

ART. XV.—*The Iron Ores of the Marquette District of Michigan*; by C. R. VAN HISE.

BEFORE considering the subject of this article, it is well to recall the general views held by the late Prof. Irving as to the Lake Superior ore-bearing formations, and those of the writer as to the position and genesis of the ores of the Penokee district. Prof. Irving maintained that the ores, jaspers and associated rocks are derived directly or indirectly by the alteration and silicification of an original lean iron-bearing carbonate.* A detailed study of the Penokee-Gogebic district led the writer to the following conclusions:† First, the original rock of the iron-bearing formation was a lean cherty carbonate of iron, magnesium and calcium; second, the various phases of rock now found in this formation, such as chert, jasper, magnetite-actinolite schists and ore-bodies, are all produced from this original carbonate by various alterations, the processes involved in which are described in detail; third, the ore deposits occur in bodies which all reach the surface of the earth, which have a longitudinal pitch and are roughly triangular in cross-section. One of the lower sides of each triangle is bounded by an impervious dike-rock, the other by an impervious slate-formation; fourth, the ores in their present positions are concentrates produced by downward percolating waters which carried iron carbonate to the apices of the troughs, where it was precipitated by oxygen brought by waters coming more directly from the surface. At the same time silica was removed.

At the close of the description of the Penokee ores, attention was called to the fact that in certain respects the occurrence of the Marquette ores are analogous; but at that time the study of the latter had not extended far enough to give anything more than a general statement that it was probable that the same principles of concentration are applicable to the ore-deposits of both regions. Since that time a systematic investigation of the entire Marquette district has been undertaken, and while the study of the iron-bearing formation is far from complete, certain results have been reached, to set forth which is the object of the present paper.

* Origin of the Ferruginous Schists and Iron Ores of the Lake Superior region, R. D. Irving: this Journal, III, xxxii, pp. 255-272, 1886.

† The Iron Ores of the Penokee-Gogebic Series of Michigan and Wisconsin, C. R. Van Hise: this Journal, III, xxxvii, pp. 32-48, 1889; The Penokee Iron-bearing Series of Michigan and Wisconsin, by R. D. Irving and C. R. Van Hise: Tenth Annual Report of the Director of the U. S. Geological Survey, 1888-89, pp. 341-507.

In much of the field work upon which this article is based, I was in company with Prof. Raphael Pumpelly. The common conclusions reached at this time are consequent upon our joint observations. To Mr. James R. Thompson, Mining Engineer of the Lake Superior mine, I am indebted for detailed observations upon the forms and relations, and for plats of many of the ore-deposits of the Ishpeming-Negaunee area. From these plats several of the figures are taken.

Two ore-bearing formations.—The ore-deposits of the Marquette district occur in two formations. It has been recently recognized that these formations belong to different series, separated by a great unconformity, and therefore that one of the two is much older than the other.* The superior of these is here called the Upper Marquette series, the inferior the Lower Marquette series. The known ore-deposits in the upper series are much less important than those in the lower, and unless expressly stated the Lower Marquette series is always referred to.†

Character of Lower Marquette ore-bearing formation.—The ore-deposits of the Lower Marquette series all occur in or are associated with a single formation, known as the ore-bearing formation.

The non-fragmental character of the quartz and partly individualized silica associated with the ore-bearing formations of the Lake Superior region has been insisted upon in papers already published. The part of the Marquette iron-bearing formation containing the majority of the ore-bodies consists normally of bands of nearly pure silica, alternating with bands composed chiefly of oxides of iron, although frequently bearing more or less silica. The alternating layers are generally not more than an inch in thickness and are more frequently in the neighborhood of half an inch. A single layer, if followed for some distance, is usually found to gradually narrow and die out or to have a rounded oval termination. Sometimes the belts of quartz are so short as to be no more than tolerably long ovals. When the quartz is free from oxide of iron it has a white color and is usually called chert, although the microscope shows that the silica is wholly individualized. When the exteriors of the quartz granules are stained with hematite, or particles of hematite are included within them, giving the siliceous bands a red color, the material is called jasper. It is a general rule that near the top of the forma-

* An Attempt to harmonize some apparently conflicting Views of Lake Superior Stratigraphy, C. R. Van Hise: this Journal, III, xli, pp. 117-137, 1891.

† For the equivalents of the Upper and Lower Marquette series in other parts of the Lake Superior region, see paper cited.

tion the silica is all or nearly all jasperized. In passing to lower horizons less and less of it is jasperized, until in the lower parts of the formation the siliceous bands are white. In the cases in which the jasperization is incomplete, it usually affects the outer parts of the bands and progresses inward. Frequently all stages may be seen between completely jasperized bands and those in which the jasperization has begun to affect only an outer film of the layers. It sometimes happens that above a band of paint-rock or soap-rock the silica is all jasperized, while below it is the white chert. It follows from the foregoing that we have associated with many of the ore-bodies, either banded ore and chert or banded ore and jasper.

