two points. The evidence of its existence in the northwest quarter of sec. 13 is the presence of slates in two pits about 100 paces apart. North of the northern slate pit are other pits in an ore formation which has many of the characters of the Traders member elsewhere, and south of the southern pit is a trench and a line of pits exposing about 270 feet

of an even-bedded iron formation in the position of the Curry member. The Brier slate at this place must be between 250 and 300 feet in width. At the Verona mine, and beyond it as far west as the Aragon mine, the slate is so well developed by pits, ledges, and the underground workings of the mines that there is no question as to its continuation throughout this distance as a distinct and well-characterized belt between the Traders and the Curry ore beds. At several points the direction of the belt changes to conform with the folding of the Traders member. At the Norway and Cyclops mines the slate is exposed at a great number of places in the large open pits of these mines and in numerous small test pits. Its thickness is increased by the several folds that produced the Norway and the Aragon basins and by several minor folds superimposed upon these (Pl. XXXI). The presence of the belt in sec. 6, T. 39 N., R. 29 W., and in the eastern half of sec. 1, in the next township west, is doubtful (see p. 459). Near the center of sec. 1, however, the entire Vulcan series is known to disappear in consequence of an overlap. It reappears again at Quinnesec near the line between secs. 2 and 3, in T. 39 N., R. 30 W. In the Quinnesec fold the Brier slate is again met with in several belts, clue to repetition of the member by close folding. Beyond Quinnesec the Vulcan formation is exposed by drill holes, test pitting, and open mine pits as far as the Pewabic mine, but in this stretch, so far as known, it consists of but two members—an iron-bearing member to the south and a slate member between this and the dolomite to the north. The iron-bearing member is probably the Curry. The slate member seems to vary in thickness, but it never quite disappears. There is always a thin selvage lying against the dolomite, and this has the characteristics of the light-colored slates between the Traders member and the underlying dolomite. Where thicker, the upper portion of the slate seems to resemble more nearly the typical Brier slate so far as can be determined from the meager evidence at hand. These facts suggest that the Brier slate in places, like the Traders member throughout this portion of the district, has disappeared and that only where the slate belt is thickest does any of it reach the present surface. The mapping is in accordance with this view (see map, Pl. XXXVIII). West of the old Keel Ridge mine, in sec. 32, T. 40 N., R. 30 W., is a fault, and northwest of this fault the entire Vulcan formation again appears with its three members. From this point to the west end of the Chapin property the Brier slate has been exposed at many places, not only in the mine workings, but also by test pits on the surface. West of the Ludington mine the Vulcan formation is known to occur as far as the end of the bluff in the center of sec. 26, T. 40 N., R. 31 W., and many pits have penetrated it; but no series of openings exhibits an entire cross section of the formation; therefore it can not be stated definitely whether the Brier slate occurs here or not. On the dump heaps of many of the pits slates are found which in many respects resemble strongly some of the weathered phases of the Brier member, but not enough confidence is felt in their identification to warrant their mapping as such in this portion of the district.

From the fact that the Brier slate has been recognized in all portions of the Vulcan series where this has been exposed from the Hanbury slate on the one side to the dolomite on the other, it is believed that the formation is a constant one, and that under normal conditions it will be discovered everywhere between the Traders and Curry member, when exploration has been sufficiently thorough to open up the ground between them.

LITHOLOGY.

Macroscopical—The Brier slates, in their freshest and most typical phases, are heavy, black, dark-gray or dark-purple, very ferruginous rocks, with a dull, earthy luster quite different from the glistening luster of similarly colored slates belonging in the Hanbury formation. The dull luster is most noticeable on the cleavage surfaces, which are nearly always parallel to the bedding. On joint surfaces inclined to the bedding there can often be detected a little sheen, due to the shearing of hematite particles. Though a few specimens exhibit no bedding bands, the great majority present a very even and fine banding in consequence of the presence of layers richer than the average in iron oxides or of beds containing varying quantities of chloritic or other dark pigments. This banding, which is inconspicuous on fresh surfaces, is strongly emphasized by slight weathering, and consequently, since the slates are very susceptible to weathering influences, it is a characteristic feature of most exposures. With slight weathering the bands become gray and yellowish-gray, the yellowish-gray bands being very narrow, often not wider that the thickness of a sheet of writing paper, and the gray ones measuring on the average about one-fourth inch in width. At the same time the texture becomes sandy, and it is discovered that a large proportion of the rock consists of quartz grains. When the weathering is more profound, red ocher is formed and the slate becomes an alternation of narrow bands of varying shades of yellowish pink, red, and black. Where the weathering has progressed very far, however, the slates are stained an almost uniform red color, in which form they are often indistinguishable from certain phases of similarly stained Hanbury slates. Usually, however, the Brier slates are much the heavier and possess a darker tinge.

It has already been intimated that the Brier slates split easiest along their bedding planes. This tendency is greatly increased by weathering. The rocks open between the layers, become very shaly, and yield an abundant talus at the bases of all cliffs in which they are exposed. While rarely exhibiting schistosity, in many places, especially where folds have been developed, they are crossed by joints inclined to the bedding, along which they break readily, leaving fairly smooth surfaces. Often the joints are close together, and in two systems intersecting at angles of about 70°. Consequently the talus fragments are not infrequently small, flat blocks, diamond shaped in cross section and wedge shaped in

vertical section, like the combination of the prisms and basal planes in the triclinic crystal system.

Reference has also been made to the fact that the joint surfaces are sometimes made lustrous by shearing. Movement along these planes has drawn out some of the hematite constituents and produced a thin coating of flat scales, which cover the surfaces like a thin layer of graphite. This phenomenon is not common, and even when it occurs the luster produced is usually not more noticeable than would be the case had the dust from a lead pencil been lightly rubbed over the surfaces. In a few instances the coating is much more marked, causing the rocks to look very much like graphite slates, similar to some of those in the Hanbury formation. The coating is easily recognized as hematite, however, by the red color of its scratched surface. Moreover, the slate may be distinguished from the Hanbury graphite slates by the fact that the coating is not along the main cleavage surfaces, but is on the surfaces of crevices that are inclined to the cleavage at large angles. In other instances the joint surfaces are covered by a dense deposit of crystalline hematite, which before the rock is fractured forms little veins. These usually run in straight lines for long distances corresponding to the direction of the joints, but occasionally they fork, the branches occupying the places of small gashes in the rock or ending in what were little cavities, but which now are minute bodies of ore. In a few instances quartz was deposited in the joint cracks, and in exceptional cases the joint surfaces are covered by druses of small calcite or dolomite crystals.

The typical slates above described grade in several ways into others that present quite different features. All phases, however, exhibit the characteristic fine uniform banding produced by the alternation of thin layers of different compositions. By increase in the quartz the slates may become sandy in texture and lighter in color. Alternate bands may be gray and white, with occasional narrow lines of red separating adjacent bands, due to the production of ocher along the divisional planes between the layers. On the other hand, the earthy components may increase in quantity. The slates thus become less competent to resist strain, and hence slight shearing may occur and the slate may become schistose. In this case the schistosity is nearly always parallel to the bedding.

A third distinct phase is produced by the development of many small plates of glistening mica. The slates of this type are usually of a nearly uniform gray color, without very distinct banding. They are more granular than the normal type, and because of the luster of the tiny mica plates they look like fine-grained quartzites.

The most prevalent of the intermediate types are those that connect the normal slate with the jaspilites of the Curry member. The normal Brier slate is a fairly dense, earthy banded rock, containing a large quantity of hematite. In the gradation phases there is a more or less perfect separation of the iron oxides and the quartz and an accumulation of these constituents in distinct bands, as though they had been more perfectly sorted by water than in the deposition of the normal rock. The layers in which the hematite was concentrated thus became lean ore beds and those in which the quartz accumulated are impure quartzites. In the latter a siliceous cement was deposited, which increases in quantity with nearness to the Curry beds and produces a rock that more and more closely resembles jasper, until finally the fragmental quartz disappears entirely and true jasper results. Many specimens are so completely intermediate in their character that they can not with confidence be placed either in the Brier or the Curry member, except when their environment is known.

Microscopical and chemical.—Under the microscope nearly all sections of the Brier slates exhibit practically the same features. Small, sharp-edged, fragmental quartz grains, with a diameter of about 0.1 mm. and well-formed crystals of hematite with about the same dimensions, are embedded in a matrix composed of smaller quartz fragments and crystals of hematite lying in a still finer aggregate of quartz and a cloudy substance which appears to be a decomposition product of some aluminous mineral, probably feldspar. The matrix contains a few spicules of kaolin, a little chlorite, and some secondary quartz. Its cloudiness is due to the presence of innumerable hematite particles. A comparatively few large flakes of biotite and of muscovite are scattered here and there through this matrix and strewn through it in greater numbers are fragments of some mineral stained red by clumps of red ocher. The banding is caused by the greater or less abundance of the cloudy hematitic matrix in the different layers.

The different phases of the rock noticed in the hand specimens are mainly due to the varying proportions of the chlorite and magnetite present, and the wide variations in the quantity of small quartz grains and cloudy material in the matrix. Where the latter is in excess the chlorite and kaolin are also abundant. Their flakes are frequently arranged in a parallel position which is as often inclined to the bedding as parallel with it. In this way a slight schistosity is produced which is inclined to the bedding, but it is not sufficiently marked to be noticed macroscopically, partly because the quantity of the micaceous constituents present is always small and partly because of the great abundance of crystallized hematite which serves as a bond to hold together the components of the individual layers and prevent easy fracture across them. Consequently splitting takes place more easily between the layers than across them in the direction of the schistosity. When the slight schistosity is parallel to the bedding the rocks naturally break especially easily in this direction.

Nearly all types of the normal slate present the features described above. In a few places the feldspathic component was originally so abundant that the rocks are now practically clay slates, containing only here and there an isolated quartz grain. These are usually more schistose than the more quartzitic slates. The

ferruginous compounds are mainly earthy hematite or brown ocher, and this constituent is in very flat lenses and in numerous small oval bodies.

In weathering, ocher is abundantly produced, as has already been related. The chlorite and cloudy material of the matrix appears to yield most freely to the alteration processes, and as a result the rock becomes a mass of granular ocherous material, in which are embedded hematite crystals and quartz fragments. Where the hematite crystals are surrounded by the decomposed matrix they are often attacked by the weathering agencies, with the production of a peripheral zone of ocher. Adjacent crystals, in contact with quartz only, remain unaltered. Consequently, it frequently happens that the slates are banded in dull-red and black bands, the former representing layers in which there was originally much clayey or chloritic substance and the latter layers particularly rich in quartz.

In the last stages of alteration the smaller hematites and all the micaceous and feldspathic minerals have been altered to limonite, and the rock now consists of large crystals of hematite and clumps, grains, and rods of brown ocher scattered through a colorless groundmass, which under crossed nicols is resolved into fragments of quartz in a matrix of crystalline quartz; or, if the ocher is in great excess, the rock is now composed of fragmental quartz grains in a slightly granular or an almost homogeneous mass of ocher.

A second type of the rock contains considerable carbonate. Specimens of this type can not be distinguished by the eye from the siliceous types. Under the microscope, however, it is at once noticed that the matrix often consists of a carbonate in place of quartz and feldspathic material. The crystals of hematite and the quartz fragments are less abundant than in the siliceous types; nevertheless they are both present, usually in considerable quantity. The hematite crystals only rarely retain their sharp forms. Their outlines are rather ragged, and brown ocher or green chlorite nearly always borders them. The appearance suggests that the crystals were altered and that their ragged outlines are due to corrosion, which resulted in the production of the chlorite and ocher. Hematite grains and chlorite also occur in aggregates forming irregular masses embedded in the carbonate. The latter mineral is a pale-yellow, untwinned variety, which, together with small flakes and shreds of chlorite, forms a matrix surrounding the hematite and quartz grains. The carbonate is in small grains, some of which are distinct rhombohedrons, forming a crystalline aggregate. It is probable that it is all a secondary infiltration from some outside source. Sometimes it occurs in rather small quantities between the fragmental grains of quartz, plagioclase, and altered orthoclase in a manner that leaves no doubt as to its secondary character. At other times the fragmental grains are very sparse and the chlorite-carbonate aggregate makes up the principal portion of the rock, with the ocher and hematite thickly strewn through it, often in isolated grains, masses, and crystals, but frequently, also, in narrow stringers and flat lenses.

The banded character of these slates, like that of the siliceous kinds, is due principally to the accumulation of the hematite in certain layers and its absence from others.

An analysis of the carbonate, separated by solution in nitric acid from 1 gram of the black slate occurring in the open pit north of the Curry shaft, gave Mr. Allen, of the Survey laboratory, the following result: MgO, 0.0579; CaO, 0.0810, and CO_2 in about the proportion necessary to saturate the two bases. The molecular proportions of the two bases are as 1:1, and the carbonate is therefore a typical dolomite, containing 0.12159 gram $MgCO_3$ and 0.14474 gram $CaCO_3$, or a total of 0.2663 gram dolomite in 1 gram of the rock. Thus 26.63 per cent of the slate consists of the dolomite cement and 73.37 per cent of insoluble components.

The carbonate-bearing beds seem to be only locally developed. They are more noticeable in the neighborhood of the Curry mine and the No. 3 shaft of the East Vulcan mine than elsewhere. In the former place the overlying ore formation is cut by veins of a ferruginous carbonate that are unquestionably secondary. At the East Vulcan locality there is close subordinate folding of the slates and the associated rocks.

The gradation phases between the typical fragmental slates and the jaspilites of the Curry member do not exhibit such features as would readily enable one to trace the former into the latter. The most fragmental varieties differ from the typical Brier slates principally in being finer-grained and in the possession of considerable crystallized (i. e., interlocking) quartz between the finer débris forming the cement uniting the larger grains. Here and there are large cloudy areas of light-green chlorite, kaolin, and quartz, probably representing decomposed feldspar grains, and scattered all through the section are large and small crystals of hematite. Very small, dust-like particles of hematite are disseminated throughout the crystallized quartz, and tiny irregular opaque masses, that may be this mineral or magnetite, occur in the chlorite. In some of the sections there is a quantity of a micaceous mineral in small flakes, filled with a dark-brown, earthy, ferruginous compound. This is apparently a biotite. The texture of these rocks is very fine and in the hand specimen they appear very like a highly siliceous clay slate. It is probable that these phases contained a greater proportion of clay than most of the rocks of the Brier member and that it is by the decomposition of this substance that the biotite originated. In these phases, also, much of the hematite is in linear masses, which are apparently the cross sections of platy aggregates that developed along the bedding planes. In other cases large, irregular masses of a semitransparent red hematite occur here and there through the section. In some places these seem to have resulted from the decomposition of a mineral that has now disappeared.

In other cases, however, the masses show a concentric arrangement of layers around numerous centers like the concentric arrangement of opal in many agates. In this form the mineral appears to occupy little cavities in the rock. It is unquestionably an infiltration.

In the most jasper-like phases of the slates the grain is very fine. All traces of a fragmental component have disappeared and the rock is now a mass of interlocking quartz surrounding an occasional cloudy mass, probably representing a decomposed feldspar, and the usual crystals of hematite. In the hand specimen the rocks are finely and evenly banded and exhibit close relationship with the slates. In thin section the specimens resemble very closely some of the jaspilites except that the iron oxides are not so dense and the quartz is less clear. Its cloudiness is due mainly to the presence of little flakes of kaolin, shreds of muscovite, particles of hematite, and a host of tiny dust grains of various kinds, too small to be satisfactorily identified.

Two analyses of Brier slates follow. The first is of a specimen from the cut along the railroad north of Curry shaft No. 1, sec. 9, T. 39 N., R. 29 W. It was made by Mr. E. T. Allen in the Survey laboratory. The second is an analysis of the foot slates on the fifth level of the Chapin mine. This was furnished by Mr. E. E. Brewster.

Analyses of Brier slates.

	I.	II.
SiO_2	50.15 *.8303*	54.13 *.8962*
Al_2O_3	6.55 *.0642*	13.53 *.1326*
Fe_2O_3	33.80 *.2112*	21.23
FeO	.94 *.0131*	
MgO	.94 *.0233*	4.24 *.1052*
CaO	.16	
Na_2O	.31 *.0050*	.03
K_2O	4.38 *.0466*	3.29 *.0350*
H_2O at 105°	.81 *.0450*	[a] 2.95 .1639
H_2O above 105°	1.43 *.0794*	
TiO_2	.52	
P_2O_5	.08	
S	Tr.	
Cr_2O_3	Tr.	
	100.07	99.40

[a] Loss on ignition.

From these two analyses it is seen that the Brier slates differ materially from the Traders slates in the higher percentage of silica present and greater abundance of ferrous iron. The former must be ascribed to quartz and the latter to hematite. The potash and most of the alumina are probably in orthoclase or its decomposition products, kaolin and muscovite. These constituents, together with the silica present in the remaining ones, make up about 94 per cent of the slate, the composition of which is given under I, leaving only 6 per cent to be distributed among the biotite, chlorite, and other minerals present. Of the silica present about 30 per cent must be in the form of quartz.

CURRY MEMBER.

DISTRIBUTION.

The iron-bearing Curry member lies immediately above the Brier slate, completing the series of beds comprehended in the Vulcan formation. It is probable that it is more widely spread over the district than either the Traders member or the Brier slate, though it can not everywhere be definitely identified. Wherever the Brier slate has been recognized, except where it occurs as small remnants preserved from erosion on the top of Traders beds, the Curry member has been discovered closely associated with it and always between it and the Hanbury slates. Moreover, in several belts of country from which the Brier slates are absent, but in which some of the Vulcan formation is present, this member is believed to be the Curry member. However, the continuity of the Curry beds is not so well established as that of the lower members of the formation for the reason that it has not been as thoroughly explored. Fewer valuable ore deposits have been discovered in it than in the Traders member, and consequently it has not been thought worth while to explore it as carefully.

On the north side of the Huronian trough the only places at which the Vulcan formation is known to occur are in sec. 14, T. 40 N., R. 30 W., and at the Loretto and Appleton mines, in sec. 7, T. 39 N., R. 28 W. In the first-mentioned locality the rock is exposed only in pits, but since the character of the material on the dumps is more like that of the Curry member than like that of the Traders member where this has been seen elsewhere, the underlying iron-bearing series is thought to be the Curry. At the Loretto and the Appleton mines there are few outcrops now visible, and none of these are of rocks belonging with the Curry beds. Pits and drill holes have exposed siliceous slates like those belonging in the Brier member, underlain by an iron-bearing series closely resembling the beds of the Traders member. The slates are the youngest Huronian rocks yet disclosed in this vicinity. They are now at the surface; the Curry member, which overlies these stratigraphically, has been removed by erosion.

Since the Loretto beds are in an eastern-pitching syncline and a southern-dipping monocline, the Curry member may still exist to the east of the Appleton mine and to the south of this and the Loretto mine, but if so, there is, as yet, no evidence to this effect, as the country to the east and south of these mines has not been explored and there are no natural outcrops of the Vulcan formation in either area. Near the mine the surface is covered with sand, and, farther away, by a thick layer of sandstone.

In the center of the trough the Curry member exists at the Traders and the Old Indiana mines, but it has not been encountered elsewhere. At the Traders mine (Pl. XXIV) there are two pits in an iron formation north of the compressor at the end of the trestle extending from the Traders mine pit, and between these and the main ore deposit of the mine is a belt over 200 feet wide in which

are pits of Brier slate. Moreover, at 320 feet west of the compressor, on the north side of the railroad running into the Clifford pit of the same mine, is a small exploration that uncovered graphitic slates belonging at or near the bottom of the Hanbury formation. In this interval there is scarcely room for the full development of the Curry member, but since the graphite-slates must be very near the eastern limit of the Hanbury formation at this place, it seems necessary to assume that the Curry beds occupy the space.

The presence of the Curry member at the Old Indiana mine is shown by drill holes south of the slate member south of the Indiana ore beds. At this place the Curry beds are magnetic.

At the Forest mine exploration has not proceeded far enough at this writing to warrant a statement as to the absence or presence of the Curry member, but since a belt of slates 350 to 400 feet wide is known to exist between two belts of ore-bearing beds it is probable that the southern of these is of Curry age.

The best development of the Curry member is in the belt lying south of the southern dolomite belt. At Waucedah it is exposed in the Emmett and Breen pits (Pl. XXXVI), and it has been traced by test pits and ledges westward for a distance of about three-fourths of a mile. It has again been uncovered by a trench and test pits in sec. 13. T. 39 N., R. 29 W., and has been opened up by exploring pits and mine workings as far west as the Aragon mine. For a short distance beyond this point only one ore-bearing series has been found. It was traced to the west side of sec. 6, T. 39 N., R. 29 W., where it gradually disappears by the overlap of the Hanbury slate, which has buried the entire Vulcan formation in sec. 1, T. 39 N., R. 30 W. On the Cundy, the Pewabic, and the Chapin properties there is abundant evidence of the presence of the Curry member, not only in the underground workings of the respective mines, but also in the surface pittings and occasionally in ledges. Between the Cundy and the Pewabic mines and between the Ludington mine and the Menominee River only one iron-bearing horizon has been detected. It is true that in these two stretches the explorations are mainly limited to the lower portion of the Vulcan formation, but here and there test pits and drill holes show that the ore-bearing horizon is narrow, and that there is not sufficient room between the known position of iron-bearing series that has been located and the slates regarded as Hanbury slates to the south to admit of the occurrence between them of the Brier slates and the Curry beds. The iron-bearing series in these two portions of the Vulcan belt is therefore placed provisionally in the Curry member, the underlying Brier slates and the Traders beds being considered as having disappeared by overlap. If the southern slates are not members of the Hanbury formation, but are Brier, then the iron-bearing series would have the position of the Traders bed (see pp. 456-457).

LITHOLOGY.

Macroscopical.—The rocks of the Curry member comprise even-bedded jaspilites and quartzose slates and irregular-shaped ore deposits intersecting the bedded series more commonly at or near their base than elsewhere. There are present also locally developed interbedded cherts and hematite layers. These are much more common than they are in the Traders member, nevertheless they are greatly subordinate to the jaspilites, from which they seem to differ principally in the color of the siliceous component. Of the jaspilites two distinct varieties are recognizable. The first resembles strongly the corresponding rocks in the Traders member. These are even-banded, dark-purple, sometimes almost black varieties, consisting of inter-laminated layers of jasper and ore. The former are in beds that vary in thickness from a small fraction of an inch to nearly 2 inches. The jasper is dark purple in color, a little denser and more flinty than the greater portion of the jasper in the Traders member, and very much like the dense variety near the base of the member. Occasionally this jasper has the granular appearance characteristic of the major portion of the Traders jasper and rarely it exhibits the spotted appearance so noticeable in this rock—a structure which, in the Traders jaspers, was regarded as indicating the presence of fragments of jasper derived from some preexisting source. The ore bands are usually much thinner than the jasper layers, though occasionally they reach a considerable thickness through the replacement of the jasper by hematite. More commonly the individual ore bands are not more than one-tenth inch thick, the apparently thicker bands being made up of a great number of laminæ of the thickness of a sheet of writing paper. Between them are equally thin layers of jasper. Because of their composite character nearly all the hematite layers of this variety have a stratified appearance. In all cases the stratification is parallel to the banding produced by the alternation of ore and jasper. The material of the ore bands is a hard, dense, flinty, steel-gray hematite without definite structure. It resembles closely the dense black ore forming the small veins in the Traders beds.

None of the jaspilites of this type present any evidence of the intense shearing to which the Traders jaspilites have been subjected. This may be due to the fact that the Curry beds are at a greater distance from the contact plane between the Lower and the Upper Menominee series.

The second and more common form of the Curry jaspilites differs considerably from the form just described and has practically no counterpart in the Traders member. This type, although distinctly banded, has not usually the definite clear-cut banding characterizing the first type, nor is the contact between siliceous and ferruginous bands as striking. The materials are more or less thoroughly intermingled, the jasper bands containing a large proportion of hematite and the ore bands containing much silica. Where the

two kinds of material are most distinctly differentiated the siliceous bands can be made out to be long, flat lenses, overlapped at the ends by the ferruginous material. Toward their edges and ends the jasper passes over gradually into ore. The jasperized bands are sometimes dark red or purple, but more frequently they are dark pinkish-gray and cherty looking. In some places the siliceous bands are well-characterized chert of a light gray or nearly white color, but, as before stated, these varieties are only locally developed. In other places narrow seams of the white chert penetrate the jasper and the ore bands along their bedding planes, and sometimes they occur between the ore and the jasper. In the latter case the chert seems to be a vein filling; in the former cases it is similar to the normal jasper in all respects save color.

In every instance the siliceous material is granular looking, as though it were composed largely of sand grains. In some specimens this texture is so marked that the rock resembles closely a fine-grained quartzite or a dense sandstone.

The ore associated with the jasper is also sandy looking, as though it were mixed with an appreciable quantity of sand grains or were itself a mass of small fragments. Upon close inspection it is found to consist of many little plates of hematite lying in one direction, which is the same as that of the banding of the jaspilites, and innumerable little crystals of the same mineral, with glistening surfaces. On cleavage surfaces the ore sometimes presents a micaceous appearance, but the plates are small and the structure is therefore by no means as marked as in the micaceous ores of the Traders member. More frequently the surface is slightly rough and granular, like that of a poorly cleavable clay slate. The splitting appears to have taken place between two sedimentary layers which had not been moved with respect to one another. In some specimens the arrangement of the little ore particles is so regular that the rock appears to be schistose throughout, and this structural feature is often emphasized by the occurrence within the ore of many small lenses of jasper with their long axes in the plane of the apparent schistosity. Usually, however, the ore presents no appearance of schistosity but is a dense, fine-grained, lusterless aggregate of small grains of hematite with occasional flakes of a light-colored micaceous mineral, which the study of thin sections shows to be muscovite. Like the ore bands of the first kind, those of the sandy texture are also very frequently laminated, the laminæ sometimes consisting of alternating thin layers of jasper and ore and sometimes of light- and dark-colored ore.

Mention has been made of the fact that the banding of the sandy jaspilites is not as distinct as that of the denser variety, because of the gradation of the siliceous into the ferruginous layers. In some few cases, however, the banding is quite definite, especially where the siliceous layer consists of gray chert in place of purple jasper; but this definiteness is usually more apparent than real. The borders of the chert layers are often stained by dark-red iron oxides or they are bleached to a white color. Where the alteration has proceeded inward to a uniform distance a sharp line of demarcation occurs between the altered and the unaltered chert, and thus a definite band of gray chert between white borders is produced, or a gray band with a uniform thickness for some distance is bordered by narrow dark-red bands that grade off gradually into the black ore. In either case the siliceous bands seem to be regular and continuous, but when closely inspected in large hand specimens and in the ledge they may be seen to wedge out at each end, i. e., to be large flat lenses.

The flinty and the sandy jaspilites grade into one another both through the ore bands and the jasper layers, but more commonly through the latter. The gradation phases of the ore are identical in appearance with the mottled ores of the Traders member. On fresh cleavage surfaces little dots of glistening micaceous ore are interspersed through a less brilliantly reflecting mass of the same mineral. In the jasper layers a distinct mottling is also apparent. Little oval particles of a bright-red or dull-purple jasper are thickly strewn through a dark-purple or purplish-gray matrix, in which lie also minute lenses of ore measuring one-half millimeter or less along their larger axes. With the increase in the number of inclosed particles of jasper in the siliceous bands and of ore particles in the hematite bands these assume more and more the characters of the flinty jasper and the micaceous ores until finally, with the entire disappearance of the matrices, the rocks pass over into the typical flinty jaspilites.

Although rarely schistose to any great extent the Curry jaspilites are jointed and gashed in a few places. Hematite has sometimes entered the cracks thus formed and veinlets of ore have resulted. When parted along these joint cracks their surfaces are found to be coated by druses of tiny hematite crystals. At the angles between intersecting joints the jasper is sometimes crushed to a fine breccia and the fragments thus produced are cemented together by quartz or hematite. In other instances the cracks and open spaces in the rock are filled with a yellow clay-like ocher, or with druses of yellowish-brown calcite crystals. Small veins of quartz and of calcite also traverse the rock in divers directions, and narrow seams of white chert are interposed between the ore and jasper bands, or penetrate the ore and the jasper bands parallel to their bedding. In either case they seem to have insinuated themselves between the laminæ, which separate readily in many instances, especially in the ores, and give these a platy structure. In other cases larger open veins of crystallized calcite occur cutting through the ore bands approximately, but not quite parallel to their lamination. The laminæ are cut across obliquely, showing that the openings were made, not by separation of laminæ, but by solution. The ore bordering the veins is saturated with calcite for a distance of about one-half an inch from the borders of the veins and the walls of the openings are lined with druses of small white or brown-stained

crystals that are modified rhombohedrons. Here and there the vein widens and large vugs partially filled with crystals are developed. These veins are quite distinct from the veins of granular red carbonate cutting the rocks in the neighborhood of the Curry mine (see p. 339). These phenomena indicate that the Curry member has suffered considerable fracture since its deposition. Its deformation by this process was, however, by no means so severe as that of the underlying Traders member. It will be observed later that its folding was likewise less severe. The reason for this is probably that the Curry member lies above a slate belt which absorbed most of the stresses to which the formation was subjected while the Traders member lay between these slates and an underlying very competent dolomite bed that transmitted the stresses almost unimpaired.

The interbedded quartz-slates and ores differ markedly from the jaspilites described in the foregoing paragraphs in the fact that they are not definitely banded in distinct jasper and ore bands, but, on the contrary, are made up of a regularly interlaminated series of thin ferruginous and siliceous layers forming a rock with nearly uniform characteristics through out. In many instances, it is true, the siliceous layers predominate through a thickness of one-fourth to 1 inch, and these are followed by a thickness of the same extent in which the ferruginous laminæ predominate. Thus a certain sort of a banding is produced, but the contrast between the contiguous bands is very slight, since each is composite, being made up of laminæ of the same materials but in slightly different proportions. As may be inferred from what has been stated, these rocks are all beautifully laminated, and because cleavage takes place so readily between the laminæ they are often platy in structure. In many places the layers are so rich in iron oxides that they almost constitute lean ores. Where enriched by a secondary deposition of hematite, as at the Curry mine, they furnish an ore of considerable value.

In their general aspects the quartzose slates and interbedded ores look very much like the more ferruginous forms of the Brier slate. They are found most frequently at or near the base of the Curry member, passing below into the slates by gradual transitions through the increase in number and size of the siliceous layers and upward into the banded jaspilites by the aggregation of the ore laminæ into layers and the gradual passage of the siliceous layers into jasper layers, partly through the withdrawal of the more highly ferruginous laminæ and the further silicification of the remaining material by the deposition of secondary quartz. The resemblance of some of the rocks to the Brier slates is so striking that it seems necessary to infer that they were formed by the gradual replacement of the slates by ferruginous material. All these rocks are dark brown or black and very fine grained. Some of the layers occasionally have a greenish tinge because of the presence of chlorite, but this is rare. Occasionally there are also met with a few layers of a pinkish-gray, fine-grained quartzite and sometimes a layer or vein of gray chert interlaminated with the more usual type.

None of the beds are schistose, but in some of them the ore and other particles are platy, with their long directions lying in the plane of the bedding, and in these cases the cleavage surfaces parallel to the bedding are somewhat lustrous.

At the Klondike shaft of the West Vulcan mine, in the northwest quarter of the southwest quarter of sec, 10, T. 39 N., R. 29 W., there is intimately associated with the ore in the dump a light-gray calcareous cherty rock quite different from the usual cherts of the formation. This occurs in bands or layers one-half inch or less thick, interlaminated with a dense black ore. The ore appears to grade into the chert and to cut it in numerous tiny veins. Although dense as a rule, the chert contains some open cavities, and on the walls of these are druses of crystallized hematite. A rock resembling this in its external aspects has also been found on the south side of the Curry ore beds on the fifteenth level of the Vulcan mine, about 1,200 feet below the collar of the shaft. Here it is distinctly laminated parallel to the bedding, and is crossed by at least four systems of joint cracks, most of which are filled with a dark-green earthy chlorite. On the thirteenth level of the same mine, about 400 feet east of the locality on the fifteenth level and about 140 feet above it, the same rock seems to have been met with again. At this place it is more massive and less distinctly stratified, and is extremely rich in pyrite, which is uniformly distributed through it in small grains and irregular masses rather than in veins. These rocks will be referred to again in the descriptions of the West Vulcan ore deposits (p. 439).

In the neighborhood of the Curry mine the rocks of the Curry member are traversed by coarse-grained veins of a dark-pink dolomite. Some of the narrower veins and a few of the coarser ones cross the beds diagonally, but most of them run parallel to the bedding and preferably along the contact between neighboring beds. The same carbonate occurs also disseminated as small crystals through the ore, and in some beds it forms a matrix in which ore particles and small masses are scattered. In this form the ore looks like a granular aggregate of hematite and carbonate. In other places certain of the ore bands, which upon casual inspection look no different from the contiguous ones, are found upon closer study to be saturated with carbonate. This reveals itself only in broken cross sections when the bands fracture along the cleavage planes of the carbonate and consequently reflect uniformly from large surfaces. Often a narrow layer will reflect evenly for distances of 2 inches or more, while the neighboring bands are completely devoid of such reflecting surfaces. The rocks seem to be well impregnated with carbonate, but this appears to have selected for saturation certain definite layers. These carbonated ores are gray when fresh and brown where weathered.

Microscopical.—The flinty, or more typically cherty, jaspilites of the Curry member differ very little from the

corresponding rocks of the Traders member. In the siliceous layers quartz predominates, though ore particles are often present in great numbers. The majority of these consist of hematite in small opaque crystals and in minute transparent plates. Another portion, and a much larger portion than in the Traders jaspers, consists of large crystals of hematite and of magnetite. These ore particles are often disseminated through the quartz grains, but more frequently they lie between them. For the most part they are distributed uniformly, but in nearly all sections it is observed that the hematite especially, and sometimes the magnetite, is arranged along lines that run in the direction of the rock bedding. Besides these two iron oxides there is also present in a large number of sections an abundance of brown ocher which is usually in small irregular masses between the quartz grains. The latter interlock in the usual manner characteristic of the jaspers. Liquid inclusions containing bubbles, some of which are movable, are common in them and strain shadows are almost universal, more particularly in those specimens in which the grains are elongated. Besides the minerals mentioned, the jaspers of this kind often contain also small plates and wisps of a light-green chlorite, an occasional shred of kaolin or sericite, and little grains of a highly refractive, light-yellow, transparent substance that yields ocher by decomposition. This was at first thought to be siderite, but since it is not attacked by hydrochloric acid it can not be a carbonate. An undoubted carbonate, which from its color is supposed to contain some iron, is present in little nests here and there through the rock. This is plainly secondary.

The banding of these jaspilites, like that of the Traders jaspilites, is due to layers alternately richer and poorer in hematite. In structure and composition the ferruginous bands are not essentially different from the siliceous ones except as influenced by the greater proportion of hematite present. This is commonly in the larger grains and crystals, although there are intermingled with them some of the small transparent plates. In the richer bands the hematite is practically in solid masses of snugly compacted granules. In many instances these bands are so narrow, so uniformly parallel, and so close together that it seems as though the ore must have been infiltrated along bedding cracks. Indeed, in some sections there are visible cracks into which ore has penetrated, and vein-like streaks of a very finely granular quartz along the sides of which are narrow borders of hematite and limonite. Sometimes the veins enlarge and inclose small cavities, on the walls of which there are likewise thin coatings of hematite. In the wider ore bands the ore is usually denser on the sides than in the centers, but even in this case the ore is rarely sharply defined from the jasper through which it cuts, since each grades into the other in consequence of the increase in the quantity of one of their constituents and the diminution in the quantity of the other.

Some of the specimens, which appear homogeneous when examined megascopically, are found to be minutely brecciated when viewed under the microscope. The fractures caused by the brecciation are healed by quartz. Veinlets of the same substance also traverse unbreceiated specimens in different directions, but most frequently parallel to the bedding, and small veins of calcite and hematite are also common. In the straighter portions of the quartz veins the grain of the vein filling is nearly of the same size as that of the surrounding jasper, but in curved portions, and particularly in the triangular areas between the fragments of the brecciated jaspers, the grain of the quartz filling is much coarser. From the great abundance of these veins it is clear that the jaspilites have been subjected to silicification processes subsequent to the silicification which gave rise to the jasper.

The granular or sandy jaspilites are more varied in character than the flinty varieties. In some of them the layers of jasper seem to differ little from those of the flinty jasper except in the presence of a few apparently fragmental quartz grains and of a small number of jasper fragments. The greater part of the rock consists of the usual aggregate of interlocking quartz grains, hematite particles, and here and there a scattered magnetite crystal. In natural light the quartz mosaic appears entirely uniform in structure, but between crossed nicols it often breaks up into many oval or rounded areas composed of aggregates of a few or many small grains which are distinctly marked off from the surrounding matrix by differences in the size of their grains. In some cases the components of these areas interlock, while in other instances they are in crushed fragments. Although no definite evidence is at hand to confirm the view, it nevertheless seems probable that these areas represent original sand grains in a sedimentary rock. Nearly all the quartz grains, whether in the rounded areas referred to or in the surrounding matrix, contain great numbers of small hematite plates. The greater part of this mineral is, however, in little crystals and irregular masses between the grains. In nearly all respects the iron oxides are in the same forms and they exhibit the same relations with the quartz as was noted in the case of the ores in the flinty jaspers. As in the latter case, the ore bands are simply layers in which the proportion of hematite is largely in excess of silica. Sometimes magnetite is present in considerable quantities, in certain instances in sufficient quantity to impart to the whole rock a recognizable magnetism. Occasionally a fragmental grain of zircon is observed. Besides the constituents already mentioned there is noticed in not a few specimens a finely fibrous aggregate of a light-green, very feebly polarizing mineral. It occurs as little nests scattered between the quartz grains in the jasper bands and between the hematite grains in the ore bands. It also occupies the central portions of many quartz veins, and forms rather large masses where these widen out. This mineral, which is probably serpentine or some nearly allied species, is undoubtedly an infiltrated substance introduced after the rocks had assumed nearly their present character. Calcite is present also in little isolated nests, more frequently in the jasper layers than in the ferruginous ores, and much more frequently

in both than in the corresponding rocks of the Traders member. In some specimens a little earthy green chloritic substance is also observable. Quartz, calcite, and hematite veins cut both ore and jasper.

The greater number of the sandy jaspilites possess a very beautiful oolitic or nodular structure, which is much more distinctly apparent in the jasper layers than in the ore bands (Pl. XIX, *C, D*). It is due partly to the prevalence of this structure that these rocks are more granular than the other jaspilites of the district. The nodular structure has already been referred to in the description of some of the beds of the Traders member (p. 303). It is, however, so very much more common in the Curry jaspilites than it is in the corresponding Traders rocks that it may well be considered the characteristic structure of the former. Only rarely can the structure be recognized in the hand specimen and then only when the concretions are composed of ore lying in a matrix of jasper. In thin section, however, it is seen in great perfection. Of course, all traces of the original material of the concretions have disappeared, but there remain as proofs of their former existence a great number of beautiful pseudomorphs composed of quartz and hematite. In some specimens these are sparsely scattered through a ground-mass with the features of the nonoolitic jaspers; in others they are closely crowded together, constituting more than three-fourths of the rock visible. In the majority of cases, however, the nodules are present only in certain bands separated from one another by bands devoid of them, as though the rock had been composed of alternating layers of oolitic and nonoolitic material.

The nodular structure is best studied in natural light. As already related, the original material of the concretions has entirely disappeared. It is now represented by the same constituents as those forming the matrix in which they lie, viz, quartz and hematite. The quartz is usually identical with that in the surrounding matrix. It is in interlocking grains filled with hematite dust and abundant liquid inclusions. As a general thing the coarseness of the grain is the same in the nodules as in the matrix (see Pl. XIX, *F*), but occasionally the nodules are a little finer grained. The characteristic feature of the concretions is the arrangement of the hematite. This mineral usually occurs in one or several concentric lines producing circles, ovals, or other curved forms, inclosing a quartz mosaic, which, as has been said, is identical with the mosaic outside of the lines (Pl. XIX, *C, D*). Sometimes the lines are continuous and thin, often they are thick, and occasionally the ore occupies nearly the whole area of the nodule (Pl. XIX, *E*). In other cases the hematite is in little crystals, arranged along a curved line indistinctly outlining an area.

When viewed between crossed nicols the entire field of view of an oolitic band is resolved into an aggregate of small quartz grains, broken here and there by opaque ore masses. The general impression produced is that of a practically homogeneous rock. When viewed in natural light, however, the appearance of the section is strikingly different. The concretions stand out plainly against a nearly colorless background and give the impression that the rock is composed of a great number of black-bordered sand grains of a uniform shape and size lying in a quartzitic groundmass. It is only when the nicols are crossed and the interiors of the supposed grains are discovered to be composed of an aggregate indistinguishable from the surrounding matrix, and many of the grains of this aggregate are found to be continuous with grains in the surrounding mass, that this view is dispelled and the ovals, circles, etc., are recognized as sections of concretions.

Within some of the bands the concretions are elongated and arranged indiscriminately with their longer axes in any direction, but usually the elongated forms lie with their long directions in the plane of the bedding. In schistose phases, in which all the components are elongated, the nodules are much flattened and drawn out to several times their normal lengths, and often their quartz components, as well as the corresponding constituents of the groundmass, are also slightly elongated and are crossed by strain shadows. The ore masses are also often drawn out to great lengths, appearing as lenticular stringers or thin bands woven in and out between composite lenses of quartz.

Many of the concretionary masses are identical in all essential respects with the ore concretions observed by Van Hise and Irving in the Gogebic and Grunflint Lake rocks, and by Van Hise in the Marquette jaspilites.[a] Others are like those observed by Leith in the ferruginous cherts of the Mesabi area. The concretions in the Gunflint Lake beds are shown to have been without doubt originally nodules of siderite in a ferruginous cherty carbonate, and most of those in the Gogebic and Marquette rocks have almost as certainly been shown to have originated in similar concretions. The nodules in the Mesabi cherts were derived partly from siderite, but principally from granules of a magnesium iron silicate which Leith calls greenalite. Some of the structures in the Menominee jaspers are identical with those pictured in the report on the Penokee series,[b] but the concretions differ from most of those illustrated in the Penokee monograph in the fact that no original siderite or other ferruginous carbonate has been detected in them. A single quotation from a description of the jaspers in the Marquette district will reveal the close similarity in appearance between the concretionary structure in these rocks and that in the Menominee jaspilites. In his account of the microscopical features of the Negaunee jaspers, Van Hise writes:[c]

> In the jaspers * * * is also a beautiful concretionary structure exactly similar to that of the ferruginous cherts of the Penokee district. The concentric zones of red hematite, separated by a greater or less distance, appear as if painted upon the quartzose background, the grains of which seem in no way to be affected by the hematite. * * * In some slides the concretions are decidedly flattened by pressure.

Except for the statement that the hematite is red, this description will apply word for word to many of the

Menominee jaspers. In these, however, the hematite is generally opaque.

Most of the nodules in the Menominee jaspers are, however, more like those described by Leith as characteristic of altered greenalite rocks. Some of the illustrations published by this author[d] might easily be duplicated in photographs of Menominee jaspers.

[a]Irving, Roland Duer, and Van Hise, Charles Richard, The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 200-209 and 260-265. Van Hise, Charles Richard, and Bayley, William Shirley, The Marquette iron-bearing district of Michigan, with atlas, including a chapter on the Republic trough by Henry Lloyd Smyth: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 873, 376.

[b]Mon. U. S. Geol. Survey, vol. 19, 1892, Pl. XXII, figs. 1 and 2, Pl. XXVI, figs. 1 and 2, Pl. XXVIII, fig. 2.

[c]Mon. U. S. Geol. Survey, vol. 28, 1897, p. 373.

[d]Leith, C. K., The Mesabi iron-bearing district of Minnesota: Mon. U. S. Geol. Survey, vol. 43, 1903, Pls. XIV and XV, *A*, *C*, and *D*.

Besides the masses of concretionary origin there are also present in many of the Curry sections quartz ovoids that are not outlined by rings of ore. These are distinguished from the surrounding matrix by the fact that they are very fine grained and that their material is filled with minute particles of dust. They are thought to be small jasper fragments that were intermingled with the sediments in which the nodules were formed. A few small fragments of quartz with the usual peripheral enlargements are also met with in some specimens. The fragments are usually composite, though occasionally a homogeneous one is discovered. The composite character of most of these shows conclusively that the entire rock in which they occur has been silicified, and that even the quartz of which these fragments probably consisted was dissolved and new quartz like that of the main body of the rock was deposited in its place. Although in some instances fragments and concretions are found in the same layer, they usually occur in different layers, separated, perhaps, by a thin seam of ore. One layer may consist almost exclusively of concretions embedded in a sparse matrix, while the next layer, distant only a small fraction of an inch, may be made up of many round and oval quartz grains greatly enlarged by additions of quartz in optical continuity with them, some homogeneous, others composite, and all embedded in an abundant fine-grained jasper. The conditions of deposition must have varied rapidly to give rise to such a marked difference in sediments within such short vertical distances.

In the ore bands the oolitic structure is likewise in evidence, but here the material is opaque and the structure is much more difficult to recognize, especially if the ore is very dense. In the less dense bands the ore borders around the ovoids are much thicker than those around the concretions in the siliceous bands, and in many instances entire concretions consist of ore. Moreover, ore crystals abound within the concretions, and a great deal of ore occurs in the interspaces between them. A sparse quartz matrix containing an occasional jasper fragment lies between the ore masses. In the dense ores the entire matrix is replaced by hematite; but even in these a nodular structure is revealed on the edges of the section where the grinding has caused the ore to split along curved lines into round and oval masses like the concretions in the jaspers.

The slaty varieties of the Curry member do not differ as much from the flinty and sandy or granular varieties as might be inferred from an examination of hand specimens alone. In composition and structure they are gradation phases between the Brier slates and the normal phases of the more siliceous portions of the jaspilites, always approaching more closely the jaspers than the slates. Some of the samples which in the hand specimen present the appearance of only slightly altered slates are found to be entirely changed to jaspers. In spite of the fact that they retain in great perfection the definite banding and the characteristic texture of the slates, they have been very completely silicified. All fragmental material has disappeared and the rocks are now completely crystalline. Many of the specimens afford excellent illustrations of the manner in which a rock may be entirely changed by the replacement of its original components, while still retaining its fundamental structures.

The most jasper-like varieties of these rocks differ but little from the normal jaspers in their essential features except that they contain more chlorite. The varieties most like the Brier slates differ from these rocks in possessing a groundmass of crystalline quartz in place of the fine fragmental groundmass of the slates. Moreover, the smaller fragments have been entirely replaced by a fine-grained aggregate of interlocking quartz.

The intermediate phases present a greater individuality, though even these do not differ markedly from the jaspilites. They are characterized by the presence of a great abundance of light-green chlorite in plates and in aggregates of tiny fibers in the jasper layers, and by the presence of plates and small flakes of a darker-green chloritized biotite in the ore layers. The chlorite occurs in the interspaces between neighboring quartz grains and the biotite plates between the magnetite grains and usually attached to them. The small biotite flakes are scattered through the quartz grains. In most specimens a brown or reddish-brown ocher is also very common. It appears as an irregular coating on the quartz grains, as small masses between them, and as little radial groups sometimes within and sometimes between them. It is especially abundant in some of the hematite layers, constituting a large proportion of the mass in which the ore particles are embedded. In all instances it seems to be a decomposition product of chlorite.

The ore bands are usually not unlike the siliceous bands except in the possession of a large quantity of hematite and in the presence of a chloritized biotite in place of the chlorite of the jaspers. In a few distinctly slaty ores the rock is practically a sandstone with a quartz-hematite cement. It consists of numberless enlarged quartz

grains, a few cloudy masses that look like decomposed feldspar fragments, and a few small masses and plates of chlorite surrounded by an aggregate of opaque and transparent hematite and quartz. In this cement the hematite predominates to a very large degree over the quartz, the latter seemingly occurring merely as a filling of little spaces in a porous aggregate. Many of the quartz grains show strain shadows.

In the preceding paragraphs repeated reference has been made to the fact that many specimens of the Curry rocks contain calcite or some other carbonate. Usually the mineral is uniformly distributed in small quantities between the quartz grains of the jasper bands, but sometimes it occurs in very considerable masses both in the jasper and the ore, and occasionally in series of little nests nearly, but not quite, connecting with one another along lines parallel to the bedding. Distinct calcite veinlets are also sometimes met with. The characters and distribution of the mineral leaves no doubt that its origin was subsequent to that of the major portion of the rocks. It was infiltrated after the rocks attained approximately their present condition and crystallized in pores and crevices that already existed, or that were made by the removal of some other component. No original carbonate has been found in any of the Curry rocks. The material that was referred to as original siderite in the preliminary report on the district, upon closer study is discovered to be a secondary carbonate.[a]

The rocks containing carbonate in greatest amount are those in the workings and the immediate vicinity of the Curry mine. In addition to the large masses and veins of red dolomite that have already been mentioned as being conspicuous in the Curry ores and jaspilites the rocks contain also dolomitic material which is revealed only by the microscope. In these phases of the rocks the carbonate has almost completely replaced the quartz. Nearly all the silica that was probably once present has disappeared and in its place is a coarse aggregate of dolomite in which magnetite crystals and hematite plates and grains are embedded in the same manner as they exist in the siliceous ores and jaspilites elsewhere. In most specimens much of the entire portion of the section in the field of view at any one time is occupied by a continuous mass of carbonate that polarizes uniformly. In the cases where the beds are brecciated the carbonate cements the fragments together. In extreme cases both fragments and cement are carbonated. The brecciated structure remains, but all the original components except the ores have been replaced by the carbonate. In some portions of a few sections the ore is in round and circular masses and in concentric rings that look like pseudomorphs of nodules; but these also are carbonated, nothing remaining of their original components but the ores.

[a]Geologic Atlas U. S., folio 62, U. S. Geol. Survey, 1900, p. 5.

It is quite evident that these rocks have been completely permeated by carbonate-bearing solutions, and that these solutions have carried off all the silica and chlorite that was originally in the rocks and deposited a dolomitic carbonate in their place. That none of this carbonate was an original component of the rock in its present position is apparent without discussion.

The identification of the carbonate as dolomite is confirmed by analyses of the ore from the Curry mine furnished by Mr. F. A. Janson, engineer of the Penn Iron Mining Company. Analysis I is of the ore obtained from the Curry member, and II that of an ore taken from the Traders beds.

Analyses of carbonated ores from Curry mine.

	I.	II.
Fe_2O_3	73.41	68.04
Al_2O_3	.62	1.41
MnO_2	.89	1.04
SiO_2	3.42	11.72
$CaCO_3$	11.59	CaO = 4.91
$MgCO_3$	10.61	MgO= 5.41
		CO_2 = 7.31
Total	100.54	99.84

In the first sample the calcium and magnesium carbonates constitute about 22 per cent of the ore, and in the second about 15 per cent. In the first the two carbonates are nearly in the proportion demanded for typical dolomite of the formula $(CaMg)CO_3$, which would require 12.63 per cent of $CaCO_3$ to 10.61 per cent MgO. If all the CaO in the second analysis is present as CaC03, the proportion of the two carbonates in the ore is 6.59 $MgCO_3$ and 8.77 $CaCO_3$. Typical dolomite would require 7.36 $MgCO_3$ to 8.77 $CaCO_3$. It is therefore quite certain that the carbonate which replaces the silica in these rocks, like that which saturates the Brier slates near by (see p. 328), is almost a pure dolomite of the type $CaCO_3 + MgCO_3$.

RELATIONS BETWEEN THE MEMBERS OF THE VULCAN FORMATION.

Where no marked disturbances exist between the Traders member and the Brier slates, the first grades into the second by diminution of the amount of ferruginous material and increase in the proportion of slaty material. At the same time there is a diffusion of the quartzose component and the gradual disappearance of the distinctively quartzose layers. The silica, moreover, changes from the crystalline variety characteristic of the jaspers to the plainly clastic quartz characteristic of slates. When the ferruginous material is much reduced in quantity and the fragmental components are correspondingly increased, the ore-bearing Traders bed becomes the Brier slate. This gradation occupies only a very short vertical range, so that the line between the Traders member and the Brier slate is usually determinable within a few feet.

Where marked disturbances have occurred, as in the vicinity of Norway and eastward for several miles, the relations between the two members are very different. Wherever it can be seen, the contact between the Traders and Brier members is sharp. In many places the contact seems to be slickensided and often to be a plane of differential movement. At the open pits of the Norway and the Cyclops mines and those north of the

Curry mine, and between this mine and the West Vulcan, the Traders rocks are in places pseudoconglomeratic. The Brier slates also may be brecciated (Pl. XXI, *A* and *B*). Moreover, the brecciation is not confined to these two members, but the underlying dolomite is at some places likewise brecciated for a short distance beneath its upper surface. The phenomena, wherever studied, appear to indicate that the relations between the dolomite, the Traders member, and the Brier slates were originally normal, i. e., the ore-bearing beds were principally detrital material lying upon the dolomite, and that the Brier slates were conformable deposits upon the ferruginous beds. At the time of folding slipping occurred along the contact between the Upper Menominee series and the Lower Menominee series, and between the Traders and Brier members. The dolomite was brecciated to some extent, the Traders detrital ores were crushed and brecciated, and in several instances the lower portions of the Brier slates were likewise included within the zone of movement and were fractured and brecciated. Talc and serpentine were developed along the slickensided surfaces and were deposited in joint cracks and openings made in the rocks, and, later, the breccias were enriched by the deposition of hematite and other iron compounds. Thus both the Traders member and the lower part of the brecciated Brier slates became sufficiently ferruginous to warrant mining. This line of contact is marked by large open pits in the southeast quarter of sec. 5 and the northeast quarter of sec. 9, T. 39 N., R. 29 W. The ore belonging to the Traders member was taken from them some years ago. But it was not until the summer of 1899 that the demand for lean ores was so great that the ferruginous phases of the Brier slates could be mined with profit. In this year, however, some of the Norway mine product consisted of this material.

From the descriptions of these pits given in the Tenth Census reports[a] it maybe inferred that at the time the pits were visited (1880) the relations of the breccias to the ores now mined out could be easily seen. The entire Traders member was evidently not brecciated, for there were distinct bands of specular and slaty ores near the foot walls of pit No. 3 (West Vulcan), and at various places in the Perkins, the Saginaw (afterwards north portion of the Perkins pit), the Norway, and the Cyclops pits. Since the rock forming the walls of the pits is brecciated on the strike of the material that has been removed, which was presumably ore, it seems probable that pockets of nonbrecciated ore actually existed in the midst of the breccias. They may have been finely comminuted breccias which were so completely ferruginized that all of their original components disappeared, and which later, by slight movements, became schistose and lost their brecciated structure. In other words, the same conditions seem to have controlled the deposition of the ore in the breccias as elsewhere. While the entire brecciated zone was enriched, certain portions of it, being more crushed than others, gave rise to the richest ores.

[a]Reports of the Tenth Census, vol. 15, 1886, pp. 441-447.

The change from the Brier slates to the Curry member proceeds in the opposite manner from that of the Traders member into the Brier member. The argillaceous constituent diminishes, the quartzose component becomes aggregated into bands and at the same time loses its fragmental character and becomes crystalline or cherty, ferruginous material is introduced, and hematite increases in abundance and becomes segregated into distinct layers. Sometimes the gradation is sudden, occupying but a foot or more; sometimes it is more gradual. Jasper layers appear in the slates 10 feet or more from the fully developed beds of the Curry member. These increase in number and thickness as higher horizons are reached. The interlaminated slates grow more ferruginous and lose their fragmental texture, hematite is introduced along their bedding-planes, and finally the slaty layers are transformed into lean ores. Thus typical jaspilites are produced. The transition can be seen at a number of places on the surface and at many more in the underground workings of the mines. In the mine workings the transition is often so sudden that there is no difficulty in drawing a sharp line between the two sets of beds. On the surface the case is somewhat different, since weathering oftentimes masks the characteristic features of the slates and causes them to resemble the Curry rocks. At the Curry shaft No. 1, in the southwest quarter of the northeast quarter of sec. 9, T. 39 N., R. 29 W., the transition is seen to occur laterally as well as vertically. At this place is an excavation in the hillside exposing the upper portion of the Brier slates and the lower portion of the Curry member. The north side of the excavation is bordered by slates. On its west side the vertical gradation between the slates and the iron-bearing beds can be profitably studied. It exhibits the gradation by means of the interposition of jasper bands described above. On its east side, only 200 feet distant from the west side, the rocks are principally well-defined beds of the Curry member. Since no evidences of folding except slight plication can be detected in any of the rocks, and since the jaspilites are on the direct strike of the slates on the west side of the cut the inference that there is also a horizontal gradation here is unavoidable.

At one or two places the contact between the two series is extremely sharp, no transition of any kind being observable. In most of these instances there is plainly a small fault between the two sets of beds. Such are the conditions on the fourth level of the Pewabic mine, on the sides of some of the pits of the Cyclops, Curry, and West Vulcan groups of excavations, and more particularly in the dividing wall between the pit in which No. 4 shaft of the West Vulcan mine is situated and the pit to the west of this one (see map, PI. XXXIII).

No stratigraphical break has been discovered anywhere within the Vulcan formation.

GENESIS.

From the descriptions of the various members of the Vulcan formation that have been given it is evident that this formation comprises a series of sediments laid down

in water in successive beds from bottom to top. The bottom layers are slates and coarse quartzites or conglomerates, composed largely of waterworn quartz grains and fragments of jasper and ore. Plainly these layers are mainly fragmental sediments derived from a preexisting land surface. The slates were laid down at some distance from the shore line and were derived from a land surface which at the time of their deposition consisted largely of dolomite. The quartzites and conglomerates were deposited nearer the coast. They were derived from a land surface composed partly, at least, of jaspilites, quartzites, and crystalline rocks. The absence of coarse conglomerates indicates that the deposits now exposed were formed at some distance from the shore line rather than along beaches. Currents or waves caused a sorting of the sediments and produced interlaminations of hematitic and quartzose layers. The crystalline quartzose cement in the quartzites and the conglomerates, and the nodules of ore in the latter rocks suggest that there was deposited with the fragmental material some of the ferruginous carbonate and greenalite[a] nodules which at higher horizons gave rise to the jaspers of the jaspilites. If this is so, as it seems to be, the Vulcan epoch was ushered in by conditions favorable to the accumulation of fragmental sediments at the bottom of a sea or bay that was depositing a cherty ferruginous carbonate or silicate, or both. Thus, in the lower portion of the Traders member clastic and chemical sediments were intermingled, with the former largely in excess. In the course of time, probably after the district was folded, the slates were altered and much talc and serpentine were deposited in them, partly by circulating waters emanating from the underlying dolomite and probably partly in consequence of changes set up in the dolomitic material of the slates themselves. The cherty ferruginous cement of the quartzose layers was changed to a crystalline quartz and hematite and the layers were enriched by deposits of hematite between the original grains. With deepening of the water in which the deposits were being laid down these became finer grained. The proportionate quantity of the ferruginous compounds precipitated was increased and the series of mixed mechanical and chemical sediments grew to a considerable thickness. In some places and at certain horizon, the deposits were almost purely chemical. At other places the mechanical sediments were in great excess. In most places the two kinds of sediments were precipitated together. There thus resulted the Traders series of beds, consisting of alternating layers of carbonates, greenalite, ferruginous and quartzose sands, and mixtures of the three.

[a]For theory as to deposition of greenalite see Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 247-259.

The conclusions as to the existence of original carbonate and greenalite in the Vulcan formation is based principally on the analogy that exists between the character of the iron-bearing beds in the Menominee district and that of similar beds in the Marquette, the Gogebic, and the Mesabi districts, which have been shown to have developed either from cherty ferruginous carbonate or from deposits of greenalite. The conclusion is confirmed by the presence of hematite and jasper pseudomorphs after concretions and nodules in the rocks of the Traders member, and more particularly in those of the Curry member of the Vulcan series, and by the existence of the ores in the Menominee district in just such situations as are demanded by the assumption that they were concentrated by descending waters (see p. 396).

Since the steps in the theory that derives the jaspilites from a ferruginous carbonate were worked out mainly by Van Hise in his studies on the Gogebic, the Gunflint Lake, and the Marquette districts, we can do no better than quote his statements concerning the origin of the jaspilites in general, as explaining the mode by which the iron-bearing beds in the Menominee district finally came to have their present characters. With respect to the origin of the iron in the carbonates, he writes:[a]

When the individual districts are taken up, it will be seen that a greenstone, often ellipsoidal, in many places porous and amygdaloidal, in many places schistose and rich in iron, is the most characteristic rock of the Archean, and that similar rocks occur abundantly in the Huronian. Where these igneous rocks were adjacent to the seas they would be leached by the underground water and the iron transported to the adjacent seas. It is possible that to some extent this leaching process also went on below the waters of the sea. The iron was probably transported to the water mainly as carbonate, but to some extent as sulphate. The carbonate would there be thrown down by oxidation and hydration as limonite, and the sulphate in part as basic ferric sulphate. Much of the sulphate was probably directly precipitated as sulphide by the organic material. The limonite would be mingled with the

[a]Van Hise, C. K., The iron-ore deposits of the Lake Superior region: Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 319-322.

organic matter, which was undoubtedly present, as shown by the associated carbonaceous and graphitic shales and slates. When deeply buried the organic matter would reduce the iron sesquioxide to iron protoxide. By the simultaneous decomposition of the organic matter carbon dioxide would be produced, which would unite with much of the protoxide of iron, producing iron carbonate. The sulphate of the basic ferrous sulphate would be reduced to the sulphide by the organic material, thus producing the pyritic carbonates. Where the iron was brought to the water mainly as sulphate, the direct reduction of this salt by organic matter would form iron sulphide with little or no carbonate. Simultaneously with the production of these substances chert was formed, probably through the influence of organisms.[a] Some of this silica would unite with a part of the iron protoxide, producing ferrous silicate. More or less mechanical sediment would also be laid down. Thus the original rocks—the cherty iron carbonates, the ferrous silicate rocks, and the pyritic cherts—would be produced. * * *

The alterations of the original rocks of the iron-bearing formations have been along two general lines, depending upon whether the iron-bearing carbonate or ferrous silicate or pyrite, when altered, was at the surface or at considerable depth. Where the rocks were altered at or near the surface, so that oxygen-bearing waters were abundant, ferruginous slates, ferruginous cherts, and ore bodies were produced. * * *

The formation of the ferruginous slates and ferruginous cherts from the iron-bearing carbonate is usually a process of liberation of carbon dioxide and of oxidation and hydration of iron. Where oxidation takes place with little hydration, jaspilites may be formed. * * * Ordinarily the rearrangement of the iron and chert, emphasized the original sedimentary banding. * * *

For the development of jaspilite further alterations are commonly required. The first stage ordinarily forms ferruginous slate or ferruginous chert at or near the surface, as above described. These rocks, when later deeply buried by sedimentation and subsequently folded, are altered in the deep-seated zone in which dehydration is one of the characteristic reactions. The hydrated iron oxides of the ferruginous slates and ferruginous cherts are changed to hematite. This gives the rocks the blood-red appearance of jasper. The jaspilites therefore differ mainly from the ferruginous slates and the ferruginous cherts in the nonhydrated condition of the iron oxide.

[a]Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 246-253. Walcott, C. D., Fossil Medusæ: Mon. U. S. Geol. Survey, vol. 30, 1898, pp. 17-21.

During any of the above processes of alteration the iron oxides may be more or less concentrated. The concentration may result in bands of nearly pure iron oxide between the leaner portions of the rock. It may result in the concentration of the iron oxide in veins. It may result in the concentration of the iron oxide in large masses under peculiar conditions, as fully explained below, and thus produce ore bodies. The ores are mainly somewhat hydrated hematite, but limonite and anhydrous hematite (either earthy or specular) occur plentifully. Magnetite is also found, but is very subordinate in quantity. The great mass of the iron ore of the Lake Superior region is iron sesquioxide.[a]

After the Traders beds had been laid down to a thickness of several hundred feet, conditions again changed, the cherty carbonate and greenalite ceased to be precipitated and the deposits for a time consisted exclusively of mechanical detritus from the neighboring shores. This was comparatively fine grained, and consequently must have accumulated at some distance from land. It consisted of the débris from crystalline rocks, among which were many that were basic. What the nature of the change was that determined the cessation of chemical precipitation can not be told. Changes in the water level may have contributed to the result. Depression of the land may have reduced the rate of erosion of the basic rocks considered by Van Hise to be the source of the iron salts and, consequently, the amount of ferruginous material leached from them.

At the end of Brier time the conditions that prevailed during the latter part of Traders time returned and the chemical precipitates were again deposited, this time without much admixture of fragmental detritus. The abundance of concretionary ore in the Curry beds shows that some of these consisted largely, if not almost exclusively, of the chemical precipitate, interbedded perhaps with a few thin layers of quartz and hematite sand.

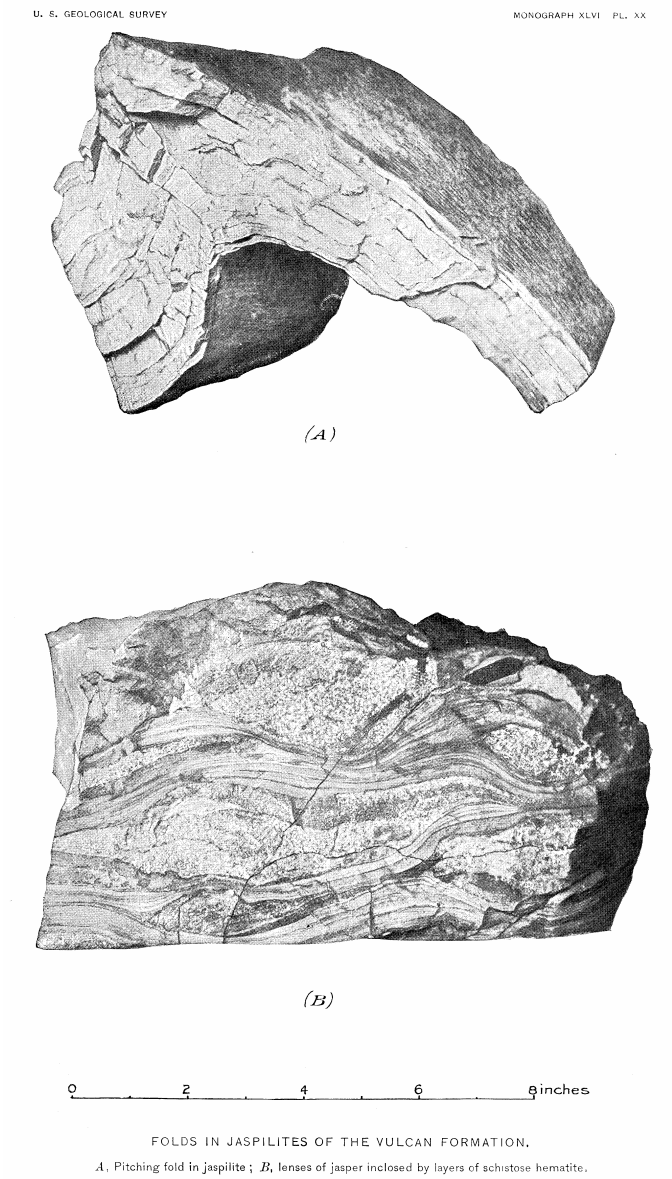
In the course of time the ferruginous precipitates were changed to hematite, the silica was rearranged, and jasper was formed. Where the iron compounds were in beds of notable thickness the resultant jasper is important. Some new hematite was deposited in thin layers along the bedding planes. Another portion of the newly formed hematite remained or was deposited along the grains of the detrital ores, thus enriching them, especially in the bottom of the folds and in areas of disturbance. In spite of the enrichment of the Curry member in iron oxide, its ores are nevertheless not profitably worked at as many places as are those of the Traders member. The ferruginous detritus in the Curry beds is usually not so rich in iron oxide as that found at the Traders horizon. Where folds exist in the member, furnishing favorable situations for rich deposits, the ore bodies may be large enough and rich enough to warrant mining, but for the greater part of its extent the member yields only lean ores.

[a]For a discussion of the chemical changes that resulted in the production of jaspilite from greenalite, see Mon. U. S. Geol, Survey, vol. 43, 1903, pp. 255-259.

FOLDING.

FOLDS OF LOWER ORDERS.

The Vulcan formation, where it is known to exist, occupies a position on the upper sides of the dolomite anticlines. Its major folds, or folds of the first order, correspond exactly to the major folds of the Randville dolomite. The folds of the second order correspond also with those of the dolomite (see p. 237). Within the formation there are, moreover, numerous still smaller folds of the third order, which, because of the hardness of the rocks and the perfection of their banding, are well exhibited. These small folds may be observed at nearly every place where mining has progressed to any considerable extent and at many other places where only lean ores have been developed. The folds of the third order pitch in the same direction as those of the second order, on which they are superimposed, but the strikes of their axes may diverge slightly. Usually these folds are directly related to folds of a corresponding order in the (dolomite, as in the Aragon mine and in the Norway syncline, but often they are apparently independent of the folding in the underlying rock. The minor folds are extremely important guides to the discovery of ore bodies. The folds of the second order determine the general position of the ore bodies, while the folds of the third order determine in many cases their more exact positions within the larger folds. The folded slates of the formation are relatively impervious, and where not shattered often furnished troughs into which the circulating waters were conveyed and the ore deposits formed. In exploring operations it is important to determine the strikes and dips of the axes of the minor folds, not only because they indicate the direction of the pitch and strike of the larger folds, but also because they direct attention to those places at which ore bodies are most apt to exist.



FOLDS IN JASPILITES OF THE VULCAN FORMATION.

A, Pitching fold in jaspilite; *B*, lenses of jasper inclosed by layers of schistose hematite.

[Plate XX. Folds in jaspilites in the Vulcan formation]

FOLDS OF HIGHER ORDERS.

In addition to the three orders of folds above referred to, there may in many places be discovered still smaller folds. These are superimposed on the folds of the third order in the same way in which the latter are superimposed on the folds of the second order. On exposed surfaces the folds of the higher orders in the jaspilites appear as a series of crinklings or flutings, with heights of from one-quarter inch to 5 or 6 inches from trough to crest (Pl. XX, *A*). In some cases the cross sections of these have smooth and flowing contours with rounded turns, and in other cases they have straight limbs with sharp, angular turns, their shapes depending largely upon the shapes of the larger folds upon which the smaller ones are superposed. In some places the folds are open and at other places they are greatly compressed. In the sharper folds the rock in the turns, i. e., at the axes of the crests and the troughs, is often crushed to a breccia, the fragments being cemented together by deposits of dolomite or siderite or of ore. In other cases the siliceous bands at the turns are replaced by ore into which the jasper passes gradually both vertically and transversely.

While the folds of the high orders are most noticeable within the troughs of the dolomite folds, they are by no means limited to these situations. Many minor folds are found also in those portions of the formation where there are no visible folds of larger dimensions, and even in comparatively small specimens of jaspilites there may be gently folded layers included between considerable thicknesses of other layers in which there is no evidence of contortions of any kind. In nearly all instances the folded layers are more richly ferruginous than the uncontorted ones, and in some instances they have been changed completely to ore, while the straight layers are practically pure jaspers.

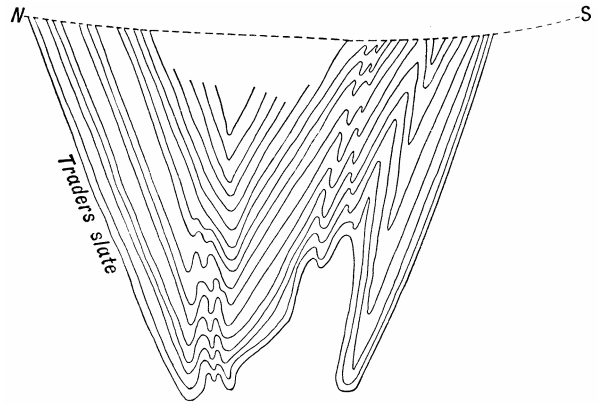


FIG. 24.—Diagrammatic sketch illustrating folding in the iron formation on east side of pit at old Keel Ridge mine. Area about 20 feet by 20 feet.

Much of the thickness of the iron formation in some portions of the district is due to the repeated recurrence of the same layers in consequence of the minor folding. The east side of the old Keel Ridge pit in sec. 32, T. 40 N., R. 30 W., exhibits this effect in a fine manner. The pit has been abandoned for some time and its walls are partly covered by fallen material, but enough of the surface can be seen to show the presence of folds of two orders (see fig. 24). Folds of tertiary and higher orders are well seen also on the stripped surface of the Traders jaspilites at the west end of the Clifford pit of the Traders mine (see fig. 25), and those of the third order can again be seen on the wall of the pit immediately under the plan shown in fig. 25 (see also Pl. XVII, *B*). The Brier slates, as would be expected, were much more subject to minor folding than the two more rigid series of jaspilites between which the slates are included. Small folds and crinkles are therefore much more frequently noticed in the slate member than in the iron-bearing members. Indeed, there is scarcely a single slate exposure of large size that does not exhibit distortions of some magnitude. Sometimes the distortion takes the form of a slight change from the normal in the dip of the slate beds, indicating the presence of a very open, gentle fold; frequently it takes the form of a sudden monoclinal bend in the bedding, and many times

it appears as a series of crinkles, flutings, or puckerings in the strata without affecting their dip as a whole. The general character of the minor folding of the slates is well shown on the east side of the trench extending south from the large pit near the center of the southeast quarter of the northeast quarter of sec. 9, T. 39 N., R. 29 W., just west of No. 4 shaft of the West Vulcan mine (see fig. 26), and again on the west side of the excavation at the Curry shaft No. 1 (fig. 27).

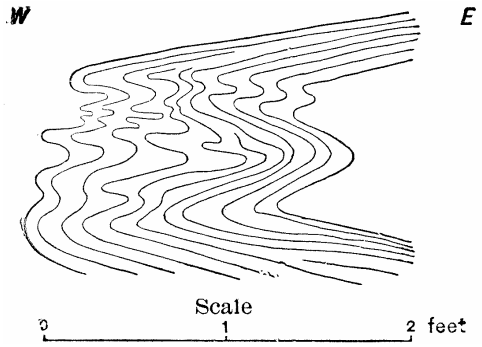


FIG. 25.—Sketch illustrating puckering in jaspelite on stripped surface, west end of Clifford pit, Traders mine, 1899.

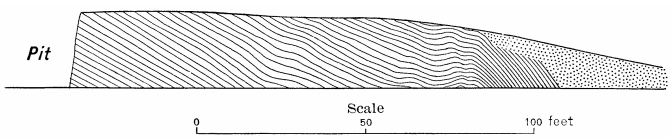


FIG. 26.—Sketch illustrating folding in Brier slates, on wall of trench from No. 2 pit extending south, West Vulcan mine.

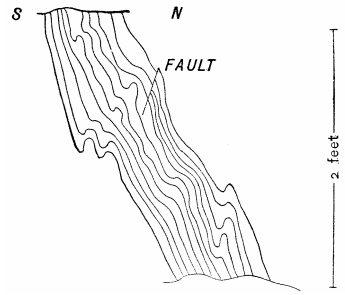


FIG. 27.—Sketch illustrating puckering in Brier slates, west side of cut at Curry shaft No. 1.

SECONDARY STRUCTURES RESULTING FROM FOLDING.

Wherever folding is observed within the iron-bearing formation, it is noticeable that it is best preserved in the siliceous bands. The iron-ore layers between the siliceous layers, while yielding to the stresses that produced the folding, were mashed and sheared and became schistose. Where the compressing forces were very powerful, a slaty cleavage developed in both the iron ore and the siliceous layers, as may well be seen on the surfaces forming the west side of the Traders open pit. In the siliceous layers this is the only secondary structure observed, while in the ores there is present in addition a schistose structure nearly parallel to the bedding-plane, unless this has been obliterated by the deposition of new ore material. Frequently, however, the conditions were not favorable to the production of cleavage in the brittle jaspers, while eminently favorable to the production of schistosity in the ores. The jasper layers are then folded into sharp folds. They are thick and thin alternately, and in some places are broken across at intervals, making a breccia of jasper fragments in a schistose ore matrix (fig. 23). The banding in the resulting breccias may be either in the direction of the bedding, when the detached fragments have not been moved far from their original positions, or it may be in a direction transverse to the bedding when they have been moved appreciable amounts; for in the latter case they have been rotated into the plane of the motion and taken positions corresponding to that of the cleavage in the ores. The rocks of the Traders and Clifford pits are principally breccias of this character. Because of the rounding of the edges of the jasper fragments, the rocks look very much like conglomerates (see plan of Clifford pit for relations between folding and schistosity at this place, Pl. XXIV, and p. 407, for descriptions of the brecciated rocks).

THICKNESS.

A number of sections offer opportunities for determining the thickness of the separate members of the Vulcan formation, but only a few present opportunities for determining its total thickness.

All along the south side of the southern dolomite belt, from the Aragon mine eastward to the Sturgeon River, the iron-bearing formation stretches as a narrow belt, which for much of the distance appears to be without important folds. At several places mining operations have afforded excellent sections from the base of the productive portion of the Traders member to the top of the Curry member, and at a few places the sections extend downward to the top of the Randville dolomite. At Brier Hill, where practically the whole formation can be seen on the surface, its thickness is about 600 feet. At the Curry shaft No. 2 it is 700 feet thick, and at the Aragon mine its thickness is about 675 feet.

The thickness of the individual members comprising the formation is easily estimated at a number of places. The Brier slates have been measured at seven places, yielding results between 100 and 360 feet. Five of these measurements fall between 320 and 360 feet. Eight measurements of the Curry member have given results varying between 100 and 225 feet. Six of these fall between 160 and 225 feet. Measurements of the Traders member have not yielded such concordant results. In the first place, its thickness probably varies widely, as should be expected of a formation composed largely of detrital deposits laid down near a shore line. Moreover, only a few sections reach as low as the dolomite; consequently the exact position of the contact between this rock and the iron-bearing formation must be guessed at. Only three measurements have been made from the known top of the dolomite to the known top of the Traders member. These give 170 feet, 85 feet, and 155 feet.

Favorable opportunities for accurate determinations of the thickness of the Vulcan formation in the southern iron-bearing belt west of Norway and in the central iron-bearing belt north of Lake Antoine are very poor. In both of these areas folding is more prominent than it is in the southern belt east of Norway, and where folding is not prominent exposures are lacking. In the Pewabic mine a measured section along a drift in the first level under shaft No. 1 gave 232 feet for the Traders member and 265 feet for the Brier slates. Near the center of sec. 6, T. 39 N., R 29 W., the measured width of the Curry member is 350 feet. The dip of the jaspilites is not known, but it is about 75°. The thickness calculated on this dip is over 325 feet. At the Traders mine 195 feet of the Traders member are exposed, but because of close folding and lack of exposures no estimate of the thickness of the remaining members of the formation is hazarded. At the Indiana mine the measured thickness of the entire Vulcan formation is about 550 feet. At the Forest mine, in sec, 25, T. 39 N., R. 29 W., a drill hole penetrated about 130 feet of the Traders member.

An interesting feature of these figures appears when we compare the estimated thickness of the Brier and the Curry members with the total thickness of the two. In almost every case where the estimated thickness of either of these members falls below the average of all the measurements for that member the thickness of the other member exceeds the average, and the total of the two is fairly constant. Thus, whereas seven estimates of the thickness of the Brier slates vary between 240 feet and 360 feet, and nine estimates for the Curry member vary between 112 feet and 325 feet, measurements of the total thickness of the two vary only between 400 and 530 feet. The apparent greater variation in thickness of each of the members than the two combined may be partly explained as due to the gradation between them and the consequent difficulty of fixing upon the exact place at which one ends and the other begins.

From a careful consideration of the figures given above and a few others that are not here recorded it is estimated that the average thickness of the Vulcan formation is approximately 650 feet, divided as follows: Traders member, where it is fully developed, 150 feet; Brier slates, 330 feet; Curry member, 170 feet—i. e., the two ore-bearing members combined about equal in thickness the intervening slates. Of course it is understood that by overlapping, one, two or all the members of the formation may disappear from the surface, though they may exist with their full thicknesses at some little depth beneath it.

RELATIONS BETWEEN THE VULCAN AND ADJACENT FORMATIONS.

The relations between the Vulcan formation and the underlying dolomite have been repeatedly discussed in the preceding pages. It seems unnecessary to repeat the statements already made concerning these relations. Under the present head the facts discovered that throw light on them, and the conclusions to which these facts lead, are summarized, and a few additional facts are described which explain the absence of the iron formation from some portions of the district where it would naturally be expected to occur.

The iron-bearing Vulcan formation, except in very limited areas, is known to rest upon the Randville dolomite. Where they can be seen the lower layers of the upper formation appear to lie conformably upon the older one, usually with an extremely sharp line of definition between them. In some places the upper part of the Randville formation is a dolomite. In other places it is a talcose schist derived from the dolomite. Where the Vulcan formation rests on the dolomite or talcose schist its basal member is either a thin bed or series of beds of slate, a quartzite which often contains ore and jaspilite fragments, or an ore and jasper conglomerate containing large and small pebbles of ore. In some cases the slate is absent, but in every case the quartzite or conglomerate is present either at or very near the base of the formation. The fragments in the conglomerates must have been derived from an older iron formation that originally rested upon the dolomite, but which was eroded at the time the Traders member was laid down. In one case, at least, the dolomite itself yielded bowlders to the overlying beds, for on the seventh and eighth levels of the Chapin mine, at a point just south of shaft "C," several large rounded fragments of the dolomite were found embedded in the iron-bearing formation. If there was originally a slight discordance in bedding between the two formations, it has been obliterated by the movements along the contact plane that took place during the folding of the district. The Traders member thus appears to be conformable in attitude with the underlying dolomite, which remained practically undisturbed during the long interval which succeeded its deposition and preceded the deposition of the Traders member.

Along the north side of the Norway syncline and in the belt north of the Curry and the West Vulcan mines in sec. 9, T. 39 N., R. 29 W., the movements along the contact plane were so vigorous that they caused brecciation in the rocks on both sides of it. On the dolomite side of the contact the rock is affected by the brecciation only to a limited depth. For a short distance beneath its upper surface it consists of a mass of large fragments and bowlders of dense dolomite embedded in a soft, sheared matrix composed of serpentine, talc, and an earthy substance often colored slightly by limonite. On the upper side of the contact the brecciation has affected the entire Traders member and a portion of the Brier slates (Pl. XXI, *A*), causing them in many places to resemble strongly true conglomerates. The resemblance of the ore breccia is so strikingly like that of the Ishpeming conglomerate at the base of the Upper Marquette series that at first glance it was taken to represent a basal conglomerate at the bottom of the Upper Menominee series. It contains large bowlder-like masses of ore and jasper in a schistose, or specular, ore matrix (see Pl. XXII, *A*) exactly like the conglomerate above the Negaunee formation in the Marquette district. When traced upward, however, the rock in some places

is seen to pass into a slate breccia in which the matrix is a serpentinized slate and the bowlders or fragments, either slate or ore, or an intermingling of both. In the Norway syncline the brecciation extends far upward into the Brier slates, in some places crushing them throughout their entire thickness. The fragments are nearly all sharp edged (see Pl. XXI, *A*). If there were any doubt as to the true character of the rock, the existence of brecciated bands crossing the rock transversely to its bedding would effectually remove it (see Pl. XXI, *B*). The lack of sharp contacts in this area between the dolomite and the members of the iron formation and the complexity of their mutual relations is thus plainly due to brecciation of the beds bordering the contact planes, and not to any confusion in their stratigraphical positions. Here, as elsewhere, the Vulcan formation was deposited upon the Randville dolomite and was followed conformably by the Brier slates. Movement in a zone near the contact plane crushed the rocks and produced brecciation and schistosity. The motion must have taken place sometime after the deposition of the Brier slates, but before the deposition of the Lake Superior sandstone which overlies the breccias in horizontal layers. It was probably contemporaneous with the folding.

The relations between the Vulcan formation and the overlying Hanbury slates are also those of conformity. The contact is usually very sharp. Little difficulty is experienced in defining the upper limit of the iron-bearing formation where exposures are plentiful. The slates, however, are often so very schistose on the upper side of the contact that their bedding planes can not be recognized. In most places the overlying slates are strongly graphitic and often very fissile. Where not graphitic they are light silvery schists from which all bedding traces have disappeared. The bedding of the iron-bearing formation, on the other hand, is still almost perfectly preserved, and is parallel to the contact. In one or two places the iron-bearing beds are separated from the slates by narrow bands of a soft earthy green rock containing remnants of plagioclase and a mass of green chloritic products such as usually result from the decomposition of a basic eruptive. The green rock has the appearance of a dike, which it probably is, that intruded the bedded series along the contact plane. Dikes of this kind are common in the Hanbury slate area, but are rarely seen in the Vulcan formation. The best preserved example of one of these contact dikes is that on the east wall of the large pit at shaft No. 1 of the West Vulcan mine. Here the dike, as far as it can be traced, follows the contact between the Curry jaspilites and the gray schistose slates of the Hanbury formation.

PLATE XXI.

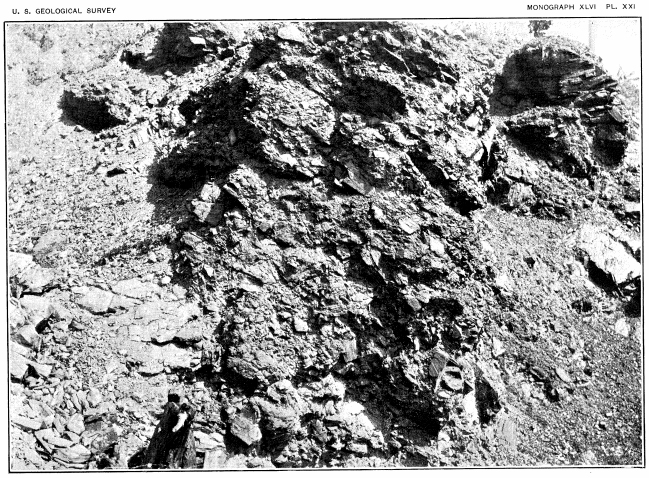
FIG. *A*.—BRECCIATED BRIER SLATES. In Norway pit, near the contact of the slates with the underlying ores of the Traders member.

The surface photographed was a portion of a wall bounding a mass of the slate near the center of the pit, This mass was left in the pit because it was not quite rich enough in iron to warrant mining. Other portions of this same breccia had been mined and shipped as lean ore (1899).

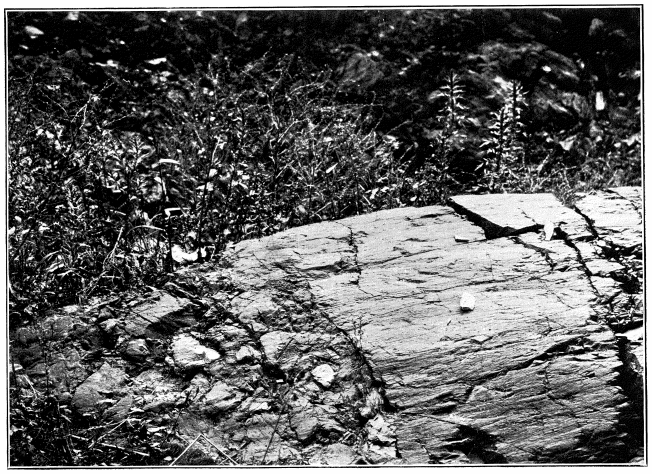
FIG. *B*.—BAND OF BRECCIATED BRIER SLATE CROSSING DEFINITELY BEDDED SLATES TRANSVERSELY TO THEIR BEDDING. In Norway pit.

The bedding of the unbrecciated slate is from right to left. The breccia band truncates the layers. In this breccia the fragments and matrix originally had the same composition, but the finely comminuted texture of the latter afforded favorable conditions for the deposition in it of ferruginous and talcose materials. Consequently the matrix is now softer than the fragments, and hence is more easily eroded, and at the same time it is more highly ferruginous.

U. S. GEOLOGICAL SURVEY MONOGRAPH XLVI PL. XXI



A. BRECCIATED BRIER SLATES IN NORWAY PIT.



B. BAND OF BRECCIATED BRIER SLATE CROSSING DEFINITELY BEDDED SLATES TRANSVERSELY TO THEIR BEDDING, IN NORWAY PIT.

At a few other places, as, for instance, in the neighborhood of the Pewabic mine, faults may intervene between the iron-bearing formation and the overlying slate. They are apparently of little importance from a structural point of view, but have not yet been sufficiently exposed to warrant any very definite statements as to their extent or position with reference to the adjacent rocks. The fault in the Pewabic mine separates the Traders quartzite from the Brier slate where it is best exposed, but it probably extends to the west, where it must pass between the Curry and the Hanbury beds unless it terminates suddenly (see map, Pl. XXVIII and fig. 35).

The relations between the Hanbury slate and the formations older than the Vulcan formation should perhaps logically be considered under the Hanbury slate rather than in this place. However, these relations are so connected with the relations of the Vulcan formation that the subject is here introduced. A further reason for this treatment is that the relations of the Hanbury slate have an important bearing upon the possible distribution of the beds of the Vulcan formation, which carry the iron ores.

At only one point has the actual contact between the Randville dolomite and Hanbury slate been seen. This is in a trench about 10 feet long in graphite-slates near the east line of sec. 2, T. 39 N., R. 30 W., a few rods west of the Bryngelson shaft. A careful examination of the relations between the dolomite and slate was made, with special reference to their bearing upon unconformity and faulting. It was found that the dolomite projects slightly into the slates halfway up the exposed portion of the contact, and recedes from them both above and below this point. The surface of the dolomite is minutely irregular, small projections and reentrants occurring throughout the entire line of contact. The slates, which are strongly graphitic, are interlaminated with cherty bands. They contain small fragments of the dolomite and are badly shattered. A slate breccia is thus formed, which might be a fault breccia or a brecciated conglomerate. There can be no doubt that there has been movement along the contact zone, for the bedding of the slate has been much disturbed for a distance of 8 feet or more from the dolomite. Whether or not the movement was along a fault plane which cut out the Vulcan formation was not determinable from the exposures. The dolomite along the contact plane is not slickensided, nor is the rock near the contact greatly mashed, so far as could be observed. This may be thought to indicate that the movement was of slight magnitude, and that it was more in the nature of a differential movement of the slates near the contact than of faulting across the beds. If the absence of the iron-bearing beds between the Hanbury slate and the dolomite is due to overlapping of the slates rather than to faulting, the lower layers of the slate should be coarse detritus, since the relation of the slates to the underlying rocks are those of a younger sedimentary series to an older series upon which the younger series is unconformable. The breccia between the slate and the dolomite referred to above may be a mashed conglomerate of this kind.

PLATE XXII.

FIG. *A*.—SURFACE OF ORE BRECCIA. Near contact of the Traders member with overlying Brier slate, No. 3 pit, Curry mine, southwest quarter of northeast quarter, sec. 9, T. 39 N., R. 29 W.

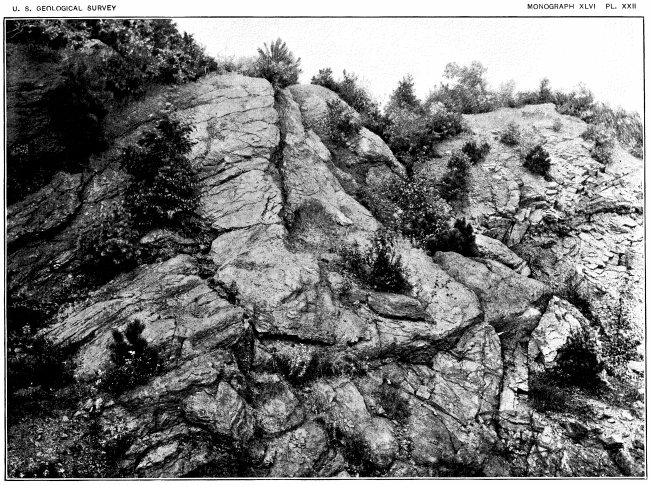
The brecciated rock was a banded jaspilite. The surface shown is the surface of a band of specular hematite. The large lenticular fragments of jasper embedded in the schistose ore matrix make their presence known by causing projections and depressions in its surface. To the right, in the background, distinctly bedded, unbrecciated jaspilites can be seen.

FIG. *B*.—CONCENTRATING WORKS AT THE PEWABIC PIT. Photograph by J. J. Eskil.

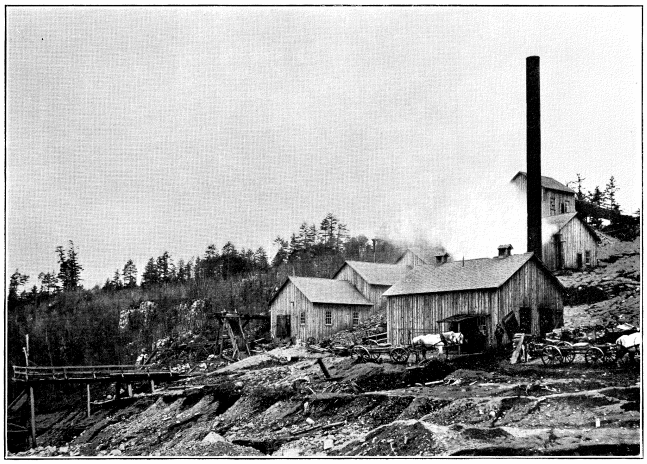
The rough ore used is the conglomerate at the base of the Lake Superior sandstone. This is crushed, and the hematite is separated from the sand by washing.

To the left of the building is a cliff of cherty dolomite.

U. S. GEOLOGICAL SURVEY MONOGRAPH XLVI PL. XXII



A. SURFACE OF ORE BRECCIA NEAR CONTACT OF THE TRADERS MEMBER WITH THE BRIER SLATES, NO. 3 PIT, CURRY MINE.



B. CONCENTRATING WORKS AT PEWABIC PIT.

At Iron Hill, in sec. 32, T. 40 N., R. 29 W., the Hanbury slate is believed to lie immediately upon the Randville dolomite, although no contact between the two is seen (see Pl. XLII). The dolomite ends in a number of small knobs having steep faces toward the south. At the