CHAPTER X.

THE FORMATION AND STRUCTURE OF THE ORE DEPOSITS.

The term *ore-deposit* is relative, and is here applied to those concentrations of iron which are large enough and pure enough to repay mining. As the profit in mining fluctuates with changing conditions, the minimum size of a body of iron oxide which may thus be called an ore-deposit is by no means fixed. Neither is there any essential difference, except in size, between the ore-deposits and the smaller accumulations of iron which are every where found in this rock. Between the blotch of concentrated iron which is only a fraction of an inch in diameter, and the mass which is nearly a mile in its greatest diameter, there is every possible gradation, and the explanation of their concentration is in all cases the same: saturated chalybeate waters from the less accessible parts of the rock, have, on coming into a region of freer oxidation, been forced to part with their iron, and have taken into solution some silica; and this has been continued till all the silica was replaced, and the rock was of pure iron oxide. The important thing, therefore, in discussing the ore-deposits, is to explain the causes of their difference from the bands and blotches of ore, *i.e.*, of their greater size. We must first find the cause of the formation of very large areas of weakness and oxidation; and second, the reason for the concentration of a vast quantity of iron and its complete replacement of the original rock.

OCCURRENCE OF ORE-DEPOSITS ON THE MESABI.

The shape of the ore deposits is as variable as their size, but the least diameter of the body is generally the vertical thickness, while by far the greatest development is laterally. Thus the deposits are in general oriented roughly parallel to the general attitude of the Animikie strata. While none of the

large bodies have yet been mined out, so that it is not possible to discover accurately the shape of any one of them, yet in many places test-pitting has been complete enough to give a good idea of the structure. These pits show that there is no sharp boundary line between the ore-body and the barren rock on all sides, into which it runs in the most irregular fashion, but that there is a gradual transition by which the rich ore becomes successively lower in iron and higher in silica, till it is too poor to be mined; and from this to the more decomposed rocks of the oxidation and concentration series. There is no definite wall on any side, neither is there any constant shape. In the largest ore bodies the length of the vertical dimension may sometimes attain some hundreds of feet, while one or both of the nearly horizontal diameters may attain some thousands. Of these horizontal diameters, however, one is apt to greatly exceed the other, so that the generalized shape might be represented by a flattened triaxial prolate ellipsoid. In the actual outline of most of the ore-bodies, however, it would be hard to recognize this fundamental figure.

The greatest clusters of ore-deposits so far known on the Western Mesabi may be included in four rough groups, beginning with that furthest east—the Biwabik group, the Virginia group, the Mountain Iron group, and the Hibbing group. The Biwabik group comprises the mines in the vicinity of the towns of Biwabik and Merritt. The Virginia group comprises all the mines which surround the uplifted region called the Virginia area, and includes the mines near McKinley, from McKinley southwest to the Adams mine, and from the Adams north to and including the great Virginia group itself. The Mountain Iron and the Hibbing groups comprise respectively the ore-deposits in the immediate vicinity of the towns which bear these names. There are other mines, some of them very rich, but in general, aside from these four groups, they are somewhat isolated. The richest of the four groups, the Virginia group, follows, as we have seen, almost continuously the fault-lines which mark the uplift of the Virginia area; and the Biwabik group, which is also of extreme importance, lies in the disturbed and folded region situated immediately east of the Virginia area, whose uplift was probably associated with this disturbance. Unfortunately, the scarcity of outcrops and the covering of drift, necessitating the geologist's contenting himself mainly with material taken from test-pits, hinders the detailed structure being observed here, and still less on the other

and flatter parts of the Mesabi which lie to the west. The Mountain Iron mine lies in a basin, on three sides of which, to the north, east and west, rise ridges of hard rock. The surface of the ore-body is much elongated, its greatest diameter being north and south; thus the greatest axis, if continued, would run through or near the ridge which bounds it to the north. This is a steep bluff of hard "jaspery" rock, mixed with seams of hard iron, which outcrops all the way up the bluff. This outcrop is of special historical interest, since this is the one which was several times visited by explorers in the early days of the Mesabi, and was invariably reported on adversely, while a few yards away, in the valley below, the rich iron deposit comes in many places quite to the surface. The examination of the rock of this bluff, both in the hand-specimen and under the microscope, shows that it has been crushed and brecciated in a most extraordinary manner. (See description of section 97, on page 89).

This does not in any way resemble the straining and brecciation which is common, and has been described as arising from chemical causes originating within the member: the movement has been violent and abrupt. It has almost completely obliterated the original structure of the rock, which is traversed by numerous lines of fracture; and as before noted, these fracture lines are prevailingly arranged into a single well-marked parallel series, indicating a certain single and constant direction of the fracturing force. It thus appears probable that this rock was in the field of a movement of considerable magnitude, some evidence of which has been found in the rocks which constitute the ridges east and west of the ore-body. Since the fracturing forces must have acted in a plane or zone, it seems then probable that that zone lay from the bluff southward through the longest diameter of the ore deposit.

At Hibbing there are no outcrops of the iron-bearing member, and explorations have not been carried on far enough to give any exact idea of the conditions of the rock and the strata in which the ore-deposits lie.

THE EFFECT OF FAULTS UPON THE DEPOSITION OF IRON.

We find, then, that the Virginia group, the Biwabik group, and the Mountain Iron group have all been developed in regions which have been subjected to unusual regional fracturing. When we remember that this fracturing opens up large

areas to oxidizing influences. and that our explanation of the great ore-deposits needs only the discovery of the cause of these great areas of weakness, in order to be complete, we may well conclude that the development of the ore deposits has been directly dependent upon the regional tensions,—whether the tensions resulted in faulting or folding, or formed only a zone of great weakness, which might easily develop into a fault. The result of the development of such zones is that oxi- dizing agents are enabled to penetrate every part of them; and under these conditions chalybeate waters deposit their iron, and carry away silica, till the ore-deposit is formed.

Under the areas of special weakness which have thus been formed by extensive disturbance, we may name (1), actual fault-lines, where the fault has resulted in fracturing and movement; (2), incipient fault-lines, where the development of a zone of great weakness under strain has yet not resulted in actual dislocation of the strata; (3), the apices of anticlinal folds and the troughs of synclines, where the strain of folding ren- ders the rock especially weak. To the first of these divisions the Virginia group belongs, while the second appears to be represented by the Mountain Iron; and to the third probably belongs the Biwabik group. Yet in all cases the critical con- ditions are the same, and so they can be discussed together, for what is true of a fault is for our purposes true, although per- haps in a less degree, other weakened areas

We have now to consider the reason for the carriage of such enormous quantities of iron and their concentration along these lines of weakness; for, although the weakness renders these areas peculiarly subject to ferration, yet there must have been an unusual supply of iron also. This unusual supply of iron will depend wholly upon the supply of the waters which bear this iron, for in any given quantity of waters which penetrate the oxidizable region the supply of iron is somewhat constant, and is near the limit of saturation. We will therefore consider the influence of the development of faults and other zones of weak- ness upon the supply of waters.

We have already seen that the waters which have accom- plished these changes are primarily surface drainage waters, which sink into the porous rocks. In explorations under- ground, as in wells, mines, test-pits, and the like, it is found that there is at the surface a porous zone in which the fissures are filled mainly with air, except for the downward percolat- ing waters which trickle as near as may be in a vertical direc-

tion. At a certain definite depth, however, the excavation rapidly fills with water, showing that the surface of a considerable body of water has been reached.* From this point downward, the water fills all the crevices in the rock, and its course can no longer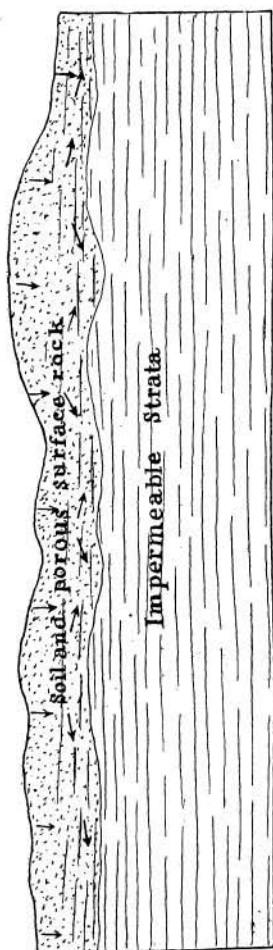 be vertical; for the body of ground-water has no apparent motion. But where this ground-water level has been determined in several places in the same neighborhood, it is found that the points which represent the ground-water level in the different pits are in a plane which is not horizontal, but is steeply inclined towards the lowest point of the region, or whatever point offers the readiest relief to the hydrostatic pressure. (See Fig. 12). Down this plane, therefore, the whole body of surface waters slowly moves, to once more reach the surface at a lower point, as springs.

"The total difference," says Posepny,† "in altitude between the water-level and the surface outlet is always the controlling factor.

"When these two controlling levels are artificially changed, as often happens in mining, the law still operates. In sinking a shaft through permeable ground, it is of course necessary to lift continuously the ground-water. The water-level thus acquires an inclination towards the shaft, which may thus receive not only the flow of the immediate vicinity but even also that of neighboring valley-systems. A shaft imparts to the previously plane water-level a depression, giving it the form of an inverted conoid with parabolic generatrix. An adit produces a prismatic depression in the water-level, and so on for other excavations. On the other hand, a bore-hole, from which the water is not removed, does not affect the water-level."

Figure 12.

Section showing the courses of shallow underground waters, in undisturbed regions where the strata are nearly level.

*See Posepny, Trans. Am. Inst. Min. Eng., August, 1893. The Genesis of Ore Deposits, p. 17, from which certain of these statements are adapted.
†Op. cit. p. 17.

The opening of any great zone of weakness such as that which attends a fault, would bring about an important change in the circulation of the surface waters. The waters in the vicinity would find their easiest passage into this fissure. The plane which represented the water-level before the formation of the fissure would be divided into two planes, each sloping towards the fissure, and the course of these two currents would be quite different from the course of the drainage before the formation of the fault. In other words, a prismatic depression of the water-level, like that produced artificially by anadit, but on a much grander scale, would be produced; and there would be deflected into this opening all the drainage waters of a large surrounding region, the size of this area depending upon the size of the fissure. The development of a vertical zone of weakness, which yet did not develop into a fault, would constitute a region permeable by water, and would have the same effect upon the drainage, though in a less degree. If the fissure should be slight, and tight at the bottom, it would soon become filled with water, the flow into it would cease, and the water-level

Compare Figure 12. This shows the deflection of the shallow underground circulation by the opening of a fissure.

