bases of the little cliffs is a swamp about 300 feet wide, and upon the opposite side of the swamp, on the north slope of a slight elevation, are several exposures of slate. The intervening swamp area has been tested at a number of places by auger borings, as has already been related, and has been found to be underlain by slates.

The uppermost layers of the dolomite formation consist of white cherts, and these are beautifully brecciated. Below these in some places lies a conglomerate containing numerous large rounded bowlders of dolomite, subangular fragments of chert, and an occasional pebble of quartzite in a matrix composed mainly of dolomite and chert débris (see Pl. XVI, *B*). Many of the pebbles are mashed and faulted, showing that the district was deformed after the conglomerate was laid down. When the conglomerate is traced eastward to the end of the set of dolomite ledges, the relations between this rock and the chert are found to be very complicated. The conglomerate apparently grades into a breccia, and this in places is between beds of dolomite or layers of the chert. At one place the conglomerate looks as though it were a breccia formed by crushing of the chert and dolomite; at other places it appears to be a layer of true conglomerate between layers of massive dolomite, and in other places it strongly resembles a conglomerate composed of fragments of the dolomite and chert lying above the dolomite. The conglomerate may be an intraformational conglomerate (one originally produced during the deposition of the formation, and therefore an integral part of it), whose complex relations to the remainder of the Randville dolomite are due to crushing and close folding; or, on the other hand, it may be a true conglomerate at the base of the Hanbury slate, made to appear like an intraformational conglomerate by repeated close folding at the end of an eastward-pitching anticline on which are superposed several minor folds. The latter is thought to be the probable explanation. If this be correct, the difference in composition of the conglomerate from the normal slates is explained by its being the first deposit along a shore line composed of dolomites and cherts. But the relations of the various rocks at this place are so exceedingly complicated that no unprejudiced observer would be willing to declare without reservation that the conglomerate is not a member of the dolomite formation, rather than the basal member of the Hanbury slate (see also pp. 256 and 481 for fuller descriptions of the relations at this place).

### *EXPLANATION OF THE DISTRIBUTION AND RELATIONS OF THE VULCAN AND HANBURY FORMATIONS TO THE UNDERLYING FORMATIONS.*

Two possible explanations suggest themselves to account for the facts of distribution of the Vulcan and Hanbury formations, their relations to the adjacent formations, and the character of their basal members, faulting and unconformity.

For a time it was thought that faulting near the contact plane between the Hanbury slate and the older rocks might explain the phenomena. Thus the absence of the Vulcan formation east of Quinnesec could be explained by the hypothesis that the Hanbury slates had been thrust over the lower formation of the Upper Menominee series so as to rest upon the Randville dolomite. The absence of the Vulcan formation between the Hanbury slate and the dolomite at Iron Hill might similarly be explained, only here it would be necessary to believe that after the faulting occurred close folding took place, else the manner in which the Hanbury slate wraps around the eastern end of the central belt of dolomite would be inexplicable.

There are undoubted minor faults in the Menominee district, but most of them are extremely small, those in the Pewabic mine being the only ones of sufficient magnitude to be mapped on the mine plat. Moreover, it is clear that the crushed zones of the Traders and Brier beds at the Norway, Curry, and West Vulcan locations are due to faulting. Further, there have been marked movements of accommodation between the different formations at their contacts, which might be called faulting. In all of these instances, however, the faults are local, and in none of them is the displacement of the faulted beds great. These few minor faults, which are easily recognized, certainly would not warrant the assumption of such numerous and extraordinary faults as would be necessary to explain the relations above described. Furthermore, the faulting theory does not explain the conglomeratic and quartzitic character of the Vulcan formation where it is in contact with the Randville dolomite, nor does it explain the apparent conglomerates found at several places at the base of the Hanbury slate.

The second explanation which suggested itself is founded on the belief that an unconformity exists between the Lower Menominee and the Upper Menominee, such as exists elsewhere between the Upper Huronian and the Lower Huronian in the Lake Superior region. The order of events producing the unconformity must have been somewhat as follows: After the deposition of the Lower Huronian series, consisting of the Sturgeon quartzite, the Randville dolomite, and the iron-bearing Negaunee formation, the area was raised above the sea. Denudation continued for a long time. Upon the southern side of the Menominee trough these formations, if deposited, were entirely removed. In the central and northern portions of the district denudation extended to a sufficient depth to remove the Negaunee formation in the larger part, if not all, of the area, and to cut into the Randville dolomite. Probably the folding accompanying this uplift and erosion was very moderate. After erosion had long continued, there was slow subsidence of the Lower Menominee land. During the early stages of the encroachment of the sea upon the land the Vulcan formation was laid down. As shown by the character of this formation, it consists largely of detrital ore-formation material. This was derived from the Lower Menominee Negaunee formation, which during the course of the erosion had practically all disappeared. However, at the end of Vulcan time the sea had not yet wholly overridden the land, for at some places certainly, and perhaps for

extensive areas, the Vulcan formation is not present. After Vulcan time the subsidence of the land continued during the deposition of the Hanbury slate. In places where the Lower Menominee series was below the sea at the beginning of Vulcan time the Hanbury slate rests upon the Vulcan formation. Where the Lower Menominee series was above the sea at the beginning of Vulcan time, but was depressed beneath the sea at the end of this period, the slate overlapped the underlying Vulcan rocks and now rests directly upon the Lower Menominee series, as, for instance, at Iron Hill and at the locality east of Quinnesec to which reference has been made.

The theory of unconformity with overlap thus fully and satisfactorily explains every fact of distribution and every known relation between the Upper Menominee, the Lower Menominee, and the Archean rocks. The presence of a great quantity of detrital ores, of quartzites, and of ore and. jasper conglomerates near the base of the Vulcan formation is fully explained. The absence of the Vulcan formation from various parts of the district also presents no difficulty, these being areas which were still above the sea during Vulcan time. The disappearance of the Traders member first among the Vulcan beds and its absence from strips of country in which the Curry member is to be found, and the gradual approach of the base of the Hanbury slates to the Lower Huronian at such places are likewise made clear.

It is therefore with great confidence that the second theory is proposed to explain the structural phenomena of the district—the theory of unconformity between the Lower Menominee and the Upper Menominee series, with a gradual advance of the Upper Menominee sea, the deposits of which slowly overlapped the earlier deposits and gradually buried the higher lands composed of the Lower Menominee rocks.

According to this theory there are in the Menominee district all the evidences of a great unconformity between the Upper Menominee and the Lower Menominee—an unconformity like that found in the Huronian of the Marquette district and other districts of the Lake Superior region, except that in the Menominee district there is no marked discordance in strike and dip between the upper and lower series. This lack of discordance does not in the least invalidate the conclusion that a great time gap separates the two series. It has been shown by Van Hise,[a] that an apparently minor unconformity may mark as great a time interval as the most startling discordance. The relations of the two series in the Menominee district are very similar to those existing in the Penokee district between the cherty limestone of the Lower Huronian and the Upper Huronian quartz-slate member.

[a]Van Hise, C. E., Principles of North American pre-Cambrian Geology: Sixteenth Ann. Rept. U. S. Geol. Survey, pt. 1, 1894.

## THE ORES.

### *LITHOLOGY.*

#### PHYSICAL CHARACTERS.

The ores occurring in the Vulcan beds have been incidently referred to repeatedly in the preceding paragraphs, and the characteristics of some phases of them have been described. Under the present head a general description of the ores is presented and a few statements are made concerning their composition, without respect to their position in the formation. In general, the Traders and the Curry ores are not very different, though there are some varieties in the lower member that have not yet been discovered in the upper member, and there are others that are peculiarly characteristic of the upper member. Under the term ores is included not only the material now being shipped, but also that which, ill the near future, must be drawn upon to meet the demand when the richer supplies have become scarcer or exhausted. The character of the ore varies from year to year in the smaller mines, as old deposits are worked out and new ones are exploited, and also, to some degree, in accordance with the condition of the ore market, which may enable ores to be profitably worked in certain seasons which in other seasons would not begin to pay the cost of mining.

A rough division of the ores of the district is into siliceous ores and rich ores; and these classes may be subdivided into different grades, based partly upon their chemical and partly upon their physical characters.

The siliceous ores are, in part, simply very rich portions of the iron formation, retaining its original physical characteristics, and in part portions of the formation in which some of the jasper of the jaspilites has been replaced by ferruginous material. In the latter class the physical aspects of the jaspilites have suffered great modifications. These two classes of ores pass into one another and into typical jaspilites too poor in hematite to warrant mining at present, and the second class grades into rich ore, from which practically all the silica has been extracted. In both classes the original banding of the jaspilites is often preserved with great perfection. This banding extends without disturbance from ore to jaspilite, the passage between the two being accomplished both by lateral and by vertical gradations. The difference between the two classes is mainly one of degree of alteration. The ores of the first class retain more nearly their original character than those of the second class. The former are but slightly changed phases of the original deposits, to which some hematite has been added by alteration of their original ferruginous component, while the latter are largely replacements of the original materials through the removal of quartz by solution and the deposition in its place of derived hematite.

In those cases in which the ores consist of enriched portions of the iron formation they possess the general aspects of the ferruginous bands in the original jaspilites. The ores may be even-banded bluish-black rocks

composed of alternating thin layers of hematite and of very ferruginous jasper, with the hematite layers greatly in excess, or they may consist of thick layers of hematite separated by thin layers of jasper. Laminæ of dense black hematite sometimes run through the deposits parallel to their bedding, emphasizing this structure and making the ore very hard. When occurring in sheared portions of the formation, the ores are more or less micaceous and specular, as at the Traders mine, but none of the ores now mined are as typically specular as some of those on the Marquette range. The micaceous varieties are limited exclusively to the lower portion of the Traders member, and are thus in the same stratigraphical position as the corresponding ores in the Marquette district. The nonspecular lean ores have in general a rather dull luster and a texture that is dense or granular, according to the proportion of the dense, flinty, vein-like hematite in them or to the proportion of quartz grains intermingled with the ferruginous material. When the proportion of quartz grains is large, the ore takes on a gray tinge and becomes more or less friable or sandy. When the ores contain but little quartz and no vein-like hematite, they are very close grained, fairly hard, and finely granular, showing fine bedding laminæ and a slight schistosity parallel to the bedding. In the Cundy ore, which is of this kind, there is considerable magnetite intermingled with the hematite. For this reason it is much harder and denser than the other ones of this class and has a black, rather than a bluish-black, color. At the Keel Ridge mine the ore is platy and schistose. Thin layers of a denser black hematite alternate with thicker beds of a finely granular sandy ore in which there is apparently much silica in the form of sand grains. The sandy constituent has a slightly pink tinge, and since this is one of the principal components of the ore this too possesses a pinkish tinge. In the trade this ore is sometimes referred to as a red slaty hematite. It is, however, quite different from the soft red hematites of the Gogebic, the Mesabi, and the Marquette ranges.

The lean ores produced by the partial replacement of the jasper of the jaspilites by hematite are not so distinctly banded as those of the first class, although their banding is still very noticeable. Usually they are more lustrous than the latter, the newly deposited hematite being crystalline, causing the ores to sparkle with the reflections from the crystal faces. The ores of this class occur both in the Traders and the Curry members, particularly in those places where the formation has been deformed by folding or brecciation.

The brecciated ores consist of large and small fragments of ore and jasper in a matrix composed of small jasper and ore fragments and tiny ore grains cemented by a porous ore. Some of the ore mined at the Clifford pit of the Traders mine and much of the Cuff ore is of this character. In some cases, as in the Norway open pit, small pieces of dolomite are occasionally intermingled with the other fragments, and in the cement is a large proportion of talc or serpentine. This type of ore has usually a reddish or purplish tinge, though when the ferruginous cement is in large quantity the ore closely resembles in general appearance the porous crystalline ores of the better grades, exhibiting here and there mottlings due to the fracturing of ore or jasper fragments. A third type of the brecciated siliceous ore is a brecciated Brier slate, in which the comminuted slate cement, as well as the fragments, are partially replaced by brown earthy hematite. These ores are purplish brown and lumpy, and often present slickensides through the mass.

Nearly all the brecciated ores containing slaty material, and those banded ores with which are interbedded thin layers of slate, are coated on the weathered surfaces of their joint planes with thin layers of a yellowish-green substance having nearly the color of epidote. This is much more plentiful along the edges of certain layers than of others, and is sometimes limited to a single layer. When examined carefully a large portion of this coating is discovered to be a vegetable growth. Another portion, however, probably consists of an aluminous silicate[a] (see also pp. 385-386). It is found mainly on weathered surfaces or along the surfaces of joint cracks to which atmospheric water has had access. In many instances the alteration has penetrated the slaty layers to some depth and has given their material a yellowish-green tinge.

[a]Putnam, B. T., Notes on the samples of iron ore collected in Michigan and northern Wisconsin: Report on the Mining Industries of the United States (exclusive of the precious metals), with special investigations into the iron resources of the Republic, etc., by Charles Pumpelly. Reports of the Tenth Census, vol. 15, pt. 1, 1886, p. 449.