The remaining important variety of rock associated with the ore is magnetite-actinolite schist. Where magnetite is the prominent oxide of iron, actinolite or grünerite* is almost always present. In this phase of material the iron is mainly concentrated into layers, giving the rock a banded appearance the same as with the ferruginous cherts and jaspers.

Recent study has shown that iron carbonate is also an important constituent of the ore-bearing formation. Messrs. W. S. Bayley and W. N. Merriam have most frequently found this material at places where the formation dips under a greenstone. In one case iron carbonate occurs abundantly in the deeper workings of a mine. Transitions are seen between the unaltered carbonate and those phases of the formation in which the carbonate is partly or wholly oxidized to limonite, hematite or magnetite.

It is believed that the cherty carbonate of iron, as first advocated by Irving, is the original source of the various forms of ferruginous rocks occurring in the ore-bearing formation. However, it is not the purpose of the present paper to consider in detail the processes by which the many kinds of rocks were produced. This part of the subject for another district has already been somewhat fully treated.†

Associated formations.—In considering the character, position and genesis of the ore-deposits, it is necessary to take into account two associated formations: the overlying conglomerate and quartzite of the Upper Marquette series, and the eruptives.

The eruptives occur in bosses and in dikes. They were originally diabases, but frequently have passed over into diorites, and these again have further altered. In the northeast part of the great ore-producing township of Marquette county, T. 47 N., R. 27 W., is a large area of greenstone. This area

* Notes on Michigan Minerals, A. C. Lane, H. F. Keller and F. F. Sharpless: this Journal, III, xlii, 505-508, 1892.

† Tenth Annual Report, U. S. G. S., pp. 393-408.

is almost encircled by a series of mines, which lie contiguous to the outer border or in the valleys between outlying bluffs. In many cases the greenstone in nearing the ore formation grades into a laminated rock, which has undergone profound alteration as a result of leaching and shearing. Thus changed, it is known as soap-rock, or when stained with iron oxide, as paint-rock. Numerous sections and diamond drill holes have so frequently shown all gradations between the massive diorite and the schistose soapstone and paint rocks as to leave no doubt whatever of their actual continuity. Beside the large masses of greenstone within or associated with the iron-bearing formation are numerous dikes of the same material. These sometimes run nearly parallel to the lamination of the ore-formation, but more frequently cut across it at a greater or lesser angle. These dikes are usually altered throughout, so that in general they have not been recognized as intrusive rocks. Like the altered parts of the greenstone bosses, they are called soap-rock or paint-rock. That they are really igneous is shown by their structural relations, and by the fact that occasionally they are traced to and found to be offshoots from the larger masses of greenstone. These soapstones, as indicated by their name, have a greasy feel, are very soft, have frequently a mottled gray and white color, although often they are deeply stained with red oxide of iron. In chemical and mineral composition these soapstones differ greatly from the original diabases. They have lost nearly all of their alkalis and very often are now largely a hydrated silicate of magnesium and aluminium.

The formation overlying the ore-deposits belongs to the Upper Marquette series and is, as has been said, a quartzite-conglomerate, the material of which is very largely derived from the immediately subjacent formation. The heavily conglomeratic part in some cases is but a few feet in thickness, in others is hundreds of feet thick. The detritus of the quartzite-conglomerate is nearly like the material of the underlying formation, except that within the former no large fragments of pure ore have been observed. This conglomerate suggests that the ore-formation was in approximately its present condition before the deposition of the Upper Marquette series.

General structure of district.—Before dealing with the ore-deposits it is necessary to speak of the general structure of the Marquette district. This can best be appreciated by examining Brooks' geological map.* The Republic tongue is a simple synclinal, the sides of which are nearly vertical, showing that the formation has been sharply folded upon itself. The

* Atlas accompanying the Geology of Michigan, Pl. 3.

southwest end of this trough, where the Republic mine is located, has a pitch to the northwest of 40° or 50° . At the west end of the Marquette district proper the mines, such as the Michigamme, Spurr, Champion, etc., are upon the sides of a great synclinal, which, however, is probably a synclinorium. In the great mining center of T. 47 N., R. 27 W., already referred to, where are the towns of Ishpeming and Negaunee, the formation has been folded into a series of rolls, which have variable pitches, as a consequence of which there are here several iron ranges approximately parallel. The mines, as in the more simply folded part of the district, are frequently at the sides of the synclinals, which, as already said, are generally flanked by diorite ridges. Whether the upwelling of the eruptives was the cause of the folding, or whether as the folding occurred fracture took place in the brittle ore-formation of which the intruding rock took advantage, it is yet too early to discuss.

Classification of Lower Marquette ore-deposits.—The known ore-bodies, with reference to their position, may be divided into the following classes: (1) deposits at the contact of the quartzite-conglomerate and the ore-bearing formation; (2) deposits resting upon soap-rock which grades into massive diorite; (3) deposits resting upon dikes of soap-rock which follow along or cut across the ore-bearing formation; (4) deposits interbedded in the jasper or chert. (See fig. 1, p. 123, generalized section of ore-formation in which ore in its more important relations is represented by cross-hatching.)