Figure 13.

would be restored to its old plane; but almost all ways this fissure communicates with another lower down, or with another porous stratum, and thus the circulation established becomes permanent. Especially is this true in the case of faults and similar dislocations, which extend to great depth with little diminution of importance, and somewhere in their downward course almost inevitably meet with some passage-way for the waters to reach the surface again. (See Fig. 13).
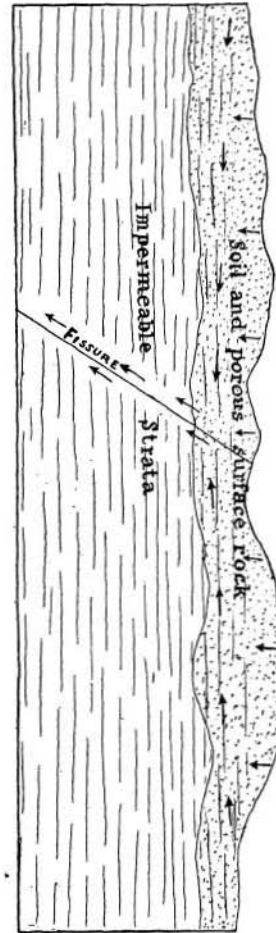
Faults such as those which have attended the uplift of the Virginia area would weaken the rocks through which they pass for a considerable distance from the actual line or lines of dislocation. The dimensions of this area, and the intensity of the straining, would depend upon the qualities of the rocks which were thus operated upon. Thus of the three most important members on the Mesabi—the upper slate member, the iron-bearing member and the quartzyte member—the quartzyte would undergo least comminution and would be at the end of the process least porous of any; for from its rigid and brittle nature, the strains would be relieved by sharp fractures, while the interstitial spaces would remain as impenetrable as ever. Next in point of strength would come the sla'es, where there would be developed a considerable degree of porosity. Weakest of all, in general, would be the iron-bearing member, in its more ordinary phases; for here the general decomposition would already have rendered the rock partially disintegrated and porous. All the materials, moreover, are very finely divided, and the application of the strain would produce in this member a vastly larger area of weakness than in the others, but especially than in the underlying quartzyte. The areas of general interstitial weakness, therefore, which result from a fault like that at Virginia, may be represented diagrammatically by figure 14.
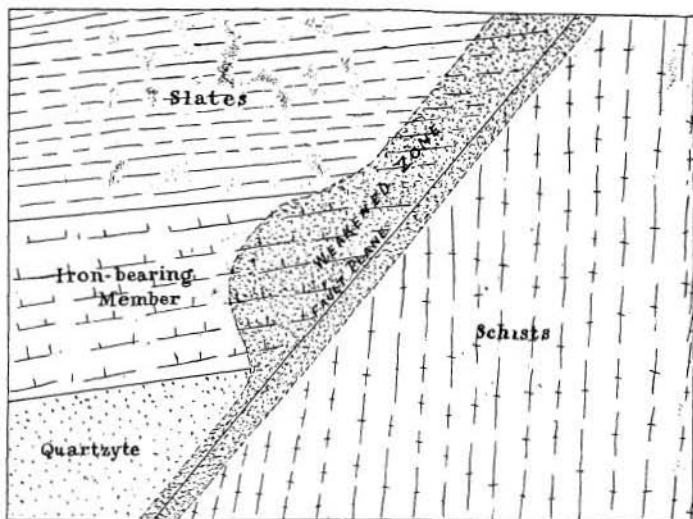

Figure 14.
Theoretical section across the Fault near Verginia, showing the relative size of the areas of weakness developed in the different strata by the faulting movement.

Where there is no fracturing, the quartzyte which lies below the iron-bearing member has very few joint planes or other fissures, and so forms a stratum practically impermeable to water. On the other hand, the iron-bearing member as a whole is porous, and affords the easiest passage for all surface waters. Roughly speaking, therefore, the thickness of surface waters is the distance between the ground-water level and the top of the quartzyte. The quartzyte forms the water shed along which, and through the iron-bearing rocks, the drainage waters pass to the point of least pressure. The waters which are deflected into the newly-formed fissure will then, in the first place, be very highly charged with iron, since their passage has been entirely through the iron rocks; in the second place, nearly all will emerge into the weakened area at that point where the fault crosses the bottom of the iron-bearing member. At this point the chalybeate waters will deposit their iron, take up silica, and pass on in the same direction, along the surface of the still only partially penetrable quartzyte, till, with the approach to the actual plane of dislocation, the fracturing of the quartzyte develops sufficiently to allow the waters to penetrate downward. What little iron they still contain may be deposited in the very topmost parts of the quartzyte, and silica taken up in return; but on account of the coarsely crystalline nature of the silica the process of replacement is extremely slow, as compared with that of the cryptocrystalline or chalcedonic silica of the iron-bearing member; so that it has never been found that such replacement has any commercial importance; moreover, the supply of iron in the waters by the time that they reach the quartzyte is so slight that it is soon exhausted, and the silica-bearing waters go on downward, depositing their silica if opportunity offers, especially as the enlargements of the original sand-grains, or retaining it and reappearing at the surface as siliceous springs.

The first deposition of iron, therefore, will be a thin film lying directly upon the quartzyte, beginning in that part which is furthest from the actual plane of dislocation, and where the oxidation is slight, in a very poor seam. This gradually increases till at the first point of free oxidation it becomes richest, for here most of the iron is deposited. From this point to the chief fault-plane it becomes successively poorer, for, although the oxidation gradually increases, yet the quantity of iron to be precipitated diminishes with greater rapidity. At the same time, what iron, silica, and other substances

have been deposited in the fault-fractures or even the inter-
stices of the strained rock (whether it be of the iron-
bearing member, the quartzyte, or any one of the formations
which may exist further down, along the course of the
underground waters), diminish the volume of these passages,
although to so slight a degree that it appears infinitesimal.
But this principle is extremely important, for every particle
which is deposited thus along the water-ways, in diminishing
their size, diminishes the quantity of water which may escape
within a given time. The quantity of drainage water which
may escape through this fissure being thus diminished, the
prismatic depression in the original plane of drainage becomes
less important, for the line along the fault where converge the
two new planes of ground-water surface, which follows the
drainage created by the dislocation, rises slightly and the plane
angle becomes slightly more obtuse. From this decrease in
the inclination of the ground-water level planes it follows that
the area drained by them diminishes slightly, and that on the
borders of the area a small outer rim returns to the drainage
which it followed before the deflection by the formation of the
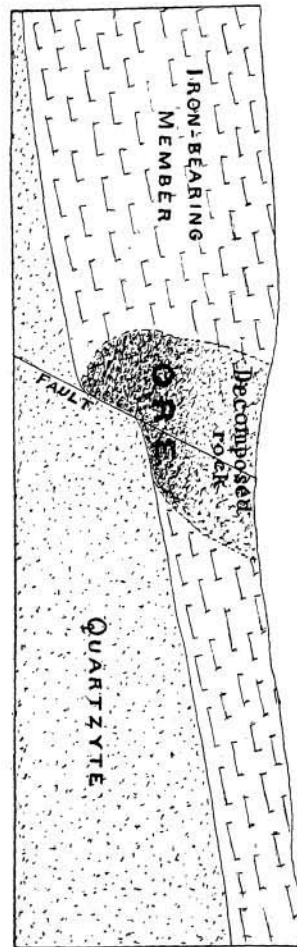fracture.

In the next deposited layer, the ground-water level will be
somewhat higher than at the first, hence a thin layer which
was not affected at first becomes oxidized. The outline of this
new superimposed layer is convex, like the first, but the circle
of which it is an arc is a much larger one than that of the first
layer. This arises from the fact that the ground-water level
has been heightened almost imperceptibly, while the amount
of iron in the waters is as great as before; thus when the solu-
tions reach the first plane of free oxidation, where was formed
the thickest parts of our theoretical first layer, it does not part
with so much of its iron as did the first solution. For the
greater part of it passes through the same rock as did the first,
where the previous deposition has diminished the capability of
replacement; moreover, the layer of unaffected rock at the
top, whose thickness is represented by the difference in the
ground-water level of the first and of the second solutions, is
extremely thin. Thus the waters pass on, and deposit their
maximum amount of iron a little further on than before.
These layers are repeated an infinite number of times, till the
richest part of the layers is deposited at the plane of greatest
dislocation. We have now arrived at the stage when the
accumulations are important enough to allow their observation

in the field. We have, at the bottom of the iron-bearing member, a thin seam of iron, of nearly constant thickness, resting upon the basal quartzyte and extending as far laterally as does the zone of weakness of the iron-bearing member, and with a general tendency to be richest in the zones of greatest weakness, and poorer as the distance from those zones increases.

The subsequent history of the formation of ore-deposits along these zones of weakness is only a repetition of these first steps. The chalybeate drainage waters, by their continual deposition of iron and their leaching of silica, keep making the lower layers more and more pure in iron, till the process is completed; and at the same time by their gradual filling of fissures and interstices by iron and silica, increasing the height of the ground-water level, so that continually a higher layer of the weak zone comes under the influence of active ferration. Progressively with this process, the depression in the original plane of drainage becomes less and less, and the underground area which sends its drainage to the weak zone becomes correspondingly smaller. In the end, there must result the replacement of nearly all of the silica of the weak zone of the original iron-bearing member by iron. This means an immense ore-deposit. The original fissure will also have been chiefly or wholly filled, and the drainage gradually restored to the single plane which it occupied before the catastrophe which induced the formation of the zone of weakness. It is to be remarked, however, that that portion of the rocks

Figure 15.