All the ores of the classes described above contain both fragmental and chemically deposited material. Much of the hematite in the banded and the brecciated ores is of fragmental origin, but with it is a considerable quantity of newly deposited material. It is probable that none of these deposits in their original form would have warranted exploitation. By enrichment, however, their ferruginous component was proportionately increased, and in many cases is now in sufficient quantity to bring the deposits within the limits of merchantable ores. Since the deposit of iron oxide in these instances is dependent on the same processes that gave rise to the rich ores that constitute the most valuable deposits of the district, the laws governing the distribution of the lean ores is the same as that determining the positions of the rich deposits (see pp. 392-401). The lean ores, like the rich ores, are found in plunging synclines and in those portions of the ore formation that suffered brecciation, jointing, shearing, close foldings or other deformation that produced conditions which afforded opportunities for the entrance of ground water into the rocks. Thus the lean ores are usually found in the lowermost portions of the Traders member along its contact with the Randville dolomite (where slipping and brecciation has taken place), along the straight limbs of folds in both the Traders and the Curry members, and in the Curry member along troughs of synclines. The last two positions are favorable for ore concentration to some extent, but not sufficiently so, as a rule, for the

production of rich ores like those found at the bottoms of troughs in the Traders member (see p. 393).

The rich ores of the district are confined, as far as our present knowledge goes, to the Traders member and to a very few exceptionally favorable situations in the Curry member. They occur in those portions of the Traders member near the contact with the underlying dolomite, especially where the two formations are separated by a layer of serpentine and talc, or by beds of impervious slates. The richest deposits are in the troughs of pitching synclines. In the Curry member they occur where folding and brecciation were both severe.

These ores are usually bluish-black, porous, friable, fine-grained aggregates of crystallized hematite. They crush easily and soil the fingers when handled. They are commonly called soft blue hematites.

In many cases the ores are entirely devoid of all evidences of bedding. These varieties are frequently penetrated by tiny seams of dense hard ore, and are cracked and gashed by openings that widen out into distinct cavities. All surfaces are covered with druses of minute hematite crystals, which reflect the light from thousands of sparkling faces. Usually, however, the ores are distinctly laminated. In these the drusy character is lacking. The ores are soft, and are earthy in luster except where they have suffered shearing. At such places they become more or less specular. Gradations between the laminated and the massive ores are common. In many of the ores dense laminæ and earthy or drusy ones alternate, producing an ore with a platy structure which, when not deformed, splits readily between the laminæ into flat, clinkery slabs. The dense laminæ are vein-like in character and appear to have been introduced after the earthy ones had attained their present features. At the Ludington shaft of the Chapin mine much of the ore is also platy. But in this instance the structure is due to the fact that laminæ of the soft, earthy, bluish hematite alternate with others composed very largely of calcite or dolomite. Between these separation occurs very readily.

At the ends of folds and at a few other places where the iron formation has been greatly shattered the ores are often brecciated and their fragments cemented together by a drusy mass of ferruginous calcite or dolomite or by a mass of porous, drusy hematite identical in appearance with the material of the drusy ores referred to above. The cavities still remaining in these breccias are often partially filled with earthy brown limonite, or their walls are coated by little crystals of red siderite. The material of the ore fragments in the hematitic breccias is like that of the hematite bands interstratified with the jasper bands in the jaspilites. Those in the calcareous breccias are fragments of the banded rich ores described in the preceding paragraph. In the latter the replacement of silica by hematite had practically been completed before the ore was brecciated, while in the former deposition of ore continued after brecciation.

The ore of the Curry shaft is so unlike any other ore of the district that it deserves at least another brief mention in this place (see also pp. 347-348). As it appears on the stock pile (1899) most of it is a dark-blue, dense, massive variety cut by veins of white and dark-red dolomite and containing here and there through it large and small nests of the same mineral. Other pieces are mottled in gray, pink, and yellow colors. These varieties are minutely brecciated by ramifying veinlets of the carbonate. While these ores may be enriched to some extent by the deposition of hematite from solutions passing through a lean ore, their present value is due largely to the replacement of their original silica by carbonates.

## CHEMICAL COMPOSITION.

The ores mined in the Menominee range during 1900 were all Bessemer, with the exception of one grade obtained from the Quinnesec mine and the ores of the Walpole and the Cundy mines. The Cundy ore contains a large proportion of magnetite, but the ferruginous component of all the other ores is almost exclusively hematite, although all contain magnetite to some extent. This varies in amount between 1.51 and 9.56 per cent[a] in the dried ores, of which complete analyses have been published. The purest hematite being shipped contains about 92 per cent of $Fe_2O_3$. In addition to the iron oxides all the ores contain varying amounts of $SiO_2$, $Al_2O_3$, CaO, MgO, $CO_2$, S, $P_2O_5$, and $H_2O$, and most of them also some manganese, $K_2O$ and $Na_2O$. In a few ores $TiO_2$ and C have been detected.

The minimum silica reported in the ores of 1900 is 2.75 per cent. The average in the richer ores is about 4 per cent. The maximum limit of this constituent fluctuates with the ore market, since an increase in silica means a decrease in the metallic contents, and a consequent decrease in market value. In 1900 the maximum silica was 38.65 per cent in an ore containing 40.93 per cent Fe (equivalent to 58.46 Fe203). The $Al_2O_3$ varied between 0.61 per cent and 1.89 per cent, the CaO between 0.18 per cent and 1.58 per cent, and the MgO between 0.21 per cent and 3.35 per cent. Manganese was found in the averages of all the cargo analyses of 1900, in quantities between 0.08 per cent and 0.43 per cent, corresponding to 0.10 per cent and 0.55 per cent MnO, but in some of the specimens collected by the agents of the Tenth Census it was not detected, or, at any rate, it was not reported.

[a]Fifteen complete analyses of Menominee ores are published in the Reports of the Tenth Census, vol. 15, 1886, pp. 437-453. While it is not pretended that these analyses represent exactly the ores shipped at present, nevertheless, they probably indicate the character, and, approximately, the degree of variation in the composition of these ores.

Sulphur and phosphorus are universally present, but neither exists in any considerable quantity. The former element is present between the limits 0.002 per cent and 0.028 per cent, corresponding to 0.0036 per cent and 0.05 per cent $FeS_2$, and phosphorus between 0.009 per cent and 0.135 per cent, corresponding to 0.02 per cent and 0.3105 per cent $P_2O_5$.

Records of the percentages of the other components present are not to be found in the recently published analyses. In those of the Tenth Census, however, they are given, and the determinations seem to have been made with great accuracy. In recent analyses the loss on ignition is specifically stated (it varies between 0.65 per cent and 3.24 per cent), but the proportion of this loss due to the escape of $CO_2$ is not recorded. In the Census analyses $CO_2$ was detected in every sample analyzed, in quantities usually varying between 0.08 per cent and 0 50 per cent. In one ore, however, that from the old Keel Ridge mine in the northwest quarter of the southeast quarter of sec. 32, T. 40 N., R. 30 W., the proportion was 7.12 per cent. No description of this ore is given in the report, but it-was probably cut by veins of dolomite like the ore of the Curry mine, which contains 22 per cent of dolomite (see p. 348), or was an ore in which the quartz had been replaced by a carbonate, like some of the ore from the Chapin mine. The ores in which the $CO_2$ was present in small quantity probably contained the substance in calcite (0.18 per cent to 1.14 per cent) scattered through them in little nests (see p. 314)

Of the alkalies $K_2O$ was found in 11 of the 15 samples analyzed and $Na_2O$ in 5 of them, but since these constituents were sought for only in those cases in which the sum of the other constituents amounted to less than 100 per cent, it is probable that they occur in a larger proportion of the ores, if not in all. The $K_2O$ was present between the limits 0.05 per cent and 2.29 per cent, and the $Na_2O$ between 0.02 per cent and 0.30 per cent. Carbon was detected three times in small quantities, viz, 0 006 per cent twice and 0.01 per cent once, and $TiO_2$ in one sample to the amount of 0.075 per cent. It was present in several other samples as traces too small to be determined.

The specific gravity of the ores is dependent partly upon their composition and partly upon their physical structure. A large number of determinations were carefully made by the chemists of the Tenth Census.[a] These showed a very wide range, i e., between 3.447 and 5.173, but their value was in no wise comparable with the iron contents of the samples, as the following short tabular exhibit will affirm:

*Density of Menominee ores compared with iron contents.*

| Mine. | Density. | Iron. | Mine. | Density. | Iron. |
|---|---|---|---|---|---|
| Breen | 3.447 | 50.17 | Curry | 5.001 | 67.40 |
| Cyclops | 3.478 | 64.38 | Quinnesec | 5.006 | 63.49 |
| Norway | 3.830 | 59.72 | Vulcan | 5.036 | 67.62 |
| Breen | 4.590 | 59.79 | Curry | 5.173 | 67.53 |

[a]Reports Tenth Census, vol. 15, 1886, pp. 531-535.

The great variation in the structure of the ores is also responsible for great variations in their capacity for absorbing water and retaining it. The ore as it comes from the mine is saturated with moisture. That removed from the mine and protected from the rain for a long time becomes dry, and on analysis yields only a trace of water. That, however, which remains unprotected on stock piles, and ore in transit, absorbs such a great quantity of water that it is a matter for serious consideration whether it would not prove profitable to dry it before shipment and protect it during transportation to the furnaces. The average cargo analyses showed the ores in 1900 to contain in their natural state, i. e., before drying, percentages of moisture varying between 2.10 and 8.97, the lean ores as a rule showing less moisture than the richer ones, mainly because of their less porous character. In the table below the moisture contents of some of the ores are indicated. The figures do not represent percentage weights of the dry ores, the analyses of which are given above the moisture figures, but they are moisture percentages based on the weights of the natural ores, i. e., of the dry ores plus the moisture, and therefore are considerably smaller than they would be if calculated on the weights of the former. The shipments of one mine alone in 1899 contained over 58,000 tons of water in addition to that which was chemically combined in its constituents.

In the following table the average cargo analyses of some of the ores shipped in 1899 are arranged in the order of diminishing silica. While it is recognized that the composition of the individual ores varies from year to year, nevertheless the general features exhibited by their analyses remain practically the same. The figures for 1899 are chosen rather than those of later seasons, because the former correspond to the ores described in the foregoing paragraphs. The analyses are not so complete as those published by the Tenth Census, but they furnish abundant data for comparison of the different grades and give an excellent summary of their characters.

The results are calculated on the weights of samples dried at 212° F. The moisture figures represent the loss of weight in drying and are calculated as percentages of weight of the natural ores before drying. The iron is calculated as $Fe_2O_3$, although it is probable that in every instance some of it is in the form $Fe_3O_4$. Except where otherwise indicated, the analyses are taken with slight modifications from Mineral Resources of the United States, 1899, Twenty-first Annual Report U. S. Geological Survey, Part VI, pages 39-40.

*Cargo analyses of Menominee iron ores, season of 1899.*

| | Clifford.[a] | Keel Ridge. | Pewabic, Genoa.[b] | Quinnesec, siliceous Bessemer.[c] | Toledo.[b] | Loretto.[d] | Walpole. | Chapin. | Pewabic.[b] | San Jose.[d] | Nimick.[e] | Millie |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fe | 41.01 | 40.64 | 44.00 | 47.20 | 54.21 | 57.067 | 58.75 | 58.13 | 63.21 | 64.405 | 62.72 | 63.705 |
| $SiO_2$ | 39.10 | 37.42 | 32.89 | 26.00 | 19.80 | 13.20 | 10.51 | 6.20 | 5.48 | 4.64 | 4.35 | 2.97 |
| Mn | .09 | .20 | .09 | .12 | .11 | .20 | .13 | .54 | .11 | .30 | .22 | .12 |
| P | .014 | .046 | .007 | 030 | .01 | .0205 | .120 | .065 | .009 | .014 | .071 | .0275 |
| S | .003 | .006 | .005 | 004 | .004 | .062 | .002 | .019 | 003 | .027 | .03 | .008 |
| $Fe_2O_3$ | 58.58 | 58.04 | 62.85 | 67.42 | 77.44 | 81.45 | 83.92 | 83.01 | 90.29 | 91.97 | 89.55 | 89.99 |
| $SiO_2$ | 39.10 | 37.42 | 32.89 | 26.00 | 19.80 | 13.20 | 10.51 | 6.20 | 5.48 | 4.64 | 4.35 | 2.97 |
| $P_2O_5$ | .032 | .106 | .016 | .07 | .023 | .047 | .276 | .15 | .02 | .032 | .163 | .064 |
| $FeS_2$ | .006 | .011 | .009 | 007 | .007 | .114 | .004 | .036 | .006 | .050 | .055 | .015 |
| $Mn_3O_4$ | .13 | .29 | .13 | .17 | .16 | .29 | .19 | .78 | .16 | .43 | .32 | .17 |
| $Al_2O_3$ | .97 | .90 | 1.10 | 1.02 | 1.20 | 2.12 | 1 30 | 1 41 | 1.04 | 1.24 | 1.25 | .94 |
| CaO | .49 | 1.35 | .79 | .27 | .88 | .32 | .79 | 1.235 | .86 | .19 | .65 | 1.14 |
| MgO | .29 | 1.00 | 1.07 | .32 | 1.08 | .57 | 1 96 | 3.565 | 1.12 | .39 | 2.24 | 1.49 |
| Loss by ignition | .45 | Undet. | 1.18 | 2.80 | 1.20 | 1.59 | 1.22 | 3.22 | 1.20 | .64 | 1.65 | 2.12 |
| Total | 100.048 | 99.117 | 100.035 | 98.077 | 101.790 | 99.701 | 100.170 | 99.606 | 100.176 | 99.582 | 100.228 | 99.899 |
| Moisture | 2.55 | 2.90 | 4.22 | 2.10 | 6.00 | 8.72 | 5.00 | 6.96 | 7.00 | 8.28 | 7.99 | 5.67 |

[a] From Traders (Antoine) mine.
[b] From Pewabic mine. Analysis of Genoa ore is an average analysis of shipments for season 1898. From Lake Superior Iron Ores, published by Pickands, Mather & Co., Cleveland, Ohio, 1899, p. 14.
[c] Analysis of shipments 1900. Mineral Resources, United States, calendar year 1900, Washington, 1901, p. 14.
[d] From Loretto mine.
[e] From Aragon mine.