(1.) *Deposits at the contact of the quartzite-conglomerate and the ore-bearing formation.*—The ores occupying this position are generally hard and either specular or magnetic. It is to be remembered that the adjacent rock of the underlying ore-bearing formation is usually banded ore and jasper, although occasionally it is magnetite-actinolite schist. Because of the constant association of the hard ores with the red form of silica this material is sometimes called "specular jasper." One of the largest known deposits of the first class is that at Republic, and this locality, because of its magnificent exposures, is particularly favorable for study. While the main bodies of ore occur at the contact horizon, the mine maps show a constant tendency to form offshoots, a part of the ore following the banding of the jasper formation, which dips at a steeper inclination than the contact plane. (Fig. 2, p. 123). A body may continue in considerable force for some depth, but when it gets far from the contact plane, it is apt to die out. At and below the place where the branch strikes off the main deposit may become somewhat narrower, but in passing downward it often gains its full magnitude, and then a second shoot may start back from the contact plane into the underlying jasper.

Of course the entire contact horizon of the quartzite and ore formation is not occupied by ore-bodies as represented in the generalized figure. The deposits occur at places along the contact where sharp subordinate folding has occurred, or where the jasper formation is broken by cross joints, or where a soapstone dike cuts the contact plane forming a trough; or, finally, by a combination of two or more of these phenomena. The last is well illustrated by the position of the great deposit of the Republic, which is at the southeast corner of the horse-shoe, where the curve, instead of being gentle, is abrupt, causing the jasper formation to become sharply plicated and often fractured (fig. 3), and where there are numerous dikes of soap-rock which usually form one of the boundaries of the ore-deposits. The mining engineer remarked that the ore-deposits cannot live long when they become separated from the soapstone. Upon the east side of the Republic horse-shoe the ore-bodies are in chimney-like forms which often continue for a considerable depth and which are often usually rather sharply separated from the banded ore and jasper adjacent. (Fig. 4). However, here, as at the great deposits, the boundaries are generally found at fractures or flexures.

A detailed examination was made of the manner in which the change occurs between the jasper and the ore. While, as remarked, the ore often terminates somewhat abruptly, it also frequently grades into the jasper. In following a jasper band toward the ore it was found that instead of remaining solid it becomes porous and frequently contains considerable cavities. These spaces in the transition zone are lined with crystalline ore. In passing on toward the ore-deposit more and more of the silica is found to have been removed and the ore has replaced it to a corresponding degree. An examination at many localities led to the conclusion that the transition from the banded ore and jasper to the ore takes place as a consequence of the removal of silica and the substitution of iron oxide. Often in these cases the fine-grained part of the ore is that of the original rock, while the coarser material is the secondary infiltration.

The above details as to the occurrence of the hard ore at Republic are typical of this class in the remainder of the district. In the Ishpeming-Negaunee area, for instance, the ore often terminates along a slip or joint crack. Also the ore-bodies are likely to be found where the folding or crushing of the jasper has been severe, and especially where these phenomena are accompanied by soap-rock.

The ore-bodies between the ore formation and overlying quartzite are not always wholly in the jasper, but often extend upward to a greater or less degree into the quartzite-conglomerate, and some deposits wholly occupy the horizon of the

recomposed rocks. It is reasonable to suppose that a thin stratum of the conglomerate overlying the richer part of the iron-bearing formation may have been nearly, if not quite as heavy in its iron content as the formation from which it was derived. In these cases a part of the iron of the ore-deposit at least is a direct mechanical detritus and differs therefore in its genesis from the remainder of the ores; but all have alike been affected by a secondary concentration, for the process of replacement has affected the siliceous detritus in the same way that it has the laminated jasper in the original formation. When the ore-bodies partly occupy the place of the quartzite-conglomerate and partly that of the ore-formation proper, as a consequence of the secondary concentration, these two formations, although of widely different geological age, have been welded together. This is well shown at the Kloman mine.

(2.) *Deposits resting upon soap-rock which grades into massive diorite.*—Here are to be placed many of the deposits of soft ore and some of the hard ores. The masses of soap-rock may follow somewhat closely the lamination of the ore-formation or they may cut across it. In either case the deposit follows along the contact plane, the impervious soap-rock always being below the iron ore and above it the fractured and porous jasper or chert (see fig. 1, p. 123). Not infrequently a mass of soap-rock or diorite forms a synclinal trough in which the ore body rests, when the maximum thickness of the ore is likely to be at the lower part of the synclinal (fig. 5). Sometimes a small dike of soap-rock or paint-rock shoots off from the large body and cuts into the ore (fig. 6). At other times the soap-rock bulges into the ore as though it had been bent into sharp corrugations. That the soapstone upon which the ores rest, actually grades into diorite is shown by many drill holes at the Lake Superior mine and very clearly at the Salisbury mine, as well as at other localities.