Theoretical section to show formation of ore-deposits along a fault-plane. Note relation of topography to the ore-deposits and the cause.

which lies above the restored ground-water level may never become completely ferrated, and, indeed, this is the normal case. It is true that in most ore-deposits at the present day the ore lies at the surface, directly below the glacial drift; but it is probable that in nearly every case there once existed above it a "capping" of less altered rock, which, together with some of the ore, has been long since removed by erosion. There are moreover, several well-authenticated cases of siliceous cappings of no great thickness overlying deposits of good ore, and these must be explained in this way. (See Figs. 15 and 16).
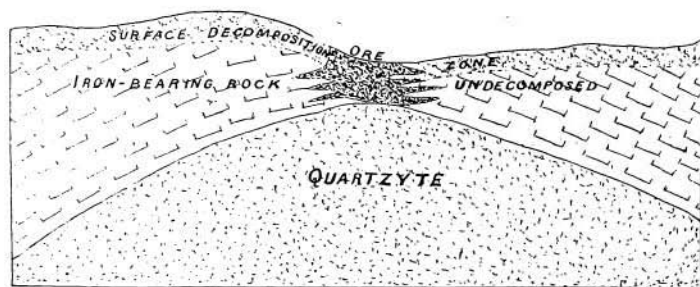
Figure 16.
Theoretical section, showing formation of ore-deposits in the weakened zone.
along the axis of an anticlinal fold.

Evidence of the gradual filling of these spaces, which we may properly call ore-basins, has already been given in the discussion of thin sections, where it is found that a rock which has been leached of its iron (in this case generally without replacement by silica) and thus reduced to a porous or semi pulverulent state, was afterwards, by the rise of the level of the ferrating waters, saturated with iron, and changed into ore. This has been particularly well observed in the siliceous rocks which form the rim of the Mountain Iron and Virginia basins. But in nearly every test-pit the transition of paint-rock to ore illustrates this. The paint-rock, as already described, is originally only the leached and decomposed residual product of the decay of the primitive iron-bearing rock; but this has become subsequently stained with iron. As we go down, the richness in iron increases, till streaks of material which may be classed as lean ore are found, and finally the gradation leads to the actual ore-deposit. The paint-rock which thus by saturation becomes transformed into ore had first contributed all of its iron to the lower levels of the ore-deposit, but with the filling up of the basin it has itself become again thoroughly ferrated.

Influence of Dikes on Ore-Deposits.

To recapitulate, the cause of the largest ore-deposits on the Mesabi is believed to depend upon the development of regional fractures or lines of weakness. So far as has been observed, there are no other points of difference between the rocks which have formed the ore-bodies and the rocks in the other parts of the member. Irving and Van Hise* have shown for the Penokee region that the ore-deposits are associated with underlying dikes, which are so arranged with the basal quartzyte as to form basins in which the ore is believed to have been concentrated; but on the whole Western Mesabi, so far as is known, there has been found no trace of any dike or other igneous rock in the Animikie. If such dikes existed, it is probable that near them would be formed ore-deposits. If the dikes formed troughs with themselves or with an impenetrable stratum like the basal quartzyte, the ore bodies might occur in the manner described in Michigan and Wisconsin.

But even if no such troughs were formed ore might accumulate near the dikes, partly on account of the less easily penetrable stratum which they would form, but chiefly on account of the weakening of the iron-bearing rock under the shearing which accompanied the introduction of the dike. We should then have this succession: First the harder, unsheared rock of the iron-bearing member; next the sheared and oxygenated zone lying on the upper side of the dike, and having its maximum of weakness not far from the dike itself; next the hard, nearly impermeable igneous rock; below this another strained and oxygenated zone; and finally the hard unstrained, siliceous iron-bearing rock, or the basal quartzyte. When these layers outcrop at the surface, drainage waters find two porous layers, lying on either side of the impermeable dike; and there are formed two chief underground channels, the one above, with its water resting upon the dike; and the other below, with its water resting upon the lower hard stratum of iron-bearing rock, or upon the quartzyte, according to the location and direction of the dike; and both bodies of water have about the same course. This circulation would begin immediately after the intrusion of the dike, and the chalybeate waters would proceed to replace the weakened siliceous rock through which they passed and to deposit iron. In both channels those solutions which were most highly charged with iron would sink by

*Tenth Ann. Rep. U. S. Geol. Survey, pp. 409-422; also plates XXXVI and XXXVII.

reason of their greater weight, and would lie closest the foot-wall. In the upper porous stratum this lowest part would also be the zone of greatest weakness, thus allowing the passage of a greater amount of waters within a given time than any other part of the stratum; this therefore, is also the zone of easiest replacement, so that the same quantity of a solution of given strength will replace more silica here within a given time than in any other part of the stratum. So the first deposition of iron will be upon the foot-wall of dike rock, and from this the ore-body will grow upward. In the lower channel the conditions are somewhat different. Here, again, the richest solutions tend to concentrate at the bottom; but, at the same time the zone of greatest weakness, of freest passage and most rapid replace ment, is near the top, in the vicinity of the dike. So here the results of the first stages of deposition will be distributed more uniformly, partly in the lower, partly in the higher zones, and the rate of growth in the different zones will remain more nearly uniform till the process of replacement is quite com-pleted. If a section should be made through the upper and the lower permeable strata, before the process of replacement is completed, there would probably be encountered at the upper layers of the upper permeable stratum, a lean, little-ferrated rock; at the lower layers of the same stratum, resting upon the dike, a deposit of rich ore; below the dike, a somewhat ferrated rock of lean siliceous ore, which should have some uniformity in all its layers, even down to its foot-wall. If, however, the section should be made in a case where the ferra-tion was complete, there would be found, in place of the original permeable strata, deposits of ore both above and below the dike, that below being usually poorer and some-times nearly absent, depending upon the relative permeability of the underlying rock.* It will be seen that this class of ore-deposits, which are not known on the Mesabi, are still included in the general statement made for the Mesabi, that " the cause of the largest ore-deposits is believed to depend upon the development of regional fractures or lines of weakness."

On the Mesabi, however, the cause of the regional fractures is folding and faulting, and not the intrusion of dikes. The date of this regional disturbance is very ancient, for the time necessary for the accumulation of these great ore-deposits is

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*C. R. Van Hise, Iron Ores of the Marquette District of Michigan. Am. Journ. Sci. Vol. XLIII, February, 1892, p. 123. Figures showing occurences of ore in the Mar-quette region. In Figure 1 deposits of ore are seen on both sides of a vertical dike. These deposits are about equal in size, and both rest on chert.

immense; so they are all hypothetically assigned to the same age as the greatest of them, the Virginia uplift, and this, with the tilting and corrugation of the Animikie strata, has been assigned to the Keweenawan.

Besides this chief cause, there are others which sometimes give rise to regions of especial weakness, which then become in time ore bodies. Ore-bodies developed in this way are smaller, but they are often of economic value. First may be mentioned the production of strain originating in the iron-bearing member, and caused by the chemical changes in it. These strains produce often faulting, brecciation, folding, or, most often, simply the development of an area of greater weakness than the surrounding rock. The effect of these upon the formation of ore-deposits is to be explained in the same way as the effect of the regional catastrophes, since they differ only in being of much less magnitude, on account of their being produced by a less powerful force. To this cause probably owe their origin many of the smaller and less important ore-bodies. Still a third class, which in some cases becomes of some importance, has no connection with any dislocation of the rock; the permeable stratum lies at the surface, and has been rendered porous by the weathering of surface agents, with no apparent auxiliary force. At the bottom of this weathered stratum the hard, little-decomposed rock forms a foot-wall, upon which, under favorable conditions, the building of a deposit of ore commences, which, as in other cases, grows upward by successive additions. (See Fig. 17). The

Figure 17.

Section showing formation of small ore-bodies along the boundary between the decomposed iron-bearing rock at the surface and the little altered rock lower down. Note the relation of the topography to the ore-deposits, and the cause.
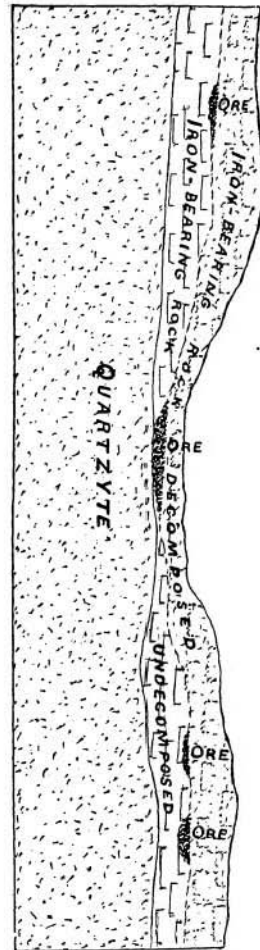
process is practically the same as before. Those waters
which have traveled for a long distance laterally along the
foot-wall of hard rock become saturated with iron. They
are being continually joined by others which come more di-
rectly from the surface, and so are more highly oxygenated.
The first effect of the meeting of such solutions would be that
the oxygen would precipitate from the saturated solution a
certain quantity of its iron as the oxide; and in this way the
ore was formed. After the oxygen, however, has been sepa-
rated from the waters by the precipitation of the oxide, these
waters, by reason of their dilution, are enabled to take into
solution a renewed amount of iron, which they carry on, all
the time depositing a certain amount in concentrated form and
taking fresh material into solution from its disseminated state.
We are best able to identify this third class where there is a
thin covering of the upper slate member, thus making it cer-
tain that we have in the upper permeable stratum of the iron-
bearing member a zone which represents the original surface;
and cannot possibly be a weak zone from above which the
harder rocks have been removed by erosion produced within
the member by some mechanical force. An example of this
has already been mentioned, the drill-hole near McKinley, of
which the record, kindly supplied by Mr. H. V. Winchell, is
as follows: (See Fig. 10).

Swamp and glacial drift material......................... 51 feet.
Slates... 58 "
Porous iron-bearing rock (somewhat leached)............. 15 "
Hard hematite.. 4 "
Hard, impermeable iron-bearing rock passed through to
the thickness of 39 feet, and then the boring was stopped.

A pit sunk by Longyear through the slates in the basin of
Embarras lake encountered in the upper horizon of the iron-
bearing member below, the same phenomenon of lean ore.