Of the four analyses given below, the first, made from a sample of the Chapin ore, was furnished by Mr. E. E. Brewster. The second and third are analyses of two

grades of "soft specular" Quinnesec ore, and the fourth of a "soft specular" blue ore from the Cornell mine. The last three analyses are taken from the Tenth Census Report. They, of course, do not represent the exact composition of any ores being mined at the present time, but they afford the best data we have for determining the mineral composition of the richer of the Menominee ores, and for this reason they are quoted. The second analysis was made from chips selected with special reference to securing a sample rich in the greenish-yellow incrusting mineral (see p. 375) that coats the ore-bearing rocks in many places.

*Complete analyses of Chapin, Quinnesec, and Cornell ores.*

| | I. | II. | III. | IV. |
|---|---|---|---|---|
| Fe | 60.54 | 55.58 | 65.63 | 57.03 |
| $Fe_2O_3$ | 85.44 | 76.14 | 91.51 | 80.15 |
| FeO | .47 | 2.87 | 1.97 | 1.10 |
| $Al_2O_3$ | 1.33 | 4.69 | 1.53 | 3.88 |
| $Mn_2O_3$ | .76 | ..... | ..... | ..... |
| CaO | 1.26 | .27 | .36 | .17 |
| MgO | 3.02 | 3.55 | .21 | .48 |
| $K_2O$ | .064 | .99 | .57 | 2.29 |
| $Na_2O$ | .066 | .02 | .03 | .30 |
| $SiO_2$ | 4.53 | 9.31 | 3.03 | 10.72 |
| $P_2O_5$ | .15 | .021 | .021 | .074 |
| S | .002 | $FeS_2$= .110 | .099 | .146 |
| $CO_2$ | ..... | .30 | .38 | .08 |
| $H_2O$ (above 100°) | 2.75 | 1.72 | .27 | .56 |
| Total | 99.842 | 99.991 | 99.980 | 99.950 |

In the course of the analyses of the Quinnesec and Cornell ores the insoluble components were determined separately, with these results:

*Insoluble constituents of Quinnesec and Cornell ores.*

| | II. | III. | IV. |
|---|---|---|---|
| Total insoluble | 12.02 | 4.61 | 16.45 |
| $SiO_2$ | 9.31 | 3.03 | 10.72 |
| $Al_2O_3$ | 1.61 | .93 | 3.21 |
| CaO | .09 | .07 | ..... |
| MgO | .09 | .06 | .08 |
| $K_2O$ | .93 | .51 | 2.23 |
| $Na_2O$ | ..... | .03 | .20 |
| Total | 12.03 | 4.63 | 16.44 |

## MINERALOGICAL COMPOSITION.

### MINERAL CONSTITUENTS OF THE ORES.

From the microscopical examination of the ores it is learned that they contain hematite, magnetite, quartz, calcite, dolomite, muscovite, and serpentine. The chemical analyses show, in addition, the presence of pyrite, apatite, and some manganiferous mineral. All of these minerals appear to occur in practically all the ores, but they are found in greatly varying amounts. In attempting to calculate their proportions in the ores, the analyses of which are given above, we are met by several difficulties which can not be entirely overcome. In the first place, no microscopical examination was possible in the case of any of the samples analyzed. Hence there is no knowing whether all the minerals mentioned above were in these samples or not; or, if all were present, which of the rarer ones were in excess. In analysis I there was no determination of $CO_2$ separately from $H_2O$, though it was known to be present. In sample II there was presumably present some serpentine in addition to the yellowish-green mineral, which is probably a soluble silicate of magnesia and alumina. But there is nothing to guide in the distribution of the $Al_2O_3$, MgO, and $SiO_2$ between these minerals, or in determining how much of the bases occur in them and what proportions are present as isomorphous mixtures in the hematite and magnetite. If we assign all the $P_2O_5$ to apatite, all the $CO_2$ to dolomite, all the FeO to magnetite, and the insoluble $K_2O$, $Na_2O$, and $Al_2O_3$ to muscovite, calculate the proportion of MgO necessary to unite with the available CaO in the formation of dolomite, and assign the balance to serpentine, the mineral composition of the first, third, and fourth of the above ores is as indicated below:

*Mineral constituents of rich ores.*

| | I. | III. | IV. |
|---|---|---|---|
| Hematite ($Fe_2O_3+Al_2O_3$) | 85.55 | 87.74 | 78.28 |
| Magnetite | 1.51 | 6.34 | 3.54 |
| Muscovite | .54 | 2.62 | 9.45 |
| Serpentine | 6.49 | .25 | 1.15 |
| Dolomite | 2.62 | .82 | .18 |
| Apatite | .35 | .048 | .171 |
| Pyrite | .004 | .099 | .146 |
| Quartz (excess of $SiO_2$) | 1.46 | 1.84 | 6.50 |
| Manganite (?) | .85 | ..... | ..... |
| Excess unaccounted for: | | | |
| $H_2O$ | .48 | .17 | .32 |
| $K_2O$ | ..... | ..... | .06 |
| $Na_2O$ | ..... | .03 | .10 |
| Total | 99.854 | 99.957 | 99.897 |

It is fully realized that the above estimates are only approximate. In the calculations all the CaO in excess of that required by the $P_2O_5$ to form apatite is assigned to the dolomite, and enough MgO in addition to saturate the $CO_2$. The remaining MgO is all considered as occurring in serpentine. If the dolomite is richer in MgO than it is assumed to be, the percentages of the serpentine in the ores are less than estimated and the percentages of quartz larger. Moreover, the excess of CaO which would then be unaccounted for would probably indicate the presence of some chlorite. Again, some of the magnesia may be in the form of talc, but that this mineral is present to any considerable amount is not probable, since talc contains less water than serpentine, and even on the assumption that all the MgO is in serpentine there is nevertheless some water unaccounted for in every analysis. Serpentine is an abundant constituent in some of the ores, as will be shown later.

If we exclude from consideration the MgO in analysis II and distribute the other oxides in the same manner as was done in the remaining three analyses, the calculated percentages of the mineral components become: Hematite, 69.77; magnetite, 9.24; muscovite, 4.55; dolomite, 0.64; apatite, 0.048; and pyrite, 0.110. This would leave 3.08 per cent $Al_2O_3$, 3.45 per cent MgO, 7.41 per cent $SiO_2$, and 1.61 per cent $H_2O$ to be distributed among the serpentine or talc, quartz, and the yellowish-green incrusting mineral. If all the MgO is assumed to be present as serpentine, there would be

required 3.72 per cent $SiO_2$ and 1.22 per cent $H_2O$ to combine with it, leaving 3.08 per cent $Al_2O_3$, 0.39 per cent $H_2O$, and 3.69 per cent $SiO_2$ (=2 $Al_2$ $Si_2O_7$ + 1½ $H_2O$) to represent the quartz and the yellowish-green incrustation. According to this calculation, however, the serpentine would be in an excessive amount, i. e., 8.39 per cent, which is not thought to be probable. Evidently the greenish-yellow mineral is a soluble aluminous silicate, but whether it contains much or little MgO can not be learned with the data at present in hand.

Of course the lean ores, since they contain a much higher percentage of silica than the rich ores, the analyses of which are quoted above, must, in consequence of this fact, contain smaller proportions of the other constituents. Moreover, since many of them are but slightly changed phases of the normal jaspilites, they contain but small proportions of talc, serpentine, calcite, dolomite, and other minerals that were deposited by the circulating waters by whose action the richer ore bodies were concentrated. Otherwise the lean ores are similar to the richer ones. Both kinds are composed of the same chemical elements, but they contain them in different proportions.

## MINERALS ASSOCIATED WITH THE ORES.

All the minerals mentioned above as being constituents of the ores are occasionally visible in the hand specimens, with the exception of the apatite.

*Quartz, dolomite, and calcite*.—Quartz, dolomite, and calcite appear in veins cutting the ores, as has already been repeatedly stated. The quartz and calcite are nearly always in small veins, most of which are straight, marking the positions of joint cracks. The dolomite is also usually in small veins, but sometimes the veins are 2 or 3 inches in width. The smaller veins, like most of the quartz veins, mark the positions of joints. The larger veins, however, cut across the bedded ores in any direction, but most frequently penetrate them along their bedding planes. The quartz and calcite are usually white. The dolomite is either white or of a dark-pink color.

Dolomite in small brownish-yellow, flat, rhombohedral crystals with rounded faces also forms druses lining cavities and vugs in the ore. This variety and the pink variety are doubtless strongly ferruginous. The former may approach siderite very closely. Often calcite is associated with the dolomite in druses, the former appearing in transparent or translucent scalenohedra or highly modified rhombohedra, and the latter as opaque white simple rhombohedra with curved faces. Sometimes the dolomite crystals are implanted upon those of calcite; at other times the two are intermingled promiscuously. In many cases calcite occurs also alone in druses covering the walls of pores and in crystallized aggregates constituting the cement of ore breccias.

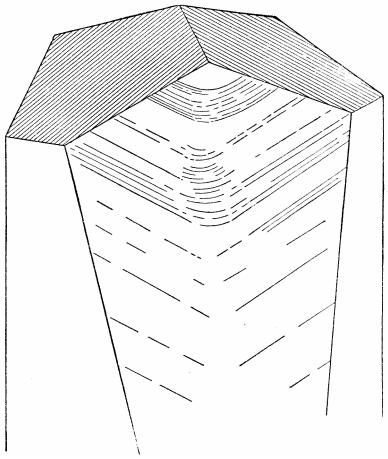


FIG. 28.—Calcite crystal of second type, in ore of West Vulcan mine.

In many instances the calcite crystals are well developed and of large size. In the West Vulcan and a few other mines water channels running through the ore are lined with numerous white calcite crystals, some of which are of great beauty. In the West Vulcan mine the crystals often measure three-fourths of an inch in length and one-fourth inch in diameter. They are of three types. The first type consists of a steep scalenohedron made up of many subindividuals. The second type is a steep rhombohedron, approaching 16 R, terminated by — 1/2 R (fig. 28), and the third type a combination of these two forms with a steep positive scalenohedron that is approximately 4/7 R 5/2 (see fig. 29). The — 1/2 R and planes of the scalenohedron are always striated by lines parallel to the intersections of these planes with a positive rhombohedron which truncates their solid angles and the planes of 16 R by curved lines approximating corresponding directions.

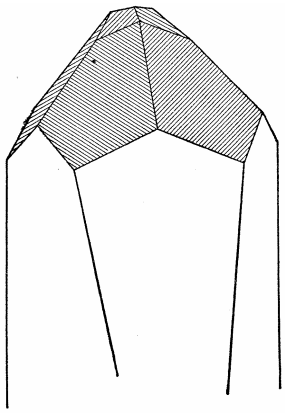


FIG. 29.—Calcite crystal of third type, in ore of West Vulcan mine.

In some places the crystals are implanted directly upon a breccia of ore and jasper fragments. In other places they cover a layer of red ocher which is about one-half inch thick, lying upon the breccia and separating it from the calcite. Again, in still other places the crystals are implanted directly upon banded jaspilite. Sometimes the jaspilite is replaced by pyrite forming a finely granular

mass in which the original bedding lines can still be detected, and the calcite crystals are attached to this.

*Pyrite and chalcopyrite*.—In many instances the calcite occurs alone on the walls of the water course, but frequently there are associated with it a large quantity of pyrite and some chalcopyrite. The pyrite appears on the whole to be older than the calcite, although the two minerals are in most cases so intimately associated that they must have been deposited nearly simultaneously. The chalcopyrite is also older than the calcite, but its age with respect to the pyrite is not known, as the two sulphides have not been seen together.

Both the sulphides also form coatings on the ore, ranging in thickness from a small fraction of an inch to an inch or more. The pyrite, moreover, occurs as isolated crystals implanted on the ore and embedded among the calcite crystals, and occasionally as separate grains disseminated through the jaspilite within a distance of an inch or more from the walls of cavities. The coatings are in a few instances mammillary, but in most cases they are crystalline. When broken their inner portions, of course, appear massive, but their outer surfaces are made up of crystals, which in the pyrite are excellent combinations of the cube and octahedron, and in the chalcopyrite are combinations of tetrahedrons. The chalcopyrite crystals are rarely more than a few millimeters in diameter. Their faces are rough and many of them are built up by parallel growths of smaller individuals. The pyrite crystals are larger. Many measure 8 mm. on an edge. All are bright and their planes are well developed.

*Other minerals in joint cracks*.—The calcite, dolomite, siderite, and pyrite are found in druses so abundantly and in the ores and associated jaspilites at so many different places that they may safely be regarded as universal accompaniments of the ores. In addition to these minerals, there are often found covering the walls of joint cracks in the ores and jaspilites of the Chapin mine, according to Mr. Brewster, druses of feldspar and of rhodochrosite, and, occasionally in the slates associated with the ores, druses of manganite and barite. The joint surfaces of the slates taken from the Pewabic mine are also in rare instances covered with a thin coating of a soft, dark-green mineral that gives the blowpipe tests for chromium and water. It has been found in such small quantities that a satisfactory determination of its nature has not yet been possible. In the only specimen seen by the writer the mineral occurred as a thin, soft, flaky coating devoid of all traces of crystallization. It appeared more like a chromiferous chlorite than anything else.

*Serpentine*.—-Serpentine, as has been stated, occurs almost universally in the ores, but usually in such small quantities as not to be noticeable in the hand specimen. Frequently, however, it can be detected as small gray or white particles scattered so uniformly through the ores as to give them a grayish tinge. It appears to be more plentiful in the lower than in the upper portions of the deposits. This fact, together with the further fact that in the Chapin mine the ore from the upper portions of the lenses is more porous than that from their lower portions, suggests that the mineral has been deposited by downward percolating waters and has accumulated near the impervious basements at the bottoms of the ore deposits. At some places in the Chapin, the West Vulcan, and other mines, the serpentine occurs in large masses within the ore and along water channels, sometimes alone and sometimes associated with calcite crystals. In many cases the walls of cavities are covered with calcite and their interiors filled, or partially filled, with serpentine, forming geodes with serpentine fillings. Rectangular masses of the mineral, almost ideally pure, have been seen by the writer which measure 5 inches along an edge. Undoubtedly much larger masses occur in the mines. The mineral is amorphous. It varies in color from dark pink to snow white, the darker varieties being more prevalent in cracks and fissures in the jaspilites and the white varieties in the geodes and along water courses lined by calcite. In some specimens of the darker varieties distinct and definite bedding lines may be noted.

The analysis by Mr. Brewster of a white soapy variety from the Chapin ore places the identity of the material beyond question.

*Analysis of minerals from the Chapin ore.*

| | Serpentine. | | Talc. | |
|---|---|---|---|---|
| | Found. | Calculated for $H_4Mg_3Si_2O_9$. | Found. | Calculated for $H_2Mg_3Si_4O_{12}$. |
| $SiO_2$ | 42.99 | 43.48 | 61.91 | 63.49 |
| $Al_2O_3$ | 1.18 | ..... | 1.06 | ..... |
| $Fe_2O_3$ | 1.40 | ..... | .39 | ..... |
| $Mn_2O_3$ | .30 | ..... | .14 | ..... |
| CaO | ..... | ..... | Tr. | ..... |
| MgO | 39.84 | 43.48 | 32.52 | 31.75 |
| $H_2O$ | 14.08 | 13.04 | 4.39 | 4.76 |
| Total | 99.79 | 100.00 | 100.41 | 100.00 |

*Talc*.—Another white mineral coating slickensided surfaces in the jaspilites and the underlying slates, and filling crevices in the latter, differs from the serpentine in being softer, having a greasy feel, and in having an obscurely flaky structure. Its specific gravity is 2.72. From Mr. Brewster's analysis given above, this mineral is seen to be talc. It appears to be less abundant in the ores than the serpentine, but is very common in the slates underlying them. Flat pieces measuring three-fourths of an inch in thickness and 3 or 4 inches in length and breadth have been picked from the dump heaps of some of the mines, but in no case were any substances attached to the specimens that would help to discover the paragenesis of the mineral. In every case the specimen seemed to have come from a crevice.

Since talc and serpentine are found so frequently along slickensides in the dolomite, and since great deposits of them occur also in the contact between this rock and the overlying Vulcan beds where slipping between the two series has taken place, the inference seems to be warranted that the magnesia of these minerals was derived from the dolomite and that the silicates were deposited by percolating water. The lime of the original

rock was carried farther and was deposited in the pores and open spaces of the ores as calcite.

*Efflorescence on ores*.—Whenever the ores are exposed to the weather in stock piles or the associated ferruginous slates are left exposed in dump heaps for any considerable length of time (six months or more), they become coated with a white efflorescence. In wet weather this washes off, but it accumulates again in dry weather, and on large specimens the thickness of the coating increases with the duration of the dry spell. Mr. Brewster has also analyzed this material with the following result:

*Analysis of efflorescence on the ores.*

| | Found. | Gypsum. | $MgSO_4+H_2O$ | Residue. | Residue, exclusive of water. | Calc. for $Na_2SO_4$. |
|---|---|---|---|---|---|---|
| CaO | 0.74 | 0.74 | | | | |
| MgO | .79 | | 0.79 | | | |
| $K_2O$ | .24 | | | 0.24 | 0.26 | 43.7 |
| $Na_2O$ | 40.58 | | | 40.58 | 44.02 | |
| $SO_3$ | 54.01 | 1.06 | 1.58 | 51.37 | 55.72 | 56.3 |
| $H_2O$ | 3.05 | .48 | .36 | 2.21 | | |
| Total | 99.41 | 2.28 | 2.73 | 94.40 | 100.00 | 100.00 |

In the course of the analysis the material was washed from the ore and dried. The determination of the water does not, therefore, represent the water content of the original mineral, but simply the quantity of water left in it after solution and desiccation. The principal mineral in the coating is probably mirabilite ($Na_2SO_4+10H_2O$), which is known to become dehydrated upon heating or upon exposure to the air. Its genesis is probably as follows: The pyrite in the ores when exposed to the air and rain becomes oxidized and produces sulphuric acid. This acts on the muscovite or traces of other sodium-bearing minerals (see analysis of the ores, p. 384) always accompanying the ores, yielding $Na_2SO_4$, which is dissolved in the rain water. This solution is then drawn to the drying surfaces of the individual lumps by capillarity. The water escapes by evaporation, leaving the sulphate as an efflorescence which, on further drying, becomes anhydrous. The dolomite in the ore is also dissolved in the sulphuric acid, yielding calcium and magnesium sulphates, which are likewise drawn to the drying surfaces, where they become intermingled with the sodium sulphates. These sulphates, however, are less soluble than the sodium salt and hence are always present in the efflorescence in smaller quantity.

## *THE ORE DEPOSITS.*

### DISTRIBUTION AND SHAPES.

The ore deposits of the Menominee district occur in the two iron-bearing members of the Vulcan formation: (1) The Traders, and (2) the Curry. The ores may occur at any horizon within these members, but other conditions being equal they are more likely to occur at lower and higher horizons than at middle horizons. However, a number of the large ore bodies extend entirely across the members in which they occur.

It has been stated repeatedly in the preceding pages, and the reasons for the statement will be discussed in the following section, that the ores are largely water-deposited material, consisting in part of mechanical sediments and in part of chemical sediments. The enrichment of the ores, which was necessary to make them sufficiently ferruginous to be mined with profit, was almost exclusively a chemical process. Ferriferous solutions penetrated the rocks along every crevice, depositing hematite and, as will be seen later, removing silica. Therefore the richer ores are found in situations where the attitudes of the rocks are such as to furnish converging channels for percolating waters, and the largest deposits are in the main channels toward which the drainage converges. Consequently, the deposits of large size rest upon relatively impervious foundations, which are in such positions as to constitute pitching troughs. A pitching trough may be made (*a*) by the dolomite formation underlying the Traders member of the Vulcan formation, (*b*) by a slate constituting the lower part of the Traders member, and (*c*) by the Brier slate between the Traders and Curry members. The dolomite formation is especially likely to furnish an impervious basement where its upper horizon has been transformed into a talc-schist, as a consequence of folding and shearing between the formations.

While all the largest iron-ore bodies are confined to the pitching troughs with impervious basements of dolomite or slate, smaller ore deposits occur at contacts between the different members and at places within the iron-bearing members where severe brecciation has occurred. The contacts between adjacent formations are favorable places for the concentration of ore, because they are horizons along which important slipping or differential movement has occurred during the folding of the district. Wherever a set of beds is folded there must be differential movement among the layers.

This is well illustrated by the slipping of the leaves of a flexible book over one another when the book is bent. In nature the contact planes between formations of different characters are always planes of weakness, hence at such places the major movements take place. These movements are sure to make the formations porous and thus produce main channels for percolating water, hence the frequent presence of ore bodies at the contact planes. Small ore deposits are found where faulting has occurred or where close plication has brecciated the formations, because the movements that result in these phenomena produce zones or areas where percolating waters are converged into trunk channels and thus favor the concentration of the iron oxide.

The combination of two or all of these conditions is more favorable than any one of them for the deposition of large ore bodies. Where the conditions are such as to combine pitching troughs with impervious basements, contact planes between formations, and faulting or brecciation, ore deposits of the first magnitude may be expected. Such are the conditions at the great mines in the district. However, in the search for an ore deposit, the first of the favorable conditions—a pitching trough

with an impervious basement—is the dominant consideration. It can not be too strongly insisted that the essential condition for the development of a large iron-ore body in the Menominee district as well as in the other districts of the Lake Superior region is the production in some way of a pitching trough which is relatively impervious. Where the pitching, impervious troughs are large and continuous, as at the Chapin, Pewabic, and Aragon mines (see figs. 30, 32, 34, 35, 40, 44, 46, and 47), the ore deposits are almost sure to be large. Where the pitching troughs are small, irregular, or broken, the ore deposits are likely to be small.

At first sight the forms of the ore deposits might be thought to be exceedingly irregular, but when the above relations are understood they appear to have orderly forms. A main mass of ore is likely to be at the bottom of a trough, but from this main mass a considerable belt of ore may follow along the limbs of the trough to a much higher altitude than in the center of the trough. The ore bodies in cross sections thus frequently constitute a U, which is very thick at the bottom, the center of the U being occupied by the iron formation which has not been transformed to ore (see plats of Aragon mine, figs. 39, 40). If the fold is very much compressed, the limbs of the U may unite at the center and produce a pitching lens, with its lower extremity rounded to conform with the shape of the trough of the fold and its upper limit, where not at the surface, more or less irregular in shape in consequence of the gradual passage of the ore into jaspilite. The Chapin deposits are good illustrations of such lenses. The deposits formed at contacts are usually much more irregular than those formed in troughs. In general, they are broad and thin, or sheet-like masses with irregular boundaries on all sides. Their lower surfaces are the most even and the best defined, but even these are undulatory. For the most part they remain near the contact of the iron-bearing formation with the underlying one, but at many places they leave this contact, rise into the iron-bearing beds, and thus become separated from the base of the formation by considerable thicknesses of jaspilites. The upper surfaces are much more uneven than the lower ones. They are not only undulatory to a greater degree, but ore projections extend upward into the overlying jaspilites, and, ramifying through these in an extremely irregular manner, often coalesce and inclose lenses of jaspilite and then continue their separate courses until the contact with the overlying slates is reached, where they again coalesce, spread out, and form a second sheet-like expansion, which, however, is usually much thinner and much less extensive than the deposit at the lower contact. In other words, the shapes of the contact deposits correspond to the shapes of channels that would be occupied by percolating water descending to lower levels mainly along the lower contact plane, but also through any openings that might offer themselves in the course of its downward passage. Where openings across the formation offered easier passages than that along the contact plane, the water, or some of it, naturally utilized these and followed them until they were intersected by other openings offering a channel with a more nearly vertical descent, when it left the former channel and continued its course in the latter one. Since the upper contact of the formation with the overlying slates is apt to offer a channel similar to that at the lower contact, we find that here also the water spread out and deposited sheet-like masses of ore like that at the lower level, but smaller. Deposits of this kind occur principally in the straight portions of the formation, where folding is absent and where the dip is not overturned. A portion of the deposits of the West Vulcan and Verona mines are of this class (see figs. 46 and 51).

## DEVELOPMENT OF THE DEPOSITS.

From the foregoing statements of facts concerning the distribution, methods of occurrence, and situations of the ore deposits, it must be evident that the ores of the Menominee district, like those of the Gogebic and Marquette districts, were concentrated by waters moving along in definite, if not always circumscribed, channels. Van Hise,[a] in his discussion of the principles controlling the deposition of ores, classified ore deposits produced by underground waters into three main classes: (1) Ores which at the place of precipitation are deposited by ascending waters alone; (2) ores which at the place of precipitation are deposited by descending waters alone; and (3) ores which receive a first concentration by ascending waters and a second concentration by descending waters. The ores of the Menominee district, like those of the other Lake Superior iron-ore districts, belong to the second class. The principal deposits are above an impervious basement, this impervious basement is in a pitching trough, and the ore formation in the pitching trough is often much broken. Smaller deposits occur without pitching troughs at contacts, fault planes, and at sharp folds, where the iron formation is fractured.

These relations of the ore deposits to the troughs (see sections and plans of mines) are such as to show clearly that the iron ores must have been deposited in their present position after the troughs were formed. No igneous or sedimentary rock as originally produced has such forms as those exhibited by most of the ore bodies. These clearly are not altogether original sedimentary rocks, such as the iron-bearing formation as a whole is, but they grade into the other rocks of the Vulcan formation. The ore bodies clearly are not igneous rocks. No igneous rocks ever grade by imperceptible stages into sedimentary rocks, such as the various members of the iron-bearing formation are. If the iron ores were deposited in their present position after the troughs were formed, as the foregoing facts seem to show beyond question, they must have been produced by the work of underground circulating waters. Further, the positions of the principal deposits in pitching troughs bottomed by impervious basements rather than in pitching arches topped by impervious covers are conclusive evidence that the ores were concentrated by descending rather than by ascending water. Descending waters would be converged by pitching troughs with impervious

basements, whereas ascending waters would be converged in pitching arches having impervious roofs. In this connection it is also to be noted that the ores are almost exclusively hematite; that is, they belong to the class of oxidized ores. The products therefore accumulated under conditions favorable to oxidation and, if secondary concentrates, they must have been precipitated by water bearing oxygen. Such waters are usually descending, hence the character of the deposits makes it probable that the waters producing the ores were descending rather than ascending. The nature of the minerals associated with the ores is also corroborative evidence that the deposits were made by circulating water, and the fact that these associated minerals are apparently more abundant in the lower portions of the deposits than in the upper portions (p. 389) might be urged as indicating that the waters were descending, or at any rate that the ore deposits lie in the courses of waters descending at the present time. Since there has been no appreciable deformation of the district since the deposits were formed, it is probable that the circulation of earlier times followed the same courses as the present circulation.

[a]Van Hise, C. R., Some principles controlling the deposition of ores: Trans. Am. Inst. Min. Eng., vol. 30, 1900, pp. 173-174.

That the ores of the Menominee district were concentrated and enriched by descending waters seems to be proved beyond question. From the nature of the ores and the character of their environment it is practically certain that the Menominee deposits were produced in the same manner and by the same processes as those of the Gogebic, the Mesabi, and the Marquette districts. But in the Menominee district the folding has been so close and the protection afforded to the original material which gave rise to the ores has been so scanty[a] that these processes have been carried to completion, so far as the surface and the depths open to our inspection are concerned, and the steps along which they have proceeded have been so thoroughly obliterated that they can not be followed with the same certainty as in the other three districts mentioned. The process of concentration has been so fully discussed by Van Hise[b] in the reports on the Gogebic and

[a]Compare Van Hise, C. R., and Bayley, W. S. (with H. L. Smyth), The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, p. 381.

[b]Irving, R. D., and Van Hise, C. R., The Penokee iron-bearing series of Michigan and Wisconsin: Mon. U. S. Geol. Survey, vol. 19, 1892, pp. 534. Van Hise, C. R., and Bayley, W. S. (with H. L. Smyth), The Marquette iron-bearing district of Michigan: Mon. U. S. Geol. Survey, vol. 28, 1897, pp. 608. With atlas of 39 plates.

the Marquette districts, and by Leith[a] in the report on the Mesabi district, that little can be added to the explanations there given. These explanations apply as well to the Menominee district as to the other iron-ore districts of the Lake Superior region, and therefore they are drawn upon freely in the following pages.

The greatest apparent difference between the deposits of the Menominee and the other districts is the comparatively large quantity of clastic ore in the former. In addition to this fragmental ore, a large portion of the iron of the ore bodies in the Menominee district was deposited in its present position as an original sediment, containing silica and other impurities, which has since been chemically changed; that is to say, some of it was deposited as iron carbonate or as greenalite, and later transformed to iron oxide in situ. Another part is iron oxide secondarily deposited, by which the originally lean material has been enriched, forming an ore body. The process of enrichment involved concentration of the iron from a source capable of yielding it, convergence of solutions carrying it into trunk channels, and conditions favorable to its chemical precipitation. The source of the iron for the enrichment of the ores is believed to have been partly iron carbonate and partly greenalite. In spite of the fact that the iron-bearing members of the Vulcan formation are largely fragmental and contain no residual iron carbonate or greenalite, it is probable that originally mingled with their material were large quantities of these compounds. The jaspilites, which constitute a considerable portion of the formation, have elsewhere in the Lake Superior region been genetically connected with iron-bearing carbonates and silicates, and there is every reason for believing that they have had a similar origin in the Menominee district. The ferriferous compounds within the Vulcan formation were originally, therefore, probably somewhat abundant. If this is so, the concentration of the ores at the particular places where they now occur may be fully explained. However, we are not restricted to the iron compounds of this formation as a source of the iron for the solutions. The Hanbury slate still contains a considerable amount of iron carbonate, from which there have been developed within the slates small bodies of chert, jasper, and iron ore (see p. 480). While no workable ore deposits have been found in the Hanbury slate in this district the siderite there present may have played an important role in the production of the iron-ore deposits in the Vulcan formation. These iron carbonates are more abundant at low horizons than at high horizons; that is, are more plentiful adjacent to the Vulcan formation. The foregoing facts render it highly probable that percolating waters within the Hanbury formation took up iron carbonate, passed down into the Vulcan formation, and contributed iron-bearing solutions for the enrichment of the ore bodies.

[a]Op. cit., p. 316.

The chemical reactions which resulted in the concentration and enrichment of the ores depend upon the mingling of waters containing oxygen with those containing iron carbonate.[a] The waters following circuitous routes, and especially those passing through the Hanbury slate, had their oxygen abstracted by the iron carbonate in an early stage of their journey. In this way the limonite and hematite of the Hanbury slate developed (see p. 476 et seq.).

In the process of precipitation of these oxides carbon dioxide was liberated and dissolved in the descending

waters. Thus carbonated waters freer from oxygen were produced, and these took up in solution more iron carbonate. Large quantities of these solutions were converged upon the sides or at the bottom of the pitching troughs, or in other places where there were trunk channels for water circulation. Water more directly from the surface, and especially that passing only through the Vulcan formation, which contained little iron carbonate, at least in the later stages of the process, retained its oxygen. The waters bearing iron carbonate and oxygen were thus commingled. The result was the precipitation of iron sesquioxide. Furthermore, the great quantity of downward-moving water, converged into the troughs, took silica into solution and transported it elsewhere, and thus abstracted this deleterious element, its place being taken by the deposited iron oxide.

It has been seen that the waters which carried iron carbonate to the ore deposits were carbonated. The precipitation of iron oxide from carbonate liberated more carbon dioxide, so that the waters were very heavily charged with carbonic acid, and consequently were particularly efficient solvents for the iron carbonate.

The iron oxide of an ore body thus consists in part of iron compounds originally deposited in situ and in part of iron brought in by underground waters. Which of the two constituents of the iron ore, the original material or that added by underground water, is on the average more abundant it is impossible to say. It is almost certain that in some eases the original detrital iron oxide is the more abundant, and in other eases that the material added by underground water is more abundant; but in all cases it may be said that were it not for the secondary enrichment by underground waters through the addition of iron oxide and the abstraction of silica the material would not be iron ore. The evidence of this lies in the fact that the ore bodies are universally confined to the places where underground waters have been converged into trunk channels. In order that this process should have produced the large ore bodies, it is necessary that it should have continued for a long period during progressive denudation. Many of the large ore bodies known in the district somewhere reach the surface. The secondary material now found near the surface must have been derived largely from the upper portions of the Vulcan formation and from the Hanbury formation, i. e., from material which was once at higher levels, but which since has been removed by erosion.

[a]Cf. Mon. U. S. Geol. Survey, vol. 43, 1903, pp. 260-265.

During the process of denudation the ore deposits must have begun to be formed shortly after the iron-bearing formation was cut through. For a time they increased in size, but it is probable that later the increase in size practically ceased, for when the oxidizing waters reached the limit of their working depth denudation must have removed the ores at the top as rapidly as they were formed beneath. However, with lowering of the upper surface there was a corresponding lowering of the inferior limit at which the waters worked, and a consequent continuous migration of the deposit downward pari passu with denudation. On account of the pitch of the basements in which the deposits were formed, lateral migration must have accompanied downward migration. We therefore must conceive of the iron-ore deposits as slowly migrating downward through thousands of feet, their lower surfaces at any given time being just in advance of the plane of erosion. As denudation proceeded a part of the ores must have been carried away mechanically and thus lost. Another, but probably a relatively small part, was doubtless taken into solution and carried downward, to be precipitated again at lower levels. However, as erosion extended downward and swept away the ore at the surface, the process of concentration also continued downward, so that the amount of ore existing at any one period through much of the pre-Glacial time was roughly constant, although there was doubtless considerable variation in its quantity depending upon topographic and climatic conditions during the different periods.

For that portion of an ore deposit which now reaches the surface or is overlain by completely altered cherts, it is probable that there is little addition in iron oxide at the present time; for it has already been explained that the iron oxide for an ore deposit is mainly derived from that part of the iron-bearing formation which has been removed by erosion. However, it does not follow that the enrichment of an ore deposit by the abstraction of silica has not effectively continued after practically all of the iron was added. Indeed, there is every reason to believe that the solution of silica has continued to the present time, and, moreover, this process has probably been more effective in those parts of an ore deposit near the surface; for there the waters have been longest at work in abstracting the silica. It is a well-known fact that in many mines there is a tendency for the silica to run somewhat lower in the upper than in the lower levels of the deposits, and this is readily explained by the greater depletion of silica in the upper than in the lower parts of deposits. Also many of the ore deposits have a broken and porous character, and appear to have sagged, as if some compound or compounds had been abstracted. The material abstracted was doubtless mainly silica. Moreover, as has been indicated in a preceding page (p. 389), silicates appear in some cases to have been leached from the upper portions of the deposits, if not also deposited in lower portions. It is probable that some of the porosity referred to above is due to the abstraction of serpentine and talc, although the cavities which these substances occupied may have been formed originally by the removal of silica. The tendency of the abstraction of these two minerals would be to diminish the contents of magnesia, silica, and water in the ore, and, as a consequence of this diminution, to increase the percentage of iron.

Furthermore, the ore deposits seem to have been made more valuable by the abstraction of phosphorus and sulphur compounds by descending waters in a way similar to the abstraction of silica and silicates. The most notable published cases illustrating this process are those of the Ludington mines, described by Browne

(see p. 89), and of the Pewabic and Aragon mines, described by Brown[a] and Larsson,[b] where the deposits near the surface are low phosphorus and those deeper down are high phosphorus ores. In general the phosphorus seems to be low where the iron is high and the ore porous, and therefore where the water circulation was very effective. The same is true of sulphur, but to a much less noticeable extent, because of the very slight quantity of this element in the ores of the district. The formation of sodium sulphate as an efflorescence on the ores exposed in stock piles indicates that the sulphur is oxidized under the influence of meteoric waters and forms a soluble salt, which naturally must be carried off by moving water. The oxidizing waters that gain access to the ore deposits should produce similar effects, and, as a consequence, the ore should be rendered more valuable thereby. It is a well-substantiated fact that iron ores which have been exposed to the atmospheric agencies for a considerable lapse of time lose both phosphorus and sulphur.

[a]Brown, E. F., Distribution of phosphorus and system of sampling at the Pewabic mine: Proc. Lake Superior Min. Inst., vol. 3, 1895, p, 49.

[b]Larsson, Per, ibid., p. 55.

In conclusion we may therefore say that the chemical processes have tended to make the ore deposits more valuable at the present time, although the additions of iron may have long since ceased.

## TOPOGRAPHIC RELATIONS OF THE DEPOSITS.

In order to produce great masses of ore, such as some of those characterizing the Menominee district, the water circulation must have been long continued. The volume of water which circulated through the ore deposits must have been many thousand times, probably hundreds of thousands of times, as great as the volume of ore. It is certain that as depth increases the rocks in the earth's crust become more and more compact, until finally the zone of rock flowage is reached, into which the water can not be assumed to pass. We therefore must conclude that water converged into trunk channels must again reach the surface. Hence we find that the majority of the ore deposits where they approach the surface are on the slopes of the elevations, the crests being usually occupied by the Randville dolomite or the Cambrian sandstone. This is true for all of the important mines of the district with the exception of the Chapin, the Aragon, and the Loretto. However, each of these deposits is so connected with troughs which rise toward the higher grounds as to make it almost certain that they had elevated feeding areas. Moreover, while the Chapin deposit was discovered in low-lying ground, a little way to the west is the broad valley of the Menominee River, which is still lower. Probably, therefore, there were lower areas where the water issued. However, it is possible that in the subordinate cross valley at the Chapin mine descending oxidizing waters met ascending carbonate-bearing waters, and thus precipitated a part of this deposit.

The crests of the elevations above the Ludington, Millie, Walpole, and Pewabic mines rise to 1,500 or 1,600 feet above sea level. The broad valley of the Menominee to the west has an elevation of about 1,060 feet, and this valley is probably filled to the depth of 100 feet or more. Between Prospect Hill and Hughitt Bluff is a subordinate cross valley. In this valley is the Chapin mine, the surface of which has an elevation of only about 1,150 feet, or not more than 90 feet above the valley of the Menominee River; but if the valley of the river is filled to a depth of 100 feet by sand and gravel the elevation of the present surface at the Chapin mine is 190 feet above the rock floor under the river channel.

With respect to the other mines of the district the relation between the topography and the ore deposits is in strict accord with the theory that the ores are the result of the action of descending waters; although in this district this relation does not corroborate the theory as effectually as it does in some of the other districts. While it is true that nearly all the ore deposits of the Menominee district thus far discovered are on hillsides, nevertheless it is also true that the iron formation is nowhere at low levels except in the vicinity of the Chapin, Aragon, and Loretto mines, as before mentioned. The great dolomite constitutes the dominant factor in determining the positions of the elevations. The iron formation lies immediately upon this, and consequently must of necessity be on the slopes of hills, and, since the ore deposits are in this formation, these, too, must be on hill slopes. The principal value of the discussion of the relation between the topography of the Menominee district and its ore deposits is to show that this district offers no important exceptions to the generalization that the iron-ore deposits of the Lake Superior region are usually situated below slopes or crests.

East of Iron Mountain it is notable that adjacent to each of the localities where important mines are found there are valleys across the south limestone range and the Vulcan formation, although these valleys are now partly filled with thick deposits of drift. East of the Quinnesec mine is the low-lying area now partly occupied by the road running north. Northeast of Norway is another transverse depression. The Norway mine is located on the hill to the northwest. The West Vulcan mine is located on Brier Hill, to the northeast. The Aragon mine is in the depression. East of the East Vulcan and Verona mines is the valley of the Sturgeon River. The Breen mine is on a slope with a cross valley immediately to the west. The Loretto mine pitches directly below the valley of the Sturgeon River. Adjacent to the central range of dolomite the most important deposit is the Traders. This mine is on the westward slope of a hill which rises to an elevation of 1,500 feet. The ore deposit pitches toward the valley of the Menominee only a short distance to the west.

Thus it appears that nearly all of the large ore deposits in the Menominee district are either related to the topography in the same manner as are the deposits in the other Lake Superior iron-ore producing districts, or

that their relations are such as can be explained on the supposition that before the district was denuded by erosion agencies they were surrounded by elevations greater than those at which the surfaces of the deposits then lay.

## TIME AND DEPTH OF CONCENTRATION.

The beginning of the final concentration of the Menominee ores must have been after the folding which produced the troughs and after the removal of the Hanbury formation covering the Vulcan formation—that is, in the interval between the Upper Huronian and the Upper Cambrian. In this district it is certain that the process of concentration was carried far toward completion before the end of Cambrian time, for considerable areas of the Huronian rocks and certain of the ore bodies themselves, as, for instance, parts of those of the Traders, Cuff, Chapin, Pewabic, Walpole, Quinnesec, Norway, Cyclops, Breen, Emmett, and other mines, are capped by the Upper Cambrian sandstone, at the base of which are detrital ores derived from the ore deposits below during the Cambrian transgression over the area. It is therefore highly probable that the main concentration of the iron ore of the deposits of the Menominee district took place before the end of the Cambrian period, although since that time there probably has been additional enrichment, mainly by the solution of silica, magnesia, phosphorus, and sulphur, and the deposition of some iron oxide.[a]

[a]A large portion of the above discussion of the development of the ores and their relations to the topography, as well as the statement as to the time and depth of concentration, is taken almost verbatim from Van Hise's paper on the iron-ore deposits of Lake Superior, "The iron-ore deposits of the Lake Superior region:" Twenty-first Ann. Rept. U. S. Geol. Survey, pt. 3, 1901, pp. 323-332, 396-400.

## ILLUSTRATIONS OF DEPOSITS, INCLUDING GEOLOGY OF THE IMPORTANT MINES.

The ore deposits now being exploited and those that have been worked in the past are confined to three belts:

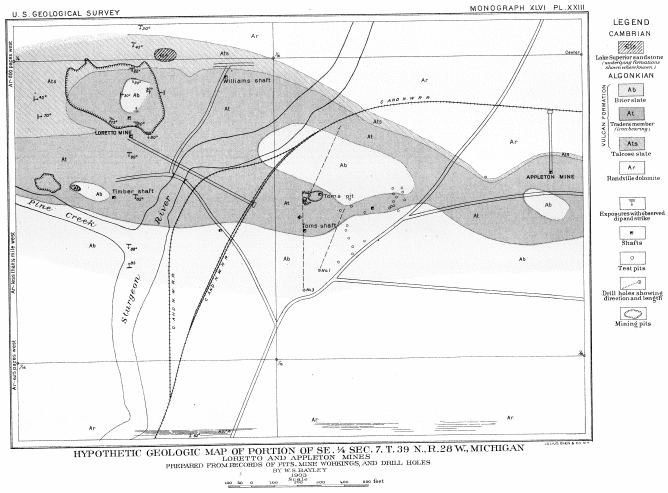
(1) The Loretto-Appleton belt, east of the locality where the northern and southern belts of dolomite unite, or, at least, where they approach very near to one another.

(2) The Traders, Cuff, Cornell, Indiana, and Forest belt, mainly south and west of \he central dolomite belt, and possibly also in one case north of it.

(3) The belt extending from the Menominee River on the west to Waucedah on the east, lying on the south flank of the southern belt of dolomite. On this belt are situated the Ludington, Chapin, Walpole, Pewabic, Keel Ridge, Vivian, Quinnesec, Cundy, Norway, Perkins, Cyclops, Aragon, Brier Hill, Curry, West Vulcan, Central Vulcan, East Vulcan, Verona, Breen, and Emmett mines, besides many as yet unnamed explorations to the west of Iron Mountain.

## LORETTO-APPLETON DEPOSIT.

The Loretto-Appleton deposit, more particularly that portion being exploited by the Loretto mine, furnishes one of the most typically developed trough deposits to be found in the district. West of the Loretto mine the northern and central belts of dolomite probably join (see maps, Pls. IX and XXIII), giving continuous dolomite from the Sturgeon quartzite on the north to the southern iron-bearing belt on the south, or, at any rate, if not at the surface, the dolomite bridges this interval a short distance beneath the surface, the surface rocks in this case being a thin layer of the lowermost beds of the Traders member of the Vulcan formation. East of this bridge of dolomite, between the northern and southern belts of dolomite, is the iron-bearing Vulcan formation. To the west of the bridge are possibly the iron-bearing Vulcan formation and certainly the Hanbury slates. It is therefore clear that a cross anticline here exists which brings to or near the surface the dolomite that to the east and west is buried beneath the younger rocks. Hence it follows that the major structure adjacent to the Loretto mine is that of an eastward-plunging syncline, the dolomite being to the north, to the south, and to the west. From an inspection of the surface map of the mines it will be seen that this syncline is widest to the west and is here composed of a northern subordinate syncline, separated from a southern monocline (see cross section, fig. 30) by a narrow, compressed anticline. These folds pass to the east into what appears to be a simple syncline, which continues at least as far as the Appleton mine. The rocks involved in the folds are the Randville dolomite, the Traders quartzites and jaspilites, and the Brier slates. The dolomite nowhere reaches the surface, but it is found in drill holes under the jaspilites at several points. The Brier slates occur in three small areas, capping the jaspilites along the axis of the syncline. Thus in longitudinal section there are three synclines and two anticlines from the west side of the Loretto mine to the east side of the Appleton property.




[Plate XXIII. Hypothetical geological map of the Loretto and Appleton areas]

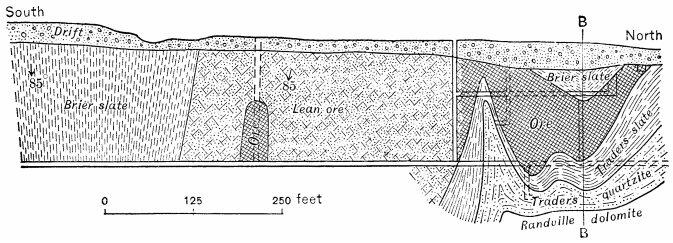



FIG. 30.—Vertical north-south cross section of the Loretto mine. (Section A-A in fig. 31.)

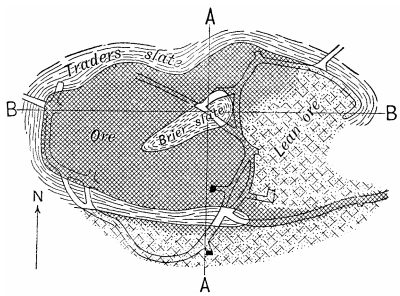



FIG. 31.—Horizontal section of the Loretto mine at the first level. Scale: 1 inch=250 feet.

The principal surface rocks within the boundaries of the syncline are the Traders jaspilites. These are bounded on the north by the Traders quartzites, and the same rocks may occur at the surface at the crest of the first anticline west of the Loretto mine. No exposures of the quartzite are to be found here, but the eastern workings of the Loretto mine show that it approaches very close to the surface, and that a short distance farther east it may actually reach the surface. The structure of the area, if the inferences above outlined are correct, is that of an east-west fairly compressed syncline to the north, passing into an anticline to the south, and followed farther south by another syncline, the south portion of which has not been seen. These folds are moreover affected by three cross (north-south) synclines, separated by two anticlines, all of which are open.

The character of the fold in which the main Loretto deposit occurs is beautifully shown by the horizontal outline of the ore body (see fig. 31). The outer limit of the ore makes a broad U which opens to the east; the bottom of the U being to the west. The cross section of the main ore deposit also makes a wide U, the southern limb of which passes into a sharp subordinate anticline (fig. 30). In the center of the syncline slate caps the ore. Moreover, the longitudinal section of the mine is also a syncline (fig. 32) likewise capped by the slate. East of the slate capping is lean ore-bearing material, which passes into ore under the slate and under the drift west of the slate. The failure of the rock to change to ore east of the slate is apparently due to the cross anticline, which has prevented the convergence of downward-moving currents of water, and therefore the transformation of the rock into ore. No better illustration of an ore body in a trough on an impervious basement could be desired than that furnished by this deposit.

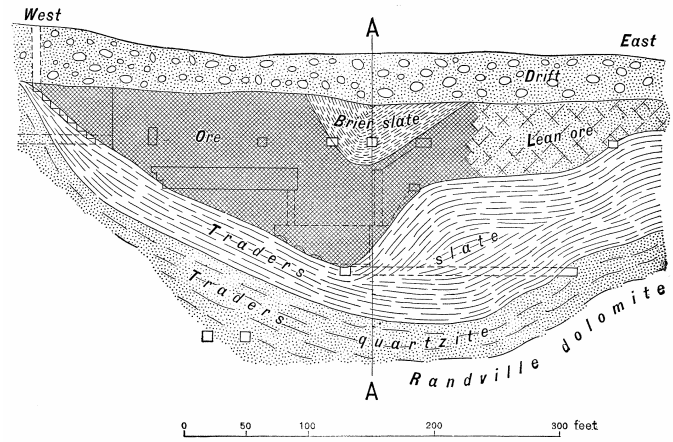
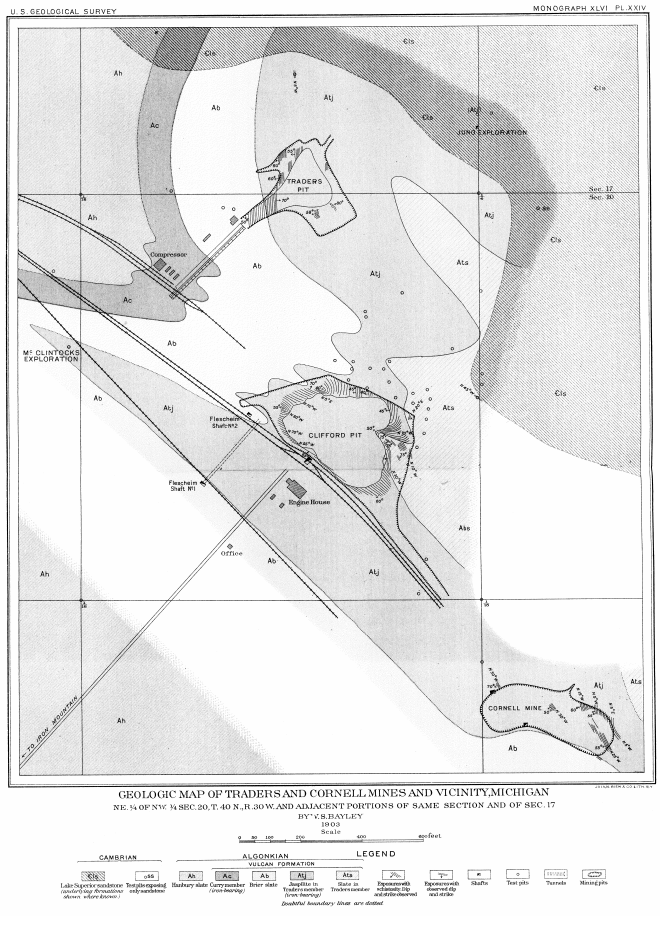



FIG. 32.—Vertical east-west longitudinal section of the Loretto mine. (Section B-B in fig. 31.)




[Plate XXIV. Geological map of Traders and Cornell mines and vicinity]

The southernmost deposit of the Loretto mine and the deposit in the Appleton mine had not been sufficiently developed to warrant statements as to their relations to folds. If the slate south of the south deposit of the Loretto mine is Brier, as is supposed, this deposit may be a contact deposit at a little greater depth than has yet been reached. The slate dips slightly to the north at its contact with the iron-bearing beds, producing a steep slope dipping toward the ore body, which slope must have served to some extent at least to direct descending

water in this direction. At the Appleton mine the greater portion of the ore that has been taken out (12,102 tons between 1892 and 1895) was obtained from north of the shaft on or near the contact of the jaspilites with the underlying Traders slates.

### TRADERS-FOREST BELT.

The second belt of the Vulcan formation, that adjacent to the central belt of dolomite, is now being worked only at the Traders and the Forest mines at the two extremities of the belt. Formerly the Cornell, the Cuff, and the Indiana mines were also in operation. The Cornell mine ceased shipment in 1887, having mined 49,302 tons of ore, and the Indiana ceased work in 1886, having raised 17,871 tons. The Cuff shipped 20,210 tons in 1899. At the Forest mine exploration has not proceeded far enough to warrant a definite statement as to the character of the deposit.

### TRADERS MINE.

The Traders mine is at the west end of the Traders-Forest ore-bearing belt, which in this vicinity constitutes a westward-plunging anticlinorium. On the mine property are two pits—a northern one, known as the Traders pit, and a southern one, known as the Clifford pit (see map, Pl. XXIV). Southeast of the Clifford pit and distant about 800 feet is the abandoned pit of the old Cornell mine. The formation exposed in both of the Traders pits is the same in character. It consists of a sheared jasper and ore breccia overlain by a red slate and underlain at the Clifford pit by a ferruginous slate. At the Traders pit the ore formation strikes nearly north and dips at 55° to 60° to the west. The rock is jointed and schistose. On the west side of the pit schistosity and bedding are approximately parallel, but on the east side the strike of the schistosity varies from N. 10° W. to N. 25° W., and its dip from 50° W. to 80° NE. The jointing is inclined to the schistosity and also, to the bedding. At the northwest corner of the pit the joints strike N. 30° W. and dip 75° W. At the southeast corner their strike is N. 45° W. and their dip 25° NE. Where the schistosity and jointing are inclined to the bedding the latter feature is exceedingly obscure. The variation in the directions of the schistosity and of the joints is evidence that folds of some kind exist here, though they have not been detected, and these may be connected in some way with the occurrence of the ore. No shipments are now being made from this pit, nor is any development work being done. The ore deposit is therefore not thought to be promising under the present conditions of the ore market. The contact of ore beds with the overlying Brier slates is plainly seen on the walls of the pit at the southwest corner. Beyond this to the west are two pits in red slates, and about 200 feet farther west is a third pit in jaspilites that may belong in the Curry member. Northwest of the pit is an old shaft, on the dump of which are fragments of red sandstone and of gray sheared quartzite. It is probable that this is a quartzose bed in the Hanbury formation; but since quartzites are found also in the Traders formation, not much confidence can be placed in this identification. If the rock is a component of the Hanbury formation, the Traders beds must swing to the east.

Northeast of the Traders pit, at what is known as the Juno exploration, are two shafts that offer another problem. Here the rocks on the dumps are sandstone and an abundance of an evenly banded jaspilite quite unlike the brecciated rock of the Traders and Clifford pits. Some of the jasper is of the flinty or waxy kind, characteristic of the typical jaspers. In other specimens, however, the siliceous component is a gray quartzite or chert that resembles very closely some of the cherty phases of the Curry jasper. Two suggestions offer themselves in explanation of this occurrence—(1) the jaspilites may belong in the Curry member on the east side of an anticline and across its crest from the Traders pit, or (2) they may be Traders beds which have escaped the severe brecciation to which the beds in the Traders and Clifford pits have been subjected. The second suggestion seems to be the more plausible one because of the short distance intervening between these pits and the east end of the Traders pit. Even in this case the beds must be separated from those in the Traders pit by an anticline.

The only deposit at present being worked in this area is that of the Clifford pit. Here the iron-bearing rocks are the same as at the Traders pit (Pl. XXIV), with dark-gray and black Traders slates to the east and red weathered Brier slates to the west. The contact between the iron-bearing beds and the underlying slates is beautifully exposed on the east side of the pit, where it can easily be followed for 250 feet or more. The upper contact of the iron-bearing member with the Brier slates can also be traced on the stripped surface west of the pit. The mapping of these contacts shows conclusively that the rocks are plicated into several minor synclines and anticlines, and a study of the relations between the ore deposits and the folds show that the richest ore is in the synclines. The best ore at present being mined is taken from the northeast corner of the pit, where the syncline in the underlying slate is largest and most typically developed (see map, Pl. XXIV). The entire area occupied by the pit is ore producing, but the ore is everywhere richer along its eastern—i. e., lower—side than toward its western—i. e., upper—side. The pitch of the folds is approximately 50° NW. The greater richness of the Clifford ore as compared with that from the Traders pit is evidently due to the repeated folding of the ore-bearing beds in the former pit and the consequent production of several pitching synclines bottomed by the black slates.

In addition to being folded, the iron-bearing beds are deformed by jointing and schistosity, the latter structure being very closely related to the former. The schistosity strikes uniformly N. 75° to 80° W., and is therefore in some places parallel to the bedding and at other places transverse to it. Although all the joints strike approximately at right angles to the schistosity, there seem to be two sets with respect to dip. In one set the

dip is about 50° to the northwest, and in the other 20° to the southeast. It has already been explained that the brecciated character of the ore beds in this pit is due to the causes that produced marked schistosity transverse to the bedding (see p. 302). It should be mentioned in addition to what has already been stated in this connection that the most conglomeratic-looking jaspilite layers are found on the north side of the pit, where schistosity and bedding are approximately perpendicular to one another.

The nature of the folding south of the Clifford pit and between this and the Cornell pit is not known, as there are no outcrops in this area and practically no explorations. A drift running about northeast from the bottom of the Fleischman shaft No. 1 (see map, Pl. XXIV) to a point under the railroad track alongside of the Traders pit was driven through ore-bearing beds throughout nearly its entire distance. At the shaft, however, a gray quartzite was encountered with the peculiarities of the quartzite at the base of the Traders member. No explanation of its occurrence at this place is hazarded. The rock may be a locally developed member of the Traders series. The wide expanse of the ore-bearing member revealed by the drift suggests its repetition by folding, and the occurrence of ore like the Clifford ore at the McClintock exploration, about 600 feet northwest of the shaft, suggests that at least one of the folds extends on the surface to this point. About 250 feet north of the McClintock exploration is a pit in graphitic slates identical with those at the bottom of the Hanbury slate south of the southern ore belt.

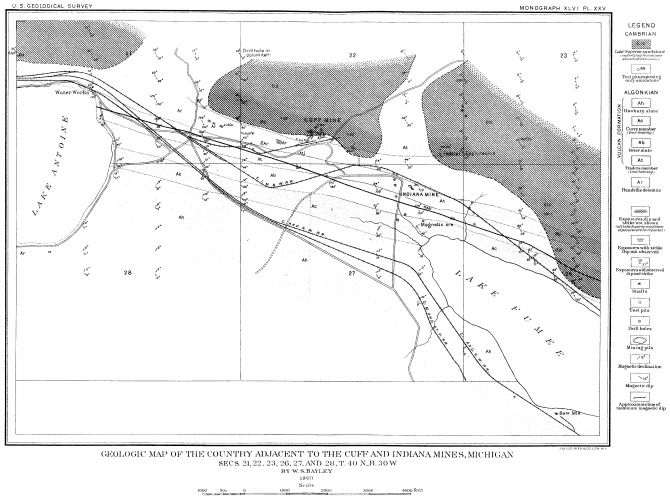
Nothing is known of the rocks in the intervening distance. The interval is scarcely wide enough for the occurrence in it of both the Brier slates and the Curry member with their normal thickness. Their thickness, however, might be much diminished on the sides of a close fold, such as must exist here if the southern pit is in Traders rocks, and both members may occur in the interval between the two pits. An alternative theory to explain the structure at this point suggests that the McClintock pit is really in Curry beds and that the similarity which exists between the rocks in this pit and those of the Clifford pit is due to the fact that in both instances they were subjected to the same kind of close folding and shearing.

## CORNELL MINE.

The Cornell pit at present affords but little information as to the structure of the iron formation in its neighborhood. It has not been worked for more than ten years and its walls have in many places become covered with a talus of loose material. Enough can be seen of the rocks, however, to show that the ore-bearing beds are practically identical with those in the pits of the Traders mine, though they are not as completely brecciated as these. It is reported that a “conglomerate ore” exists to the north of the western shaft along a drift, running north, and that red slates occur about 200 feet south of the bottom of this shaft in a drift running about south. In the northeast portion of the pit there are indications of the existence of folds in the ore-bearing beds (see Pl. XXIV). Near its northeast corner the strike of the jaspilites is in some places nearly north. Farther west the strike is N. 30° W. Somewhere between these points there must be a syncline pitching to the south, and in this the best ore would be expected to occur. As a matter of fact, the few thousand tons shipped from this mine are reported to have come from the northern part of the pit. There are also a few gentle corrugations visible in the jaspilites in this portion of the pit. They are significant only as indicating that the beds are involved in larger folds that are not visible. The minor corrugations are too open to have afforded distinct channels for percolating waters and so have not been efficient in determining the positions of ore deposits. The absence of more distinct folds in this place may account for the absence of a larger ore deposit,

## CUFF MINE.

At the Cuff mine the exposures are not sufficiently abundant to disclose the presence of sharp folds if they exist in its vicinity (Pl. XXV). The ore-bearing rocks are very similar to those of the Traders and Cornell mines, but they are apparently less brecciated than these. In the open pit west of the shaft the strike of the jaspilites is N. 10° to 15° W., and their dip 40° N. (fig. 17); In the large pit east of the shaft the strike is the same except at the southeast corner, where it is N. 45° E. The dip in this pit is 25° N. East of this again is a small pit in red slates, believed to be at the base of the Traders formation, and east of this about 100 paces is a trench uncovering banded ore and cherts to the north and a brecciated ore, like that at the Clifford pit, to the south. Southwest of the shaft a number of openings have been made disclosing jaspilites and red slates with a wavy contact line between them that suggests the presence of minor folds.




[Plate XXV. Geological map of the country adjacent to the Cuff and Indiana mines]

At the surface just east of the shaft, at the southwest corner of the pit already referred to, is a white or light-

gray dolomitic sandstone, covering a pinkish-gray, even-banded dolomite dipping 45° N. Within the mine there is also to the east of the shaft, according to the testimony of the former superintendent, Mr. Shephard, a “horse of white soapstone” which upon investigation proves to be a dolomite. This is on the first level. It does not reach the surface, the surface rocks above it being contorted jaspilites. The great northern displacement indicated by this occurrence of dolomite in the mine very strongly suggests the existence of a fold in this rock and also, of necessity, in the overlying jaspilites. The fold is not sharp and well defined, and consequently the ore is lean, containing from 36 to 40 per cent metallic iron.

In the pit to the east of the shaft the relation of the ore to the folding and crushing of the jaspilites is well exhibited on a small scale. The jaspilites exposed in this pit are generally flat lying, their dip being about 25° N. Toward the north side of the pit, however, the rocks are bent into a small monocline. Here they are crushed into breccias and here also the richest ore is developed. All the jaspilites in this pit are characterized by the green alteration product noted in connection with the brecciated ores of the Norway and other mines on the south belt (see pp. 375 and 386). The pit lying about 650 feet west of the shaft encountered an evenly laminated ferruginous slate, or lean ore, devoid of jasper bands. It is placed in the Brier belt on purely petrographical grounds.

## INDIANA MINE.

The geology of the environs of, the Indiana mine is indicated on the map (Pl. XXV). The plats of the underground workings have not been seen. The results of drilling, however, give no indication of the presence of folds in the vicinity of the shaft, the output of which, as stated above, was only about 18,000 tons. The rocks on the dump are argillaceous Traders slates, even-banded jaspilites, brecciated jaspilites, and even-banded ferruginous slates that are probably Brier. In the little pit opened to the west of the shaft the argillaceous slates form a northern wall dipping south. Even-banded jaspilites are south of these, on the northwest and southeast sides of the pit. The dips vary slightly in different places, but no distinct folds were made out. The brecciated ores found in the dump are reported to occur between the banded jaspilites and the slates. Northwest of this pit and at a distance of only 350 or 400 feet is a ledge of dolomite with a strike that would carry the rock along the north edge of the excavation. Moreover, drill holes put down south of the mine and directed northward encountered dolomite after passing through Traders slates, jaspilites, and Brier slates in the inverse order from that mentioned. At the contact between the Traders slates and the dolomites the first-named rocks were everywhere brecciated. From these slight data it is thought probable that the Indiana deposit is a contact deposit, like that of some of the mines on the southern belt, but that it is one of small dimensions, because, as the drill holes indicate, the dip of the dolomite flattens out with increasing depth.

## FOREST MINE.

In the neighborhood of the Forest mine the exposures of pre-Cambrian beds are likewise very few (fig. 33). The shaft is at the base of a hill which partially encircles it on the north and east. This hill is capped by the Lake Superior sandstone which, of course, completely hides the underlying rocks. At the base of this sandstone is a conglomerate varying in character at different places in such a way as to show that the dolomite and the jaspilites continue under it toward the east. In some places the basal layer contains numerous large fragments of the chert that often occurs at the top of the dolomite formation. At other places the principal fragments and the largest ones consist of ore or of jasper. While, therefore, it is almost certain that the two formations continue for some distance to the east of the mine, there is, nevertheless, no evidence to indicate how far they extend. A few hundred feet northwest from the mine shaft is a ledge of dolomite forming a little cliff to the south, faced by a veneering of sandstone conglomerate. At the base of the cliff is a slate band dipping 70° S. This is exposed through a thickness of 7 or 8 feet, and is followed to the south by jaspilites. The sequence, so far as it has been worked out, is identical with that at the Indiana mine. The mine has not been opened up sufficiently to yield important geological details. There is no evidence at present of the presence of a fold in the jaspilites to account for the ore deposit, but this is in the normal position of a contact deposit.

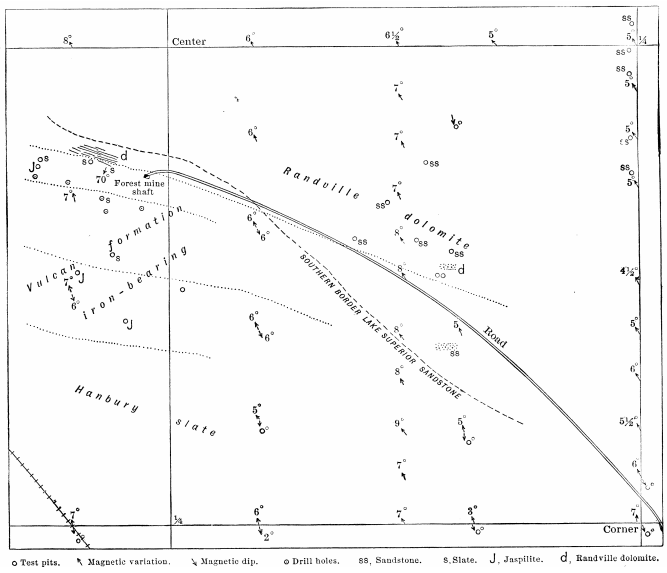



FIG. 33.—Sketch map of exposures in south half of sec. 25, T. 40 N., R. 30 W.

## THE SOUTHERN BELT.

The third belt of ore deposits occurs along the south side of the southern dolomite belt, and extends from the Menominee River on the west to Waucedah on the east. It includes the most important mines in the district and all of the older ones that are still being worked. All the mines that are at present productive lie between Iron Mountain and the Sturgeon River.

It has already been explained that the southern belt of dolomite is an anticlinorium. Further, it has been pointed out that superimposed upon this major fold are folds of higher orders (see pp. 237-246). The occurrences of the ore deposits in the Vulcan formation south of this belt of dolomite are closely related to these subordinate folds. The folds of the second order superimposed upon the major fold are a series of very close plications, which, for the western part of the district, plunge steeply to the west. The result of these plications is to produce a number of westward-pitching synclinal troughs directly underlain by some phase of the dolomite formation or by the slates of the Traders member. As the result of this folding, the surface outcrop of the southern boundary. Of the dolomite has a notched-like distribution, producing bays in the dolomite. The iron-bearing formation occupies the bays which open out to the west into the main belt of the Vulcan formation, each bay being surrounded on the north, south, and east by the dolomite.

## CHAPIN-PEWABIC DEPOSITS.

Beginning at the west, the first and most important set of folds of the second order are those adjacent to Iron Mountain. Here are two important folds, superimposed upon which are folds of the third order (Pl. XXVIII). The western one produces the troughs in which the Chapin, Millie, and Walpole mines are located (see Pl. XXVI, *A* and *B*) and the eastern one the trough in which the Pewabic mine occurs. The western trough is especially complicated, it being really composed of two minor troughs or folds of the third order, with an intervening anticline, and even these folds have folds of a higher order superimposed upon them. If one were to follow a geographical order, beginning at the west, the Chapin mine should be first mentioned, but the interpretation of the occurrence of the ore at the Chapin mine depends upon the facts furnished by the Walpole and the Pewabic mines. They are therefore first considered.

## WALPOLE MINE.

The Walpole mine has a north and a south ore deposit (fig. 34). These ore bodies occur in subordinate synclines, separated by an intermediate anticline. The synclines and the anticline together constitute the east end of the western important fold of the second order. The northern deposit is an excellent illustration of a steep pitching trough which is bottomed by slate and dolomite, and is bounded on all sides but one by the same rocks. The fold is here so close that the iron-bearing member on the south limb has all but been pinched out. The southern ore body is just as clearly in a westward-pitching syncline. Shaft No. 2 of the Walpole mine is on its southern side at the contact of the iron-bearing rocks with the underlying dolomite, and the Millie mine is near the center of its southern limb farther west. The workings of the Walpole mine beautifully illustrate the relation and succession of the formations which occur between the limestone and the Brier slate in places where the folding is of a very complicated character.

PLATE XXVI.
VIEWS OF THE CHAPIN MINE.

FIG. *A*.—View east from D shaft, Chapin mine, showing shafts on Walpole-Chapin fold. Photograph by J. J. Eskil.

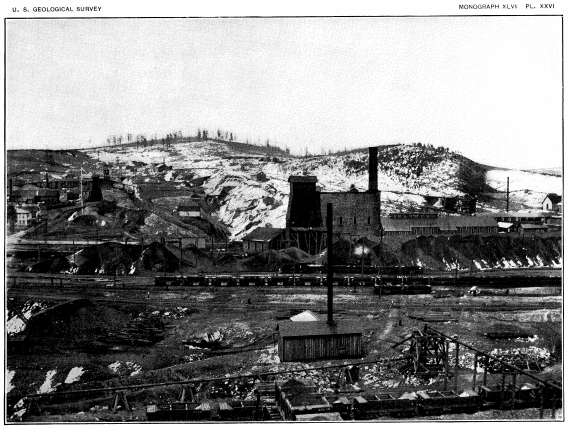
The shafts to the left of the sink hole are the C and the B shafts, the one in the distance at the end of the sunken ground is the abandoned A shaft, and that in the foreground is the D shaft of the Chapin mine. The top of No. 2 shaft can be seen projecting above the roof of the engine house connected with the D shaft. The mine in the notch on the top of the hill, nearly in the center of the view, is the Millie mine, and that in the far distance to the left is the Walpole mine. The Pewabic mine is over the hill to the right of the Millie mine. The hill behind the A shaft is composed of Randville dolomite, topped by horizontal layers of sandstone. The knob to the right is Hughitt Bluff. It consists of evenly banded Traders jaspilites. The gully to the south of the C and B shafts was caused by settling of the ground in consequence of removal of the ore.

FIG. *B*.—View west from A shaft, Chapin mine, showing distribution of shafts on Chapin property. Photograph by J. J. Eskil.

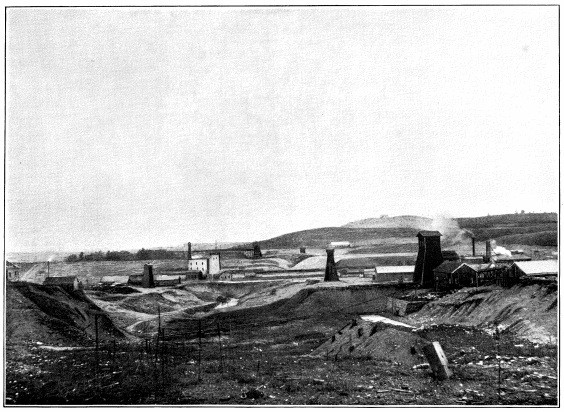
B and C shafts are to the right, No. 2 shaft to the left, and D shaft at the end of the large sink hole. In the distance, to the left of the second sink hole, is the Ludington shaft. The shaft to the right of the B shaft is the Hamilton shaft. The sink holes are produced by the settling of the ground, due to the removal of the ore from beneath.

The hill in the distance is Prospect Bluff.

U. S. GEOLOGICAL SURVEY MONOGRAPH XLVI PL. XXVI



*A*. VIEW EAST FROM D SHAFT, CHAPIN MINE, SHOWING SHAFTS ON WALPOLE-CHAPIN FOLD.



*B*. VIEW WEST FROM A SHAFT, CHAPIN MINE, SHOWING DISTRIBUTION OF SHAFTS ON CHAPIN PROPERTY.

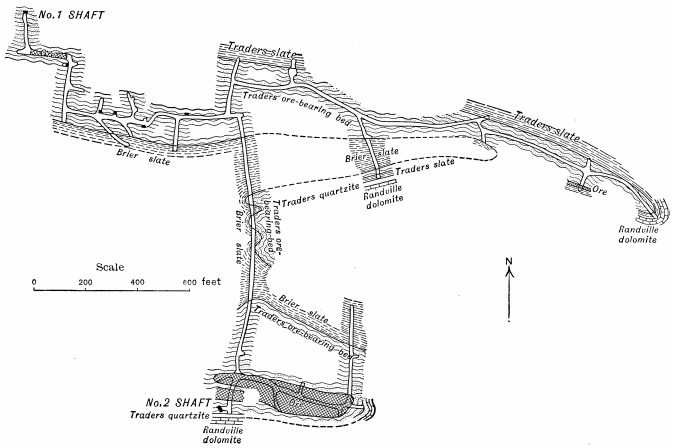



FIG. 34.—Horizontal section of the Walpole mine at the third level.

The ores of the Walpole mine and the Millie mine are often brecciated to a remarkable extent. The fragments of the rock are cemented together either by subsequently deposited ore or by drusy masses of a yellowish dolomite. This is especially true of the ores in the eastern ends of the folds where they are closely compressed. The brecciated ores are beautifully exposed on the walls of the long crosscut that connects the workings of the two shafts.

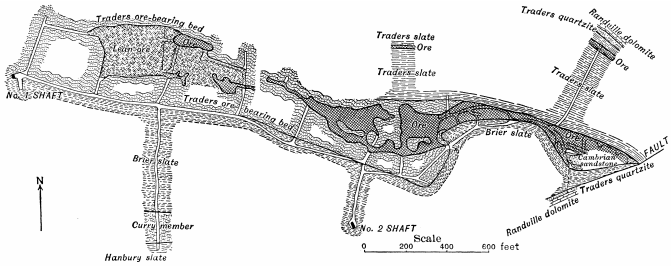



FIG. 35.—Horizontal section of the Pewabic mine at the third level.

## PEWABIC MINE.

The Pewabic mine is on a single, closely compressed fold (fig. 35). The slate and dolomite are here again found on the north, east, south, and at the bottom of the ore body. Here, however, on the south limb of the fold the ore-bearing member does not appear between the dolomite and the Brier slate. It has therefore been squeezed out by the very great pressure, or else slight faulting has taken place. A crosscut north on the first level from the ore-bearing Traders bed to the limestone shows several repetitions of the foot-wall slates, the quartzite, and the iron-bearing members, these being found in narrow belts (fig. 36). The reduplications are regarded as due to very close subordinate folding. The thickness of the Brier slate as developed on the surface by test pitting in the vicinity of the Walpole shaft No. 3 (see map, PI. XXVIII), seems to confirm this view. The succession of beds, so far as they could be seen at the time the section was examined, is indicated in the figure. The talcose slates are typical light-colored serpentinous, or talcose Traders slates. The quartzites are like those near the base of the Traders formation elsewhere, and some beds are conglomeratic. Toward the south side of the section there is a series of banded jaspilites, which for 118 feet south of their contact with the Brier slate appear to be continuous. To the south of this point, however, they are cut by seams of the Lake Superior sandstone, and contain irregular pockets of the same sand rock. Gradually the jaspilites diminish in quantity, the sandstone increasing at the same time, until finally the jaspilites appear as distinct bowlders and fragments in the sandstone, and the rock becomes a typical ore conglomerate at the base of the Cambrian. The transition from the bedded jaspilites to the ore conglomerate is so gradual that it is not possible to recognize a distinct line of demarcation between them. The conglomerate was evidently deposited immediately upon the rock which yielded its bowlders. The surface upon which it was laid down was made up of the ends of vertical layers of the jaspilites, which were fractured and shattered, and in which joints had been opened by weathering. Into the latter sand had filtered and formed the veins, seams, or dikes noted as cutting the jaspilites in the drift. The shattered parts were cemented by small quantities of sand that sifted down between the loose fragments. Near the surface of the unshattered rock the fragments had not been much disturbed in their position, and the sand consequently appears as pockets in a solid rock. Farther away from the solid surface the fragments were more separated. A greater quantity of sand sifted down between them, and made a well-defined conglomerate. At the extreme southern end of the drift the conglomerate passes into a pure sandstone.

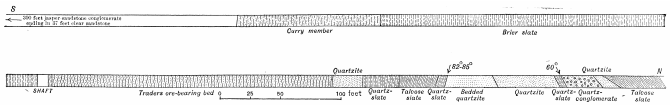



FIG. 36.—Vertical section through No. 1 shaft along north-south crosscut, first level, Pewabic mine.

A second drift passing north from the main ore-bearing belt on the third level toward the dolomite near the east end of the fold (see fig. 35) shows a similar alternation of talcose or serpentinous slates, quartzites, and an ore bed. A drill hole, put through the Brier slates south of the ore-bearing beds and starting at a point nearly opposite the mouth of the crosscut, passed through a small thickness of the slates and immediately thereafter entered a bed of Traders quartzite. The ore-bearing bed encountered on the south side of the Brier slates farther west (see fig. 35) is not met with at the east end of the fold, nor is its manner of disappearance known. It is believed, however, to have disappeared by faulting along the contact plane between the Randville dolomite and the Upper Menominee series. There is a well-defined fault on the fourth and lower levels of the mine between the Brier slate and the ore formation, but whether this is a continuation of the fault on the contact line at the east end of the mine or not has not been determined.