In some cases the first and second classes of deposits approach close to each other and might be mistaken for one continuous deposit of the same character, the two occupying opposite sides of a synclinal. This is shown by fig. 7, which shows upon one side of the synclinal the following section: diorite grading upward into soapstone, ore, jasper, quartzite-conglomerate. Upon the other side of the synclinal the section is: jasper, ore and quartzite-conglomerate.

(3.) *Deposits resting upon dikes of soap-rock which follow along or cut across the ore-bearing formation.*—The ores here belonging, like those of the second class, are usually soft. They may occur upon one side only of a dike rock, or, when it is vertical or nearly so, upon both sides. When two dikes are not far distant from each other the whole or part of the

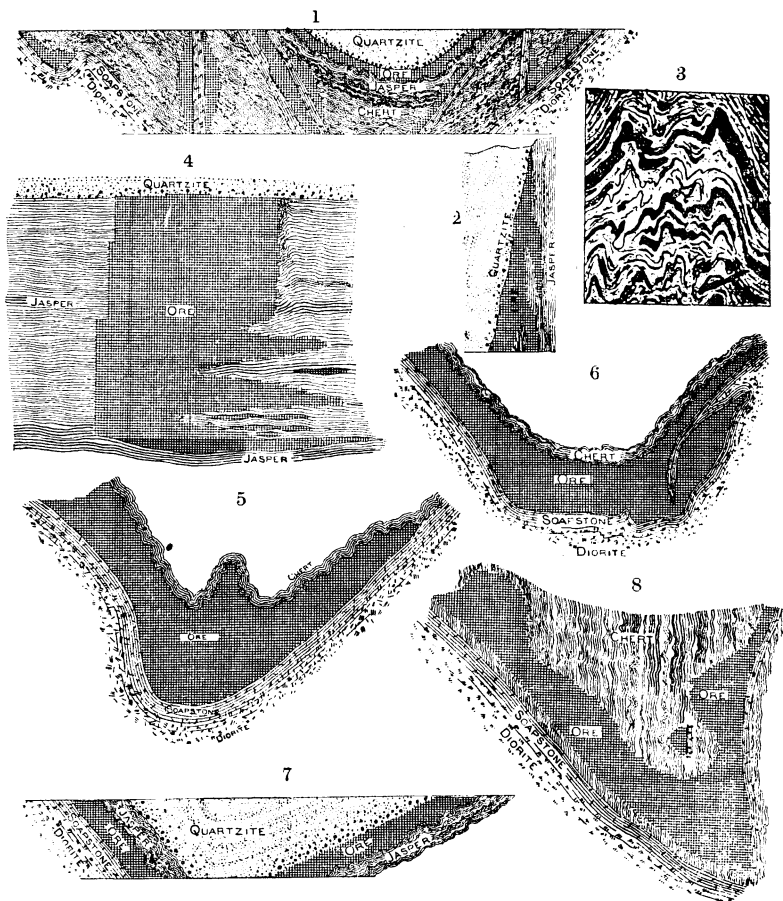


FIG. 1. Generalized section, showing relation of ore-deposits of Lower Marquette series to associated formations.

FIG. 2. Diagram showing tendency of an ore-deposit at contact of Lower and Upper Marquette series, to send offshoots into the jasper parallel to its lamination.

FIG. 3. Sharply plicated jasper (black belts) and ore (white areas), showing shattering of the jasper and concentration of the ore. The ore is proportionally greater where the folding has been the sharpest. Drawn from photograph.

FIG. 4. Horizontal section of ore-deposit on east side of Republic horse-shoe. Left side of ore bounded by a cross-joint; right side is bounded in part by a sharp flexure passing into a joint and in part grades into the lean banded jasper and ore.

FIG. 5. Vertical section of an ore-body, bounded below by soapstone grading into diorite, and above by ferruginous chert; change from ore to chert not so sharp as drawn.

FIG. 6. Another section of the same deposit shown in Fig. 5, but here is seen an offshoot of soapstone from the main mass.

FIG. 7. The ore upon left side rests upon soapstone grading into diorite and is not at the contact plane of the Upper and Lower Marquette; ore at right side is at this contact plane and rests upon jasper. The two combined have a synclinal appearance.

FIG. 8. At the left the ore rests upon the soapstone grading into diorite; at the right it is upon one side of a dike-rock. The dike is an offshoot of the diorite. At the contact of the two a trough is formed in which the ore-body becomes of large size. Figs. 5, 6, 8 from mine plats furnished by Mr. Thompson.

space between may be occupied by ore. When a dike is alone and has a flat dip the ore is always on the upper side, that is in such cases the dike-rock is always the foot-wall of the deposit. (See fig. 1.)

A dike carrying ore may unite with a large mass of soapstone varying to diorite, which also carries ore, when a trough will be formed and the deposit is here apt to become large. In this case we have a union of the second and third classes of deposits. At the locality shown in fig. 8 the soap-rock grades into diorite and dips south about 45° , constituting the main foot-wall. Standing vertical and striking 20° or 30° away from the foot-wall is a dike of paint-rock or soap-rock cutting across the formation. Resting upon both are ore-deposits, and by their union at the apex of a trough formed by the junction of the two the ore-body is of large size.

(4.) *Deposits interbedded in the jasper or chert.*—No deposits of this class of large size are known, for unless below is a soap-rock (when it would fall into a previous class) no impervious stratum is present upon which the ore can collect, unless (and this does not often occur) a layer of the ore-bearing formation itself locally loses porosity.

The ore-deposits secondary concentrations.—The ore-bodies of the second, third and fourth classes, that is all that lie wholly within the ore-bearing formation, are usually soft, and they may occur at almost any horizon within the iron-bearing formation. Being for the most part at some distance from the contact between the quartzite-conglomerate and ore-formation they are commonly within the ferruginous chert rather than in the banded ore and jasper.

The foregoing descriptions show how intimate is the connection between the ore-bodies and the paint or soap rocks. Mr. Thompson says this connection has become so evident to the miners, and they have such confidence that this material is a favorable indication, that it is called by them "the mother of the ore."

The ore-deposits in longitudinal sections are not horizontal, but generally have a pitch, which in the Ishpeming-Negaunee area is usually to the west and often amounts to as much as 20° or 30° . Consequently the ore-bodies represented in horizontal cross-section are found at different depths in following them longitudinally. This principle of pitch is equally applicable whether the underlying formation is jasper or soap-rock, whether the ore is in sheets, lenses or troughs.

While the ore-deposits of the Lower Marquette series have a greater variety of form and relations than do those of the Penokee district, it is evident that the conditions governing their formation are much the same. In both districts the

material immediately underlying the ore is relatively impervious to water. In the cases of these deposits which rest upon soap-rock this lack of porosity is nearly complete. Many of the ore-bodies are in troughs in the Lower Marquette series, as are nearly all in the Penokee district. The ore-bodies in both in longitudinal section have a pitch. In both the many phases of material found in the ore-bearing formation are nearly the same, and in both is found plentiful residual iron carbonate. It is therefore thought that the explanation of the origin of the ores in the Penokee district is applicable, with few modifications, to those of the Marquette district, although the larger number of the deposits of the latter belong to an older series.

The forms, attitudes and relations of the ore-deposits render it evident that they are not eruptives. No eruptive would be found in such strange shapes and relations. It is equally certain that these irregular masses of ore are not produced directly by sedimentation. All the facts bear toward the conclusion that the ore is a secondary concentration produced by the action of downward percolating water. When the facts are examined in detail, it is seen that the ore-deposits occur at places where circulating waters are sure to be concentrated. The soap-rock accommodates itself to folding without fracture, and while probably allowing more or less water to pass through, acts as a practically impervious stratum along which water is deflected when it once comes in contact with it. It is a common opinion among miners that a few inches of soap-rock is more effective in keeping out water than many feet of the iron-bearing formation. On the other hand, the brittle siliceous ore-bearing formation has been fractured by the folding to which it has been subjected so that where these processes have been extreme water passes through it like a sieve. That the tilted bodies of diorite or soap-rock, especially when in a pitching synclinal or forming a pitching trough by the union of a dike and a mass of diorite, must have guided downward-flowing waters is self-evident. The pitch common to other deposits is also evidence in these cases of laterally deflected downward-moving waters and indicates a wholly or partly impervious substratum even when its character has not yet been ascertained. It is also plain that the contact plane between the quartzite-conglomerate and the ore-bearing formation, that is, the plane of unconformity between the Upper and Lower Marquette series, must have been a great horizon for downward-flowing waters.

If it is true that the whole of the iron-bearing formation was originally a lean cherty carbonate of iron, with perhaps some calcium, and magnesium, or if we go no farther back than the ferruginous cherts and jaspers, it is then concluded

that in order to produce the ore, two things must have occurred: first, the concentration of iron oxide in the places where are found the ore-bodies; and second, the removal of silica from these places.

Time at which concentration occurred.—The final concentration of the Lower Marquette ores occurring at the contact of the Upper and Lower Marquette series must have taken place later than Upper Marquette time. This is indicated by the fact that while these ores are so frequently found at the contact plane the fragments of the overlying conglomerate are almost wholly of the lean chert or jasper, or magnetite-actinolite schist, and include few of the rich hard ore, which if present ought to have yielded fragments. This not only shows that the final concentration had not occurred, but that the cherty carbonate (if the assumption be correct that the ore-formation was originally of this material) at the surface had been decomposed before Upper Marquette time. These conglomerates therefore give us an indication of the early character of a part of the ore-bearing formation from which the ore-bodies were later derived. The position of these ore-bodies at the contact plane of the Upper and Lower Marquette series is also evidence that they have been here concentrated subsequent to Upper Marquette time; for it is exceedingly improbable that erosion so generally stopped at a horizon rich in ore, a material which is softer than jasper and would therefore be more rapidly cut out. Further, this contact is not at a certain plane of the ore-bearing formation, but here is at a higher horizon and there at a lower one. Bearing in the same direction, although perhaps not strongly, is the occasional welding of the quartzite-conglomerate and ore-bearing formation already mentioned.

The relations of the ore-bodies within the ore-formation to the diorites and dike-rocks give evidence that the concentration of this ore has occurred subsequently to the intrusion of these rocks. It is certain that some of these eruptives are intrusives later than the Upper Marquette series, since they cut across the overlying quartzite. Others of them appear to have yielded fragments to the Upper Marquette series and therefore antedate these rocks. Finally if the ore bodies had become concentrated before the Upper Marquette folding and erosion, their invariable positions above the impervious formations would be inexplicable. The folding would perhaps have as often left them below as above these formations. Taking all the facts together, it is highly probable that the concentration of all the ores occurred during and later than the folding and erosion subsequent to Upper Marquette time.

Manner of ore-concentration.—Surface waters bearing oxygen passing downward through the Upper Marquette series or

the iron-bearing formation of the Lower Marquette series would decompose the iron carbonates with which they came in contact and thus become carbonated. These carbonated waters would then be capable of taking other iron carbonate into solution. What proportion of the original iron carbonate still remained in the ore-bearing formation at the beginning of concentration is uncertain, but since it is still found in places sheltered from percolating waters, such as the deeper workings of one of the mines and under diorite masses, it is probable that the quantity was very considerable. The oxides or carbonates of iron may also have been taken into solution by organic acids. These downward-moving waters would pass through the iron-bearing formation until they came in contact with an impervious substance or else, if passing through the Upper Marquette series, they reached the contact plane between the two series along which they would travel. It is possible that the ore which formed along the contact horizon was contributed in part by the ferruginous materials of the Upper Marquette series, although it is probable that the greater part of the ore here found came from material of the ore-bearing formation now removed by erosion. After the ore-bearing formation had been leached for a long time, it became as it is now found, very porous along the soap-rock and along the contact plane of the Upper and Lower Marquette series. Here would be carried other oxygen-bearing waters more directly from the surface. The union of these two currents would precipitate the iron oxide. The abundant waters traversing these ore-bearing localities would also slowly dissolve the silica. That this interchange actually does occur is known of the localities in which a detailed examination has been made, as for instance at Republic. It is probable that in the ore-deposits associated with the soap-rocks the removal of silica is due in part to them. Originally diabases, they must have contained alkalies, while analyses of them show at present an almost entire absence of these elements. The alkaline waters produced by their alteration would thus furnish a menstruum capable of taking the silica into solution. This desilicification of the iron-bearing formation by alkaline waters was many years ago suggested by Brooks,* for a part of the Marquette district. Rominger† not only made the same suggestion in reference to the Jackson mine, but further held that the siliceous matter removed, was replaced by oxide of iron carried by water solutions.

The percolating waters which carried material along the readiest paths to form the ore-bodies, and which removed the silica also helped to Jasperize the ore bearing formation, i. e. it charged the white silica with oxide of iron and thus reddened it, although it cannot yet be certainly stated to what

* *Geol. of Michigan*, vol. i, p. 134.† *Geol. of Michigan*, vol. iv, p. 75.

degree this process had already gone before Upper Marquette time. Whatever the time at which the work was done, the process seems to have been as follows: The upper part of the ore formation was traversed by solutions more extensively than the deeper lying portions. It naturally follows that the ferruginous material was in part deposited about and through the minute particles of silica, reddening them and changing the material from white chert to red jasper. In some places this jasperization has extended deeper than in others and, as already said, it sometimes abruptly stops at an impervious mass of soap-rock. Prof. Pumpelly suggests that before the secondary concentration which formed the ore-bodies, the bands of silica of the ore-formation were white and perhaps in a partly amorphous condition; that at the time of this concentration a partial recrystallization of the silica occurred, affording an opportunity for the ferruginous impregnation so characteristic of the jaspers. A microscopical examination shows that while most of the silica of the entire formation is now individualized, much of the iron oxide of the jaspers is concentrated about the particles of quartz, and that numerous minute flecks also occur within their interiors, thus giving support to Prof. Pumpelly's suggestion.

One or two questions remain to be considered: First, why the ore is so frequently hard and specular along the contact horizon or in the jasper and is usually soft within the ferruginous chert. Second, why the magnetites when present occur at the contact horizon.

An examination of the jasper associated with the hard ores shows that crystallized hematite and magnetite often occur in cavities formed by the removal of the silica. In such geodal cavities these materials have been deposited in a granular crystalline condition. In the continuation of the process the silica was wholly removed and its place taken by the crystalline hematite and magnetite. The adjacent jasper also shows that numerous cracks and fissures have been filled with hematite or magnetite. The manner in which these veins of coarser crystallized material frequently cut across the finer grained substance which represent the iron oxides present before the concentration, shows conclusively that they are secondary infiltrations. The formation of the coarsely crystalline hematite and magnetite thus appears to be connected with the abundance of iron-bearing solutions along the contact plane.

Oftentimes also the hard ores are of the brilliant micaceous or specular variety. In a hand specimen composed of rapidly alternating layers of ore and silica, where the folding has been severe, micaceous ore is often found between the rigid bands of quartz. Along these ferruginous zones is seen all the evidence of slickensides, and the micaceous character of the ore is seen to be due to the shearing to which it has been subjected.

Now the micaceous ore from the large deposits, as first suggested by Prof. Pumpelly, gives the same evidence of shearing. When it is remembered that in the folding of thick formations accommodations and re-adjustments must occur, it is natural to suppose that this re-adjustment has more largely taken place at the contact between the Upper and Lower Marquette series than at any other one horizon, for this is emphatically the plane of weakness. Thus would be explained the finely laminated micaceous variety of ore. It is not impossible that the heat and pressure caused by the shearing along the contact plane would be sufficient to change soft ore into micaceous hematite, but to the writer it appears more probable that these ores represent sheared specular hematite and magnetite. Since the final concentrations of the ores occurred during and subsequent to the folding of the series, it is necessary to believe that this shearing was a contemporaneous process, or else that after it occurred residual silica was replaced by iron oxide and that this metasomatic change did not affect the prior lamination of the original ore. Doubtless both explanations are applicable in varying degrees at different places.

That it is easy to reduce hematite to magnetite is well known, and it is probable that the production of the granular infiltrated variety of this ore is due to the reducing character of some of the solutions which have passed down along the great contact plane of percolation where the magnetites are extensively found. This reducing power could readily be imparted by organic acids. That some kind of reducing agent has been present is indicated by the veins of pyrite which are frequently associated with the magnetic ores.

It is supposed that the magnetite of the magnetite-actinolite schists is due to the direct oxidation of an original carbonate of iron. This is known to be true of the Penokee and Animikie magnetites and also of the magnetite of the Lower Marquette series in the deeper workings of one of the mines. When iron carbonate is decomposed in the presence of an excess of oxygen the sesquioxide is of course formed; but if it is supposed that an insufficient amount of oxygen was present, as is quite probable, from three molecules of iron carbonate would be produced one molecule of magnetite and three of carbon dioxide, if only a single atom of oxygen was available.

Ores of the Upper Marquette series.—The ore-deposits of the Upper Marquette series, so far as studied, show that the original material was an iron carbonate and that the ores are secondary concentrates resting upon impervious formations. Sometimes this impervious formation is a black slate; at other times it is an intrusive basic eruptive; and at still others it is a surface volcanic. As a consequence of folding, or by the junction of two of these basal formations, and of concentra-

tions, the ores occupy troughs or the sides of synclinals. That the ore is a concentrate from an original impure iron-bearing carbonate is easily shown. Wholly unaltered carbonate, often accompanied by organic matter, is abundant, and all stages of the change into the soft hematites and limonites of the Upper Marquette series are seen.

Ores of other districts.—In the Menominee district the ores, as in the Marquette district, occur in two formations, one of which belongs to the Lower Menominee, correlated with the Lower Marquette series, while the other belongs to the Upper Menominee, correlated with the Upper Marquette series. The Upper Menominee is more important as an ore-producer than the Upper Marquette. A detailed study has been made of only a small number of the mines, but a general study has covered nearly the entire district. So far as work has gone, while there will be some modifications of detail, the principles have been found thus far to hold that the ores are secondary concentrations upon impervious formations, and are particularly likely to be of large size when these are folded or two combine to form pitching troughs. Also, as in the Marquette district, the basement impervious formations are often igneous and not infrequently are surface volcanics. At other times, and especially in the Upper Menominee series, the impervious stratum is a detrital slate. As typical instances of the Menominee mines may be mentioned the following: At the Armenia the ore-body is at the bottom and upon the sides of a synclinal trough, pitching at an angle of about 45°. Below the ore is an impervious black slate. At the Mansfield mine the ore-body nearly vertical laterally but pitching longitudinally, has impervious slates upon each side, one of which is clearly a volcanic rock. The ore of the Hemlock mine rests upon an impervious stratum consisting of surface volcanic material.

The ores of the Vermilion Lake district have been studied by us only in a general way, but so far as our investigation has gone all the facts bear toward the conclusion that the principles here hold which are applicable to the other iron-bearing districts of the Lake Superior region. It is true that Prof. N. H. Winchell and H. V. Winchell* have proposed a chemical theory for the origin of the rocks of the iron-bearing formation which does not derive it from a lean iron-bearing carbonate; but even if this theory be accepted (and I do not hold it), it is applicable to the ore-bearing formation rather than to the ore-deposits. The descriptions and figures of the mines published by the late Prof. Alex. Winchell and by Prof. N. H. Winchell, seem to me to be wholly in harmony with our own observations, and to indicate that the Vermilion Lake ores are sec-

* The Iron Ores of Minnesota, N. H. and H. V. Winchell: Bulletin No. 6, Geol. and Nat. Hist. Survey of Minn., Appendix A, pp. 391-399.

ondary concentrates which usually rest upon impervious formations.*

As instances among the mines figured by these authors may be mentioned the following: The ore of the Ely mine is found between impervious schists, the layers of which are inclined. At the Stone mine the ore in its upper workings is in two bodies, each of which rests upon green schists. In its deeper workings these are found to come together and make a solid mass of ore. The ore grades above into the jasper, which is like a great horse separating the upper parts of the deposit. In short, the relations so far as principles are concerned, are much the same as shown in figure 8, taken from a deposit in the Marquette district. At the Chandler mine the ore has its greatest length along and rests upon as a foot-wall, a great mass of greenstone. The upper boundary of the ore is irregular and grades into mixed ore and jasper. It is said of the Ely that the "ore is quite open to the action of percolating water," and that the material shows the effects of crushing and folding. The schists associated with the ores in the Vermilion district are regarded by the Professors Winchell as well as by us as of igneous origin.†

The facts given by these writers then seem to show that the ore is a secondary concentration, instead of that the "ore and jasper" are "of similar and contemporaneous origin." Indeed in the report upon the Vermilion ores, published soon after returning from the field, Prof. N. H. Winchell held, although this position was later abandoned, that the iron ores are later than the siliceous jasper and probably produced by metasomatic change.

It is fully recognized that the explanation above given for the ores of the Lake Superior districts in which mining is now being done, is not wholly if at all applicable to the titaniferous magnetites of northeastern Minnesota associated with the great gabbro flows near the base of the Keweenaw series. In the interstices of these magnetic ores are olivine, augite, feldspar, and often secondary quartz, the whole having a completely crystalline interlocking structure; in other words, they are no more than a very magnetic gabbro. Since these ores occur as basal horizons of the great gabbro flows, it has always seemed to me that this class of deposit is of direct igneous origin. In the crystallization of basic rocks, magnetite is one of the early minerals to separate, and in the immense masses of gabbro, before the magma has solidified the crystals of magnetite have slowly settled by virtue of their superior specific gravity to the

* Fifteenth Ann. Rept. Geol. and Nat. Hist. Survey of Minn. for the year 1886, pp. 24, 25, 221, 235, 255. Bulletin No. 6, Geol. and Nat. Hist. Survey of Minn., pp. 63-67.

† Fifteenth Ann. Rep. Minn., pp. 231, 245, 246; Minn. Survey Bull. vi, pp. 64, 394, 398, 399.

base of the flow, forming thick layers of magnetite. The residual magma has crystallized as the interstitial minerals, and thus we have the titaniferous magnetites of the gabbros. A recent petrographical study by Dr. W. S. Bayley has shown that a part of the magnetite is secondary. As these ores are associated with abundant secondary quartz it is not impossible that much of the magnetite has been brought to its present position after the solidification of the rock.

General.—It is evident that the ores of the Upper Marquette series, like those of the Lower, were concentrated during and subsequent to the folding and erosion which affected both. Thus while the ore-bearing formation of the Lower Marquette series is far older than that of the Upper Marquette, and had undergone great changes before the latter was deposited, the local concentration of the iron into workable deposits occurred simultaneously as a consequence of the same great causes. This statement also applies, so far as present knowledge goes, to the two iron-bearing series of the Menominee district. The Penokee series is equivalent to the Upper Marquette and Upper Menominee. The equivalency of the Animikie and the Penokee series and their simultaneous tilting into monoclines on opposite sides of the Lake Superior synclinal has been shown in another place.* It is also shown that this tilting, and consequently the concentration of the ores, occurred subsequently to Keweenaw time. It was suggested that the basic intrusives of the Penokee series upon which the ore-deposits rest are of Keweenaw age. Is it not probable that many of the basic intrusives of like character in the Marquette and Menominee districts are products of the same period?

It appears then probable that the local concentration of the iron ores into workable bodies did not generally begin before Upper Huronian time, while in certain districts it did not begin until much later. That the process has yet ended we have no evidence. The ores of the Lake Superior region occurring in two geological series are remarkably alike. This likeness is plainly due to their similar genesis.

This paper must be considered as an account of the progress of an investigation rather than a complete exposition. While it is possible that a further study will make necessary a modification of certain minor points, it is believed that the principle of secondary concentration along great channels of downward percolating waters, and particularly at places where these waters are converged by tilted impervious formations is nearly if not quite of universal applicability to the workable ore-deposits of the Lake Superior region.

United States Geological Survey,
Lake Superior Division, Madison, Wis., December, 1891.

*Tenth Ann. Rept. U. S. Geol. Survey for 1888-89, pp. 402-408, 458-460.