When by unequal surface decay there has been formed a
depression in the foot-wall of less altered rock, this depression
will be made the receptacle for a larger and more permanent
body of water than other parts of the surface. Hence deposi-
tion and replacement will go on here more rapidly, and in time
this ore-basin will be filled. As in the nature of the rocks and
of the decomposing processes, the conditions are so varying
that such depressions must constantly occur, they may be often
of such extent as to give rise to ore-bodies of economic im-
portance.

STRUCTURAL PECULIARITIES OF ORE DEPOSITS.

The chief structural features of ore deposits, which are not shared by the other rocks of the iron-bearing member, are the often well-developed bedded or laminated appearance, and the frequent contortions and faultings of these layers.

It is hardly necessary to reiterate that the laminated structure has nothing to do with stratification. This is quite sufficiently proven when it is remembered that the ore-deposits represent the extreme result of all the decomposing and reorganizing influences which have affected the iron-bearing rock, and so, if any trace of the original structure remained, it would be much fainter than in the less altered rocks. But as a matter of fact, there is in the freshest rocks no trace of any bedding, or even of any parallel structure; with the progression of the decomposition and rearrangement, however, a rough banded structure begins to be present, and with the change in the rocks and the obliteration of the original structure, the bands grow more numerous and more perfect. The growth and cause of these bands has already been ascertained; and in the extreme of the normal process, which is represented by the jasper and iron, the alternating bands of iron and silica are often very perfect and beautiful. But in the extreme of the oxidation and concentration process, which is represented by the ore-bodies, the alteration has gone further yet, and as a result the laminæ are still closer together and more regular. The cause of their formation is precisely the same as for the coarser bands. In the more altered rocks, where the carbonate has all been oxidized, it has been shown that the multiplication of the horizontal jointing brings the joint-planes so close together that the result resembles slaty cleavage. As the free oxidation which produces this structure is also the essential condition for the formation of ore-deposits, it happens that this much-jointed rock and the ore are found often very closely associated; as, for example, at Virginia, at the Ohio mine. When this rock is replaced, the first bands of iron are formed along the joint-planes, as are all other bands in other phases of the rock; and the rock lying between the joint-planes is not replaced till later. Thus the different ages and conditions of formation are preserved in the completely ferrated rock, and form the laminæ of the ore. These laminæ are marked, at the present time, by alternations of lighter and darker bands, of which the former contain less iron and more

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combined water than the latter.   The darker layers, in this
case, may be asumed to have been the first formed along the
joint-planes; and the lighter ones, the spaces of rock between
them, which was first partially leached and then ferrated.

The laminated structure of ore-bodies is a very common
feature, both in sedimentary and igneous rocks.   Judd* has
described many such cases in England, in ore-bodies which
have been formed by the replacement of limestone.   We quote
briefly:

The accumulation of oxide of iron, in laminæ roughly parallel with
the bedding and jointing of the rock, is by no means peculiar to the
Northamptonshire ore.   *   *   *   *   From a study of a large number of
these cases, we are led to the conclusion that in all of them the penetra-
tion of atmospheric water is the cause.   *   *   *   *

He then explains the chemistry of the process in the same
way that we have already explained the formation of the
coarser bands in the less altered rock.

Posepny,† in the discussion of "Deposits in Crystalline
Schists and Eruptive Rocks," makes the following remark :

Many indications, available in the distinctively sedimentary rocks as
guides in the determination of the relative age of their ore-deposits, are
here wanting.   The bedding becomes more and more obscure, and is no
longer distinguishable from the cleavage.   Many of the ore-deposits in
these rocks have also become in whole or in part crystalline, adjusting
themselves to the prevailing stratification or cleavage, so that most of
them present a bed-like structure and form.   Whoever believes in the
contemporaneous origin of ores with the rocks will not trouble himself
here with genetic speculations, but will see in these deposits simply "ore-
beds," according to the old classifications.

In this connection he cites the case of the zinc-blende deposit
of Ammeberg,‡ in Sweden, a case of replacement of the original
rock:

In a winding line   *   *   *   occur steeply dipping beds of gneiss in
granulite.   *   *   *   At certain points they show very beautiful close
folds.   At first glance they seem to be genuine intercalated beds of the
same age as the rocks.   The ores, however, do not continue along the
whole line, but form separate lenses, up to 15 meters (49 feet) thick, which
show a distinct stratification, consisting in layers of fine-grained to
amorphous material resembling *hälleflinta*, alternating with the coarser
granulite.   *   *   *   The entrance of the ore into the coarsely crystalline
layers seems to have been attended by an enlargement of their volume,
which resulted in their breaking through the dense layers.

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*The Geology of Rutland, etc., by J. W. Judd, p. 130.   "Mode of Formation of the
Northamptonshire Iron Ore."
†The Genesis of Ore Deposits, p. 126.
‡Ibid., p. 129.

The same explanation is required for some parts of the bed, in which, between the two plane surfaces of two fine-grained, barren strata, ore occurs in highly folded and contorted layers. This folding is due by no means to an exterior mechanical energy, but to interior chemical forces.
* * * *

This Ammeberg deposit, then, though so distinctively bedded, is by no means of primitive origin. * * * *

The contortions of the laminae in the ore deposits is often very great, and there may also result faults and folds. The fact that these faults and folds are confined to the ore body and do not extend to the less altered rock which surrounds it; moreover, and found nowhere except in the ore bodies, shows that the disturbance has taken place since the concentration of the ore. It also shows that the force which led to the folding has probably originated within the ore body itself. These contortions are particularly abrupt where the ore abuts against a hard unyielding wall of less altered rock. A good case of this was seen at the Hale mine, near Merritt, where the ore rests on its northern side directly upon the hard schist of the Keewatin. Here there have been developed much broken contortions, and the general position of the layers has been changed so that they dip to the south about forty-five degrees. The nature of these contortions makes it clear that the laminæ of ore have been pushed laterally against the unyielding wall of schist, and that the folds are the result of this compression. The force which caused the motion, therefore, was confined to the ore body, and did not affect the schist, and so it could not have been due to any regional disturbance. In other mines, such as the Ohio at Virginia, the same thing was noted, and here, as at the Hale, the contorted layers were near a bounding wall of hard rock.

It seems to be the case that the contortions are uniformly greater and the laminæ more pronounced, near the surface, while with increasing depth the ore becomes uniformly and evenly bedded, the layers running in a nearly horizontal direction. With this diminution of the disturbance there is also associated a change in the nature of the ore; at the top there is apt to be, as seen in many of the mines of the Biwabik group,* a zone of the highly hydrated yellow limonite or göthite. While this is a surface deposit, it is often of considerable thickness. The ore at the Hale mine of this character. Going downward, the ore changes, till there is reached the granular "blue hematite," which is the best and purest ore. The change is primarily a

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*Twentieth Ann. Rep. Minn. Geol. and Nat. Hist. Survey, p. 136, and plate I.

decrease in hydration. We thus find that the steep folding is in the first place confined to the ore bodies, and, in the second place, chiefly to the hydrated portions of those ore bodies. We may now easily understand the causes of the force which has produced this folding.

We may assume that the hydration of the upper horizons was subsequent to the formation of the ore-body. By the processes of replacement, there should have been originally no great difference in the condition of the ore deposited in different horizons. This original state was probably a somewhat hydrated sesquioxide. After the concentration of the iron in this form, the force of the crystallizing motive led to the dehydration of this oxide and the clustering of the earthy mass into crystalline grains of hematite, thus producing the "blue granular" ore. This hematite is considered the best, not only on account of its comparative freedom from combined water, but because the process of crystallization has somewhat purified the ore by the exclusion of many of the impurities, such as phosphorus. The ore, by its crystallization, is rendered very porous, and so the waters act with increased energy, and have operated to carry off those impurities which were not taken up by the crystallizing iron. So the blue hematite is ordinarily a high-grade bessemer ore.

When, however, by the process of erosion, it arrives that the overlying horizons are stripped off, and this crystalline hematite is brought to the surface, the great quantities of surface waters begin to affect the upper layers of the hematite and to change it into hydrated varieties. Among these limonite and göthite may be named, but there appears to be very many stages of hydration, as indicated by the gradually changing color of the ore on proceeding from the bright yellow limonite to the blue-black granular hematite.

The change from the anhydrous to the hydrous variety involves an increase in volume, in the same manner as does the change from the oxide to the carbonate, before described. If we take the change from anhydrous hematite to limonite as a typical example, the reaction which takes place may be expressed as follows:

$$2Fe_2O_3 + 3H_2O = Fe_4O_9H_6.$$
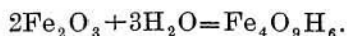
By the addition of the combined water there is an increase in weight from any given quantity of hematite to the quantity of limonite thence derived of about 14.5 per cent. Since the

density of limonite is somewhat less than that of hematite, the increase of volume would be somewhat greater. As, in this case, the rock consists entirely of ore, this must be the degree of expansion of the whole rock-mass attendant upon its complete hydration; although the amount would not be so great where the hydration was only partial. Some of this expansion would be relieved in the interstitial spaces, and the result would be to make the ore somewhat earthy; the rest has caused the crumbling and folding of the highly hydrated horizons.

With the reduction of the iron to the earthy and hydrated state, it becomes a more active absorbent of impurities, and one of these, phosphoric acid, which is contained in very small quantities in nearly all waters, is especially injurious to the commercial value of the ore, and brings it in many cases out of the bessemer limit.*

THE EASTERN MESABI.

What has been hitherto written has been chiefly concerning the Western Mesabi. It may be now well to inquire the cause of the peculiarities of the iron-bearing member upon the Eastern Mesabi, especially the reason for its comparative unproductiveness of large bodies of concentrated ore. In this connection it is necessary to consider the attitude of the Animikie strata, and the cause, for, although this topic properly concerns the whole Animikie series, yet its application is here of the greatest importance. It has been previously suggested that the tilting of the strata was probably due to the weight of the Keweenawan lavas, as is shown by the inclination of the strata towards these massive igneous rocks, the increase of disturbance as these areas are approached, and the comparative freedom from any action in the region most remote. Upon the Eastern Mesabi the Animikie strata are pierced and intermingled with the northern border of the Keweenawan rocks, so that their normal attitude is often much disturbed, and the true stratigraphy rendered very puzzling. As we go away from here, both to the south west along the Western Mesabi, and to the north east along the International Boundary division, the disturbance grows progressively less. With this change there is associated another, in the iron-bearing member, which is best shown going south-west along the Western Mesabi; for in the opposite direction the iron-bearing member is not well-developed. This is a progressive decrease of the

*Twentieth Ann. Rep. Minnesota Geol. Survey, p. 137.

crystalline state of the silica, and the magnetitic state of the iron. Nearly all the iron of the Eastern Mesabi is magnetic, whether concentrated into bands or small ore-bodies, or disseminated through the rock in shots or grains. It is furthermore associated with hard, crystalline silica. But as we get out of the immediate vicinity of the Keweenawan rocks, the quantity of magnetite rapidly decreases, although. it is found sparingly throughout the whole extent of the Western Mesabi even as far as Pokegama 'falls. But, on the whole, nearly all the iron on the Western Mesabi is hematitic or limonitic, and nearly all on the Eastern Mesabi is magnetic. It is probable, therefore, that this change in the nature of the rocks is connected with the decrease in disturbance of the strata, and that both were accomplished at the same time by the advent of the Keweenawan rocks. These views were first expressed by Mr. Horace V. Winchell.* The magnetite in the Eastern Mesabi rocks is scattered in such a way as to show that it is the result of a concentration like that observed going on upon the Western Mesabi; but in the latter place it seems probable that the iron is rarely or never deposited as magnetite in such concentrated forms, but always as the earthy, more or less hydrated sesquioxide. On the Eastern Mesabi, therefore, it must be that this iron was originally in the state of the sesquioxide, and that at the Keweenawan time it became magnetic. We may then account for this magnetization in two ways. First, the direct heat of the igneous rocks. This would change to the crystalline and magnetic condition the semi-concentrated silica and iron for, a considerable zone, perhaps for several miles, for the influence of a very slight degree of heat, if long continued, is quite sufficient to produce the magnetization of hematite. Second, and most important, the indirect application of heat through the disturbances which the Keweenawan rocks produced in the Animikie strata. Near the centre of disturbance, the internal heat developed by these movements must have been sufficient to completely magnetize the iron; while with the increasing distance the heat, and therefore the magnetizing influence diminished. But as there was some disturbance felt along the whole length of the Mesabi, so we find some small magnetizing action quite to the end of the range.

The effect of this contact and regional metamorphism would be to render comparatively stable the minerals of the iron-bearing rock, by subjecting them to a rapid crystallizing

*Twentieth Ann. Rept. Minn., Geol. and Nat. Hist. Survey, pp. 120-121, and pp. 134-136.

action. The result would be a good deal like what has been indicated as the final stage of the normal process of decomposition and rearrangement, under ordinary atmospheric influences: the molecules of iron and of silica, from their loosely united state in the earthy hematite and the cryptocrystalline silica, became firmly bound together by the crystallizing force, and thus become comparatively stable and resistant to the degrading effects of atmospheric agents. By this violent method the process of decomposition and concentration was brought to a sudden close; the attainment of stability was accomplished suddenly, and without the extreme concentration that was necessary under ordinary atmospheric conditions alone. We may believe, therefore, that since Keweenawan time the changes in the rocks of the Eastern Mesabi, and the oxidation and concentration of iron, have not been great. But upon the little-affected Western Mesabi, the processes of concentration, which were already well advanced, suffered only a slight check, and continued up to the present day. This is probably the reason for the poverty in large ore-deposits of the Eastern Mesabi. The ore there, roughly speaking, represents the concentration as accomplished up to the Keweenawan epoch, while that on the western part of the range represents the uninterrupted result of the concentrating forces down to the present time.

ORES IN THE CRETACEOUS OF THE WESTERN MESABI.

The Cretaceous occurs in small residual patches on the Western Mesabi, as has been described. Its most common form of occurrence is as a conglomerate which is generally almost entirely made up of fragments from the iron-bearing member, which in each case it has been found overlying. This conglomerate has been found, first, in the southwest quarter of section 20, T. 58-19, where it has been positively identified[*] because of the associated fossil-bearing shale. It has also been found in the southeast of the northeast quarter of section 6, T. 58-17. Finally, a conglomerate which resembles that of the other two localities, and belongs probably to the same horizon, is found in the northeast of the northeast of section 10, T. 58-18. The material of which these conglomerates are composed, and which has been derived from the iron-bearing rocks, is found here in all stages of the transitional changes. Not only

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[*] Horace V. Winchell, Am. Geol.. October, 1893. Note on Cretaceous in Northern Minnesota, p. 221.

the fragments, but the cement between them is thus com-
posed, and many things go to show that these materials have
undergone much chemical change since the time they were
broken from their original beds and incorporated in the Creta-
ceous conglomerates. One of the commonest of these is the
complete and almost general ferration, in many parts. The
fragments and cement alike, have been penetrated by the iron
oxide, and the conglomerate has thus been transformed into a
hard mass of lean iron ore, breaking with a conchoidal frac-
ture. This ore is gray and often partly magnetic, but is
distinguished from the other ores of the range by its large
content of sulphur, which, in the form of pyrites, usually gives
a yellow tinge to the mass. In other specimens there has been
a leaching without much ferration, and as a result, the whole con-
glomerate is made up of a mass of soft decomposition powder or
hardened paint-rock; in this case the fragments are often not
so completely changed as the more finely divided cement, and
contain, in the centre, hard siliceous residual cores which re-
semble some of the stained cherty or finely siliceous varieties
of the rock as we find them in place. In the conglomerate in
section 6, T. 58-17, some of the larger pebbles are even more
plain in their story. Here was noted in the conglomerate, a
boulder eight or ten inches in diameter, which on the outside
seemed to be a light red paint-rock. On breaking it open, it
was found that the centre was composed of the hard, brown,
and siliceous conchoidal-fractured phase, which is so common
in the iron-bearing member.

  But it had gradually decomposed till it formed a nearly white
powder, in a zone which was parallel to the periphery, and this
in turn had at the very outside been stained to form the paint-
rock. Smaller pebbles had been more completely changed, for
the zone of decomposition had taken up more of their volume;
and one, which was smooth in outline and subangular in shape,
suggesting considerable attrition before being deposited, was
composed entirely of the soft white pulverulent rock, and could
be broken with the fingers or cut with a knife. This was about
an inch and a half in diameter, and was plucked out from the
conglomeratic mass in which it was imbedded. These frag-
ments could never have retained their integrity in the midst of
the rolling which their shape indicates, had they been at the
time of their incorporation of the same pulverulent nature as
now; and in the larger fragment, moreover, the zonal relation
of the decomposition products, parallel to the periphery, shows

that *all* of this decomposition took place after the fragment had acquired its present shape. These rocks, then, represent the action of the oxidation and concentration process, accomplished, for the most part, since the Cretaceous period; while the highly ferrated conglomerates represent the iron which has thus been leached from these decomposed and now pulverulent rocks. The great quantity of sulphur in these ores is accounted for by the organic matter in these beds, which produced abundant sulphuric acid. In the presence of this the iron was precipitated, and as a result, a large part of it is in the form of sulphide. None of this ferrated conglomerate contains enough iron to make it of economic value in this region; and even if this were the case, the amount of sulphur renders it useless.

There is no doubt, however, that much of the iron which is found in these conglomerates was already concentrated when taken into the beds, and has since undergone no great change. In the conglomerate in section 10, T. 58-18, a pebble of this iron, about four inches in diameter, was found, which exhibits great pyritization on the periphery. But this decreases inwardly till in about one-third of the diameter the yellow tinge fades away. The ferration of this pebble is equal and complete throughout. In this case the ferration and the pyritization have probably not been contemporaneous; but the pyritization was subsequent to the completion of the former. Moreover, the zonal pyritization shows that the process occurred after the pebble had assumed its present form, *i. e.*, after its incorporation into the conglomerate; while of the ferration there is no such evidence. It is probable, therefore, that most of the ferration of this pebble was accomplished before Cretaceous time.

So, in this conglomerate, there are both pre-Cretaceous and post-Cretaceous iron; and the proportion of the two is not certain. But when we consider that even where all the evident changes have been post-Cretaceous the processes had been undoubtedly going on for a long time previous to the formation of this conglomerate, even though they had not destroyed the integrity of the rocks nor succeeded in wholly separating the iron by concentration from the silica, and that a large part of the iron was wholly concentrated in pre-Cretaceous time, we may admit that the results of the pre-Cretaceous periods are rather more important in the introduction of iron into this conglomerate than the time since. But we also conclude that the processes of change have been going on as steadily in the iron

bearing rocks since the Cretaceous as previously,—not only in the fragments in this conglomerate, but also, necessarily, in the rock which was still in place.

POST-GLACIAL CHANGES IN THE IRON ORE.

From the time of the formation of the iron-bearing member to the latter part of the Keweenawan we have nothing definite by which to measure the progress of the degradational changes in these rocks; but at this time, if our reasoning is correct, the decomposition and concentration had already progressed to a considerable degree. From the Keweenawan to the Cretaceous, again, there is a gap in which there are no available records; but at the Cretaceous we find that the processes were going on as steadily as ever. From the Cretaceous on, there is no record till we come to the glacial epoch. So slow have been these stages that our studies have indicated, that the change since the glacial period can have very little effect; and yet there is evidence to show that it has still gone on, and with as great an apparent activity as ever. Occasionally, where the drift contains many fragments of the iron-bearing rock, a post-glacial conglomerate in small lumps has been formed. A case of this was seen by the writer on the line of the Duluth, Missabe & Northern railroad, a few miles south of Mountain Iron. The conglomerate was as firm as most of the ferruginous conglomerates of the Cretaceous. The fragments were of partially ferrated portions of the iron-bearing rock and of hematite; they were mostly angular, and with the finer matter were firmly cemented by iron oxide. This conglomerate formed a crust upon a large granite boulder, and had it not been for this circumstance its appearance of solidity was so great that it would have been somewhat difficult to believe it of post-glacial origin.

PERIOD OF FORMATION OF THE ORE-DEPOSITS.

The process of concentration of ore has gone on with few interruptions, on the Western Mesabi, from the period immediately succeeding the formation of the iron-bearing member, down to the present time. Any particular deposit, however, may have been begun and finished at any points within this period, or may have been in process of formation during the whole of this time. The great ore-deposits, for example, have been assumed to have had their real beginning in the disturbances which probably took place in the later Keweenawan

time; and yet the iron that was here concentrated had proba-
bly been slowly separating from the rocks for a long period
preceding. The formation of these same deposits, moreover,
was probably completed long before the glacial period, and yet
since that time the processes have gone on in the adjoining
rocks, less effective, but as active.

EFFECT OF THE GLACIAL ABRASION UPON THE ORE-DEPOSITS.

It is quite certain that the amount of ore upon the Mesabi
range was considerably lessened by the scraping action of the
ice-sheet. The ore offered practically no resistance whatever
to such a tremendous grinding agent, and would have all been
carried away were it not for the protective action of the harder
rocks. These harder rocks, whether they were, as was often
the case, a ridge of hard granite or schist to the north, or
merely a hard rim of the iron-bearing member itself, bore the
weight of the ice, and so the bodies of ore escaped destruction.
For example, in the Biwabik group, the ores rest directly
against the ridge of the Keewatin schists to the north; and at
Mountain Iron the rim of hard rock forms an elevation which
bounds the ore-basin on three sides. But at both these places
there is evidence, of the same nature as is found elsewhere,
that the glacier has really scraped off the topmost layers of
the ore. At the Biwabik mine, there are included in the drift,
which overlies the ore, large masses of paint-rock, yellow ore,
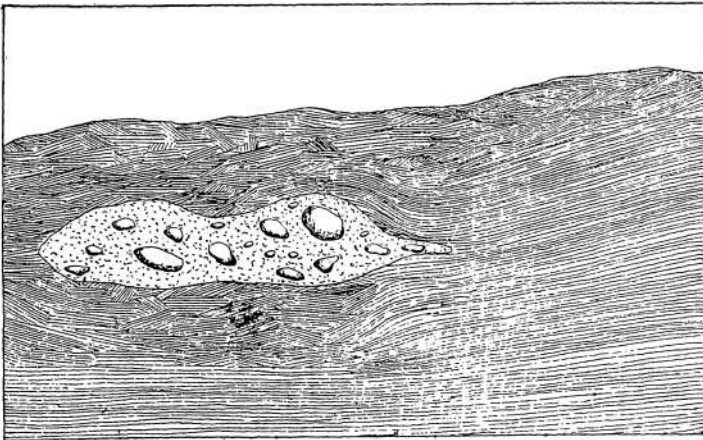
Figure 18.

East and west section of till in ore at Mountain Iron mine. To the north this tongue
comes to the surface, so that this is a transverse section of it. Scale, 5 feet to 1 inch.

and even blue ore, in irregular bunches or in thin and broken
layers.   At the Mountain Iron mine the ore is mingled with
the drift in the most intimate way at the surface.   The surface
covering of drift is full of large masses of ore; and into the ore
below have been inserted wedges of the drift.   In this case
the wedge is usually transverse to the horizontal stratification
of the ore, and by its insertion the stratification is bent and
broken somewhat; but sometimes the wedge has been inserted
between two layers and parallel with them, without disturb-
ing the bedding in any great degree.   (Figure 18).   In still
other cases sections in mining show wedges of till which run
down vertically, transversely to the bedding, without disturb-
ing it, as in Figure 19.   Where these wedges have broken
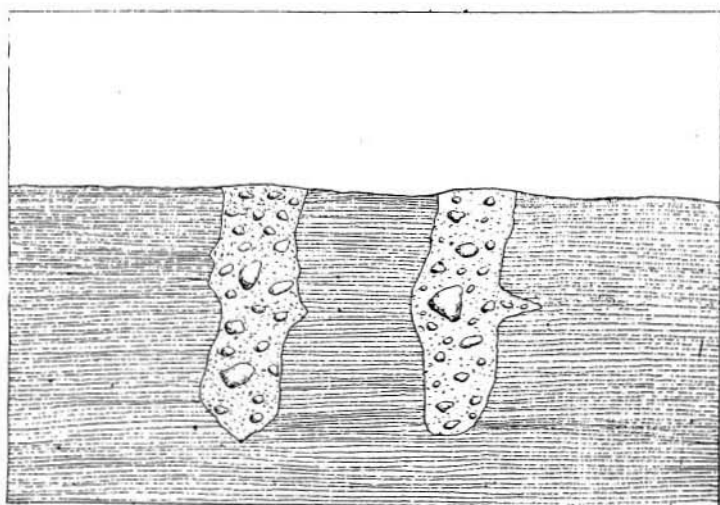
Figure 19.

North and south section at Mountain Iron mine, showing wedges of till in undis-
turbed strata of ore. Scale, 5 feet to 1 inch.

the stratification, it is probable that they were forcibly
thrust into the ore; but when the bedding is not disturbed,
there seem to have been produced, by the motion of the ice,
empty fissures, which were afterwards filled with till.   When
the wedges are vertical, it is probable that the weight of the
ice has produced the transverse fissures; when they are horizon-
tal, the ice seems to have lifted up the topmost layers from
those beneath, leaving an empty space between; and this
empty space was subsequently filled with till, the cavity being
considerably enlarged in the process of filling.

The formation of these narrow fissures conformable with the bedding is further shown by the occurrence of conformable sand-veins. They are found in considerable abundance near the surface (ordinarily within twenty feet), at the Mountain Iron mine. Many of them are quite conformable with the layers, and are persistent for considerable distances. The sand is white, with a slight yellowish tinge, and is usually very fine, the individual rounded grains being so small that their shapes can be well seen only by the aid of a magnifying glass. Many of these veins are from one to one and a half inches wide, and can be traced from twenty to fifty feet. Their true nature is shown by the transverse veins of the same material, with which they are associated, and sometimes connected. These transverse veins connect at the upper end with the surface of the ore and the bottom of the drift, and at the other with a conformable vein or an irregular pocket of sand. These pockets are also a very common feature.
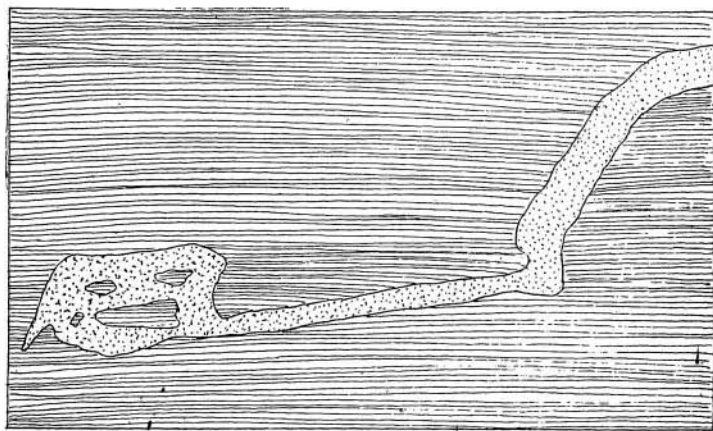
Figure 20.

Sand-vein in ore at Mountain Iron mine. Scale about 5 feet to 1 inch.

In these cases the fissures were too small to be filled by the direct packing of the glacier, but the glacial waters bearing in suspension very fine sand from the drift, have penetrated them. (See Figure 20). In considering the formation of these transverse and conformable fissures, without any disturbance of the bedding, it must be remembered that at the time of this action the ore was cemented with frozen water, and thus rendered rigid.

That the vertical wedges which .are filled with till occupy
transverse fissures which were caused by the increased weight
of ice at the southern end of the Mountain Iron mine is further
shown by the structure of the ore, as seen in a north and south
section which was exposed, after some stripping and mining.
The section is shown in Figure 21.   From the base of the
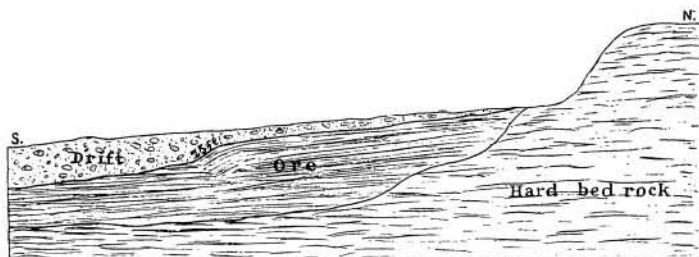
Figure 21.
Section at Mountain Iron, to illustrate the results of the glacial abrasion.

hard rock bluff which limits the ore-body on the north, the ore
runs south, with a gentle slope, which is somewhat greater
than the southward slope of the upper surface of the till, which
here forms a scant covering.   This is uniform for about four
hundred yards.   Then the till suddenly cuts down into the ore
at a steep angle, making a drop of twenty or thirty feet; so
that at the time that this observation was made the ore disap-
peared beneath the floor of the cut, and did not reappear.
The surface, however, does not participate in this sudden drop,
but maintains its uniform descent; and the thickness of the till
covering consequently becomes increased by the whole amount
of the drop.   Where the drift has thus cut down across the
nearly horizontally bedded ore, the violent nature of the pro-
cess is evident.   The layers, .which run quite straight till they
approach very near to the drop, are here bent down and broken,
and in the drift are numerous masses of the ore, which have
been broken off and mingled with it at the time of the shearing-
down process.   (See Fig. 22.)   These phenomena show the
following to have been the effect of the glacial abrasion here.
The weight of the ice-sheet was chiefly borne, at the northern
end of the deposit, by the rim of hard rock, especially the
rock bluff.   Nevertheless, the ice scraped off the more super-
ficial parts of the easily eroded ore-body, and these fragments
are still found in the drift.   The surface that was thus removed
left the space occupied by the ore lower than the surrounding
rock, and at the cessation of glacial action it had the appear-

ance of a basin, surrounded on all sides by the rim of harder rock which was left as ridges; and this appearance it retains at the present time. But after this topmost portion was removed the pressure was rather forward than downward, in the immediate vicinity where the weight was borne by the hard rock-rim. The result was the lifting up of certain layers bodily for some little distance, leaving the permanent and conformable fissures, which were afterwards filled by the sand; or, almost immediately, by a lateral wedge of till. But at a certain
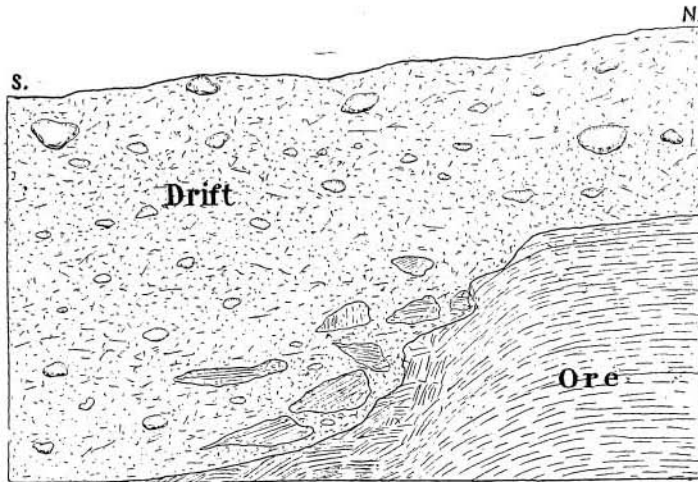
Figure 22.

Diagram, showing on a larger scale the drop (25 feet) which is seen in the profile of the ore in figure 21. This illustrates the manner in which the drift cuts down into the ore.

distance to the south the rock-rim became no longer able to support the whole weight of the ice, which thus came to rest partly upon the ore, and immediately, by the force of its weight, sunk twenty or thirty feet downward, and so continued. The effect of this increase of weight on the forward part of the ore-body produced, in that part of the rigid but brittle frozen mass further north, where the culmination of this strain came, transverse vertical wedge-shaped fissures, into which the till found entrance without serious rupture. Thus the undisturbed condition of the bedding next these till wedges is explained.

An ore-body which existed before the glacial action, but was without sufficient protection, might have been entirely removed and disseminated in the drift. It is probable that in every case where the granular blue hematite and other little-hydrated forms are encountered directly below the drift, there

has been removed a considerable portion of paint-rock and hydrated ore, together with an unknown amount of the blue ore itself.

Relation of the Present Topography to the Ore-Bodies.

It will be seen from the discussion of the condition of formation of the ore-bodies that the present topography, which is a very recent thing, being partly glacial and probably almost entirely accomplished since early pre-glacial time, can have little causal connection with ore-bodies which began to form in Keweenawan time. At the same time, the previously existing ore-bodies have undoubtedly influenced the topography, during its formation, and thus have some causal connection with it. Pre-glacial rain and stream erosion have had a greater effect upon the soft ore-bodies than upon the surrounding rocks, and so have excavated them to a greater extent, unless, as was probably very often the case, they were protected by a substantial capping of harder rock. Yet this erosion was not so great as the glacial erosion, for the great thickness of decomposed rock all over the country, deep under which lay both the hard rocks and the soft ore-bodies, formed a protective covering. But the ice-sheet, when it swept this covering away, had a discriminating effect upon the rocks below, in the way that has already been indicated. When a body of the soft ore was left with no protection from harder rocks, it was entirely swept away. Where the ore-body was surrounded on several sides by the protective covering, as at the Mountain Iron mine, there resulted, from the greater erosion of the softer parts, a rock-rimmed basin, in which the ore is found. When the protection consisted chiefly of a hard ridge on the north, as is the case at the Biwabik group of mines, perhaps aided by the harder rocks some distance south, but with no very important lateral support, the ice cut at its lower surface a plane slope. At the summit of this slope the weight of the ice was all borne by the hard ridge, but as the distance from it increased the weight must have been partly borne by the harder rocks to the south; or what existed intermingled with the ore-body on either side; or by the ore-body itself. In the shelter of these ridges of Keewatin schist are found many of the larger ore-deposits. So it happens that a gradual slope, preferably southern, especially it it has on either side slight elevations to give it a somewhat basin-like appearance, is considered on the Mesabi an important topographical aid in the discovery of the location of the ore-bodies.

ARTICLES OF COMMERCIAL IMPORTANCE, OTHER THAN IRON,
IN THE IRON-BEARING ROCKS.

Manganese.

Manganese in small amount is disseminated through certain areas of the iron-bearing member. It is closely associated with the iron ore, in many places, especially in the ore-deposits of the Virginia basin. Here is the only place where it has been found in any appreciable amount. Through most of the mines in this basin the manganese ore occurs in the form of the small shining crystals of the peroxide pyrolusite, which are intimately mingled with the granular hematite, and in certain limited areas increase so as to form a large percentage of the mass. Such highly manganiferous masses have been seen by the writer at several of the mines in the immediate vicinity of Virginia, especially at the Rouchleau. On the Moose property, in the southeast of the southeast of section 8, T. 58-17, a pocket of nearly pure ore was found, in the midst of the larger deposit of iron ore. In prospecting this deposit in the summer of 1893, over a hundred tons of ore were taken out; of which analyses, the results of which were kindly supplied me by Mr. Horace V. Winchell, showed 53 or 54 per cent. of metallic manganese, together with a small amount of iron, and some phosphorus, the latter averaging about .07 per cent. Although this is the only place on the Range where manganese in merchantable quantitity has been found, it often occurs incrusting the rock along joint-planes, in dendritic forms of an earthy variety of the oxide.

The method of formation of the manganese deposit at Virginia has already been hinted at, in discussing the fault at this place. The fact that it is situated in the midst of one of the largest iron ore deposits upon the Range, and that this is, so far, the unique location, points to the fact that the origin of the manganese has been dependent upon the same causes as that of the iron. The weakness of the fault line has induced the accumulation of the manganiferous solutions, which were at the same time highly ferruginous, and the oxidation along the fault zone has precipitated the manganese oxide, in the same way as the iron oxide. The constant association of manganese and iron in all horizons is well known, and the causes of their association and their separation have been well summed up by R. A. F. Penrose.* Manganese has a close relation and a chemical

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* Report on Manganese, pp. 569-573. Vol. I, Ark. Geol. Surv. Rep. for 1890.
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resemblance to iron. Both are taken into solution by the same solvents and are precipitated by the same causes. The waters which brought the iron solutions to the Virginia region also contained a small amount of manganese, in the same form; and when both arrived at the oxidized zone, by the release of the carbon dioxide which held them in solution they were precipitated together; the iron as the hydrous sesquioxide, the manganese as hydrated peroxide, or perhaps carbonate or sesquioxide. When the subsequent process of crystallization produced from the original earthy hydrated ore the granular blue hematite, the manganese also became dehydrated, and crystallized as the pyrolusite. Thus was formed the iron ore which is thickly sprinkled with the crystals of the manganese ore; and this is the most common form. In the pocket at the Moose mine, the ore has been obtained in the same way as that which is thinly disseminated; but there has been some modifying circumstance which has induced the precipitation of the manganese for a while separately from the iron. The cause of this separation probably lies in the slight difference of oxidability of iron and manganese. While the iron and the manganese are held in solution and are precipitated by the same agents, yet there has been noted a difference in their ease of precipitation. The oxide of iron is rather more easily precipitated than the oxide of manganese; and the carbonate of manganese appears to be a more stable salt under atmospheric influence than the corresponding iron carbonate. So it happens, as observed by Fresenius,* that freely moving waters, on coming into a region of ready oxidation, deposit first the oxide of iron, and, further on the carbonate or oxide of manganese. By the continuation of this process, separate deposits of iron and of manganese, on the same horizon and running into one another, may be formed. If, on the other hand, the metalliferous waters move very slowly through the oxidized region, the precipitation of the manganese and the iron in each supply of the solutions will be very near together, and the result of many such solutions will be the intimate mixture of the manganese and the iron. This must account for the difference in habit of the sparsely disseminated manganese and that of the ore-pocket. In the greater part of the weak zone which accompanies the fault line, the passage of percolating water is necessarily so slow that the manganese and the iron are precipitated very closely together; while the exceptional occurrence of the pocket demand the ex-

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*Quoted by Penrose, op. cit., p. 570.

ceptional conditions of freely moving water. The depth of the pocket shows that the channel of the waters must have been a fissure, since on both sides are the deposits of iron ore; and from the locality, almost exactly in the centre of the zone through which the fault passes, it may be suspected that this fissure was cn the actual fault-plane.

The dendritic manganese which often lines the joints in the iron-bearing rock, and which is composed of wad or some other of the oxides,* has evidently been brought in the same way by waters which have found in these crevices a passageway.

Source of the Manganese.

From the intimate association with the iron of the manganese at Virginia, and from the evident fact that they were both deposited by the same percolating waters which had taken them into solution; moreover, from the incrusting of manganese in the joint-planes over a large part of the rocks, it is at first natural to believe that both the iron and the manganese were derived from the same source. The iron has been determined to have been in the iron-bearing member from the very beginning, where it originally existed in the form of a silicate, and from this form it has been altered and concentrated into its present form. If the manganese has had the same origin as the iron, we should expect to find it in the same conditions: first, almost invariably, in association with the original silicate of iron; second, in various forms of the rock which result from the metasomatic changes of this first rock; finally, in the completely decomposed and concentrated rock, we should expect to find it almost invariably associated with the iron ore. But the analyses made of the various primary and secondary phases of the iron-bearing rock have not reported any trace of manganese; the only traces found are in rocks which have been profoundly decayed or in other ways exposed to the free action of percolating waters. The amount of manganese in connection with the ore-bodies is variable, for while at Virginia it is common, at other places it is rare, and many deposits contain only the merest trace. So there is no evidence that the original source of the manganese was the same as that of the iron, i. e., in the original condition of the iron-bearing rock. It must be remembered, however, that manganese is much rarer than iron, and that possibly quantities so small as to be over-looked are constantly associated with the less-altered phases

*Op. cit., p. 83.

of the rock, and that these small quantities, by the process
of concentration, might become large enough to be recognized;
but until this is shown to be the case the evidence points
the other way,—that the original source of the manganese was
not necessarily in the iron-bearing member. In this case, it
must be that the waters, which bore the manganese in solution,
and which undoubtedly were slowly filtered through the iron-
bearing rocks, had previously dissolved the manganese in very
small quantity from other strata. The very circumstance of
the small quantity of manganese, in comparison with the
enormous amount of iron, makes it easy to account for the
former on this ground. The source from which such mangan-
iferous solutions must probably have come is the overlying
detrital slaty series, the underlying schists of the Keewatin,
and the intrusive granite. It is extremely probable that the
material of the slates consists almost entirely of the material
from the schists and the granite, laid down in a finely com-
minuted state, without great admixture from other sources,
except in the calcareous portions. So, to go a step further
back, we must look to these older crystalline rocks for the
source of the manganese in the very beginning. In the
crystalline rocks manganese is very common, in the form of
manganiferous silicates. A list of these silicates is quoted
from Penrose.*

"Among the most common of these are: rhodonite; the manganiferous
forms of pyroxene, amphibole and garnet; the manganiferous minerals of
the olivine group, such as tephroite, roepperite, knebelite, danalite and
helvite; the manganiferous epidote known as piedmontite; the minerals
ilvaite, ardennite, trimerite, and numerous others."

Besides the silicates, manganese often occurs in the form of
carbonate, and occasionally as the oxide. Many of these min-
erals are found in the crystalline rocks of the Western Mesabi,
especially in the variable and complex schists of the Keewatin.
When the schists were eroded and laid down as slates, in a de-
posit of great thickness, the finer division of these silicates
made the manganese more liable to decomposition and solution
by percolating waters. When we consider the enormous lapse
of time which has been required for the formation of the iron
deposits, and that the same period must be allowed for the ac-
cumulation of the manganese, it is clear that the solutions de-
rived from the manganiferous silicates of the slates have been
quite sufficient to produce, under favorable conditions, the

*Op. cit., p. 545.

amount of manganese which we find; and that the agency has been simply that which has operated in the concentration of the iron—the percolating drainage waters.

We thus obtain an explanation of the occurrences. At Virginia, the great fault which traverses the present ore-bodies passed at its origination through an unknown but undoubtedly immense thickness of slates. These covered the iron-bearing member, not only to the west, where the slates exist at present, but to the east, forming a covering to the uplifted area. The fault weakened the slates, although probably in less degree than the iron-bearing member; as in the iron-bearing member, there was an increased circulation of surface waters, an increased solution of the former constituents, and an increased deposition of the concentrated products. As the covering of slates upon the Virginia area were slowly eroded, each horizon in turn was bared to the surface and profoundly decomposed; and during all this time the waters which had taken into solution the soluble parts of these decomposed silicates found one of their readiest passages through the fault-fissure. The materials deposited here would be chiefly iron, with some manganese; of these the iron was confounded with the vastly greater amount derived from the iron-bearing member itself; while the manganese remains conspicuous.

SILICA POWDERS.

When the iron-bearing rock has reached in a certain part, by perfect concentration, the condition of a chert, and subsequently disintegrates, there is formed a powder which consists essentially of silica, with a variable amount of impurities. The disintegration appears often to result in part from the dissolution of the carbonates which are very often associated with the cherty silica. These are generally in small bunches of crystals, minutely disseminated; so that their removal destroys the strength of the rock, which then easily crumbles away. The carbonate is generally siderite, and in the process of its dissolution, a small part is precipitated throughout the rock as oxide, between the grains of the silica; this minute amount of the oxide acts as a wedge, which forces the grains apart and thus the comminution become progressively finer. The size of the grains of the silica in the chert is such that when completely separated, the result is a powder of great fineness. An example of this is in the powder described on page 126, speci-

men 230, from near the Mesabi Chief mine, in section 23, T. 57-22. The following is an analysis of this by Mr. Alonzo D. Meeds:

ANALYSIS OF SPECIMEN 230 (CHEMICAL SERIES NO. 242.)

Silica..SiO_2	98.17	per cent.
Sesquioxide of iron......................Fe_2O_3	1.03	" "
Alumina...............................Al_2O_3	0.50	" "
Lime..CaO	tr.	
Magnesia... ....MgO	tr.	
Soda....... ....Na_2O	0.25	per cent.
Potash....................................K_2O	tr.	
Loss on ignition................................	0.19	per cent.
Total.................................	100.14	

This material has a possible economic importance, on account of the abrasive qualities of the powder, should it be found, on further exploration, in sufficient quantity and of as great purity as the sample analyzed. This class of abrading and burnishing powders is already largely used. The most widely known is the tripoli powder, chiefly quarried near Seneca, Missouri, and found in many other places in the same region. This powder is the result of the alteration of a chert, "white, gray, or yellow, occasionally rose or flesh-colored," which is among the most important ore-bearing-rocks in south-western Missouri.* In the nature of its immediate origin, it is thus identical with the Mesabi powder; it also resembles it very closely, being of the same cream color. The almost exact identity of chemical composition is shown by the following analysis of tripoli, taken from the pamphlet of the American Tripoli Company, at Carthage, Missouri.

ANALYSIS OF TRIPOLI.

Silica..SiO_2	98.100	per cent.
Oxide of iron $\{$ ....Fe_2O_3 / ....FeO	0.270	" "
Alumina.......... ....Al_2O_3	0.240	" "
Lime..CaO	0.184	" "
Soda..Na_2O	0.230	" "
Water and loss on ignition....................	1.160	" "
Organic matter	0.008	" "
Total	100.192	

Silica soluble in 10 per cent. solution of caustic soda boiled for three hours.

*Geol. Survey of Missouri. Vol. 1, p. 403.

Another analysis from the same place (at Seneca) is as follows:[*]

Silica.	SiO_2	98 28 per cent.
Alumina	Al_2O_3	0.17 " "
Sesquioxide of iron	Fe_2O_3	0.53 " "
Lime	CaO	Very slight trace.
Magnesia	MgO	Extremely slight trace.
Potash	K_2O	0.17 per cent.
Soda	Na_2O	0.27 " "
Loss on ignition	(H_2O)	0.50 " "
Total		99.92 " "
Water at 110-115° C		0.21 " "

In Arkansas, similar deposits are found at various places, and, as in Missouri, they are the result of the decomposition of a chert. A sample of pure white powder from one of these localities gave the following results: [†]

ANALYSIS OF SILICA POWDER FROM ARKANSAS.

Silica	SiO_2	97.32 per cent.
Alumina	Al_2O_3	1.61 "
Sesquioxide of iron	Fe_2O_3	0.35 "
Lime	CaO	trace
Magnesia	MgO	slight trace
Potash	K_2O	0.13 per cent.
Soda	Na_2O	0.12 "
Loss on Ignition	(H_2O)	.63 "
Total		100.16 per cent.
Water at 110-115° C		0.029 "

Up to the present time, however, the Arkansas deposits have not been extensively worked, partly, perhaps, on account of the lack of transportation facilities.

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[*] Griswold on Novaculites. Ann. Rep. Ark. Geol. Survey for 1890, Vol. III, p. 387.
[†] Griswold, op. cit., p. 388.

CHAPTER XI.

ORIGIN OF THE IRON-BEARING ROCK.

The origin of the iron-bearing rock has long been a subject of doubt, discussion, and speculation, for the original characters are not plainly seen, even in a comparatively careful examination. It will be the object of this chapter to attempt to furnish some evidence as to the probable original nature of the rock and the origin of the iron.

One of the most striking things about the iron-bearing member is its individuality. While it has not been clearly made out heretofore to what this was primarily due, yet it has always been possible to recognize it as totally distinct from the associated rocks. The contact between it and the quartzyte below and the slates above appears to be generally well marked, and neither of these members have any resemblance to the greater part of the iron-bearing member. This same characteristic has been noted by Irving and Van Hise for the corresponding rocks of the Penokee series.[*]

The present material of the iron-bearing member has been found to be the result, almost entirely, of internal metasomatic changes, which have so altered the rock that few traces of its original structure remain. These changes have been effected by the ordinary agents of atmospheric decay, and these have acted upon the other rocks of the series as well as upon the iron-bearing member, but without producing in this latter case any very great effects, or at all obscuring the original structure, in the larger part of the rocks. The original iron-bearing rock, then, must have been of peculiarly unstable nature, strikingly different from the commoner detrital rocks with which it is associated. It was not originally a quartzyte, as has sometimes been supposed, for the main body of the quartzyte is

*Tenth Ann. Rep. U. S. Geol. Survey, p. 380.

quite fresh and unaltered, showing distinctly every original detrital grain. Near the contact of the quartzyte with ore-bodies, there has sometimes been a slight replacement of the silica by iron, and, indeed, specimens might be found which would show every stage of the change from the quartzite to iron ore;* but this change is local and superficial, and is never found within the quartzyte itself. The sharp distinction between the original nature of the quartzyte and that of the iron-bearing member is well shown by those specimens from the iron-bearing member, near the contact with the quartzyte, which contain scattering grains of detrital quartz, such as make up the quartzyte. These grains are usually fresh and little altered, and are sharply contrasted in the sections with the rest of the material, which is all of undoubtedly secondary origin. This secondary material is mainly silica, which is usually finely cryptocrystalline, and in this there is finely disseminated or bunched iron oxide. The change which has altered the original characteristic materials of the iron-bearing member to these secondary products has not affected the truly detrital quartz, which has been present in association with the other materials from the very beginning.

For the same reasons, the rock could not have been originally a simple argillaceous sediment, for the presence of the slates in great thickness above, practically unaltered and distinguished by the most evident of characters from the typical iron-bearing rock, shows that the two could not have been primarily of the same nature. The calcareous layer at the very bottom of the slates is suggestive, and is undoubtedly important for the purposes of our inquiry; but there are insurmountable objections to considering the iron-bearing rock as having been of a simple calcareous nature. One is the distinction which exists between this horizon of impure limestone and the typical rock of the iron-bearing member beneath, both in structure and chemical composition. The limestone retains most of its original structural peculiarities, so that its nature is readily recognized; but the iron-bearing member, near the contact, has the same peculiarities as in the central parts of the horizon. It is marked by the ground mass of finely divided silica, through which are scattered the granules, made up of silica, the various forms of iron, the green chloritic substance, with the secondary products. The analysis shows a difference

*Twentieth Ann. Rep. Geol. and Nat. Hist. Survey of Minnesota, p. 140.

as great. In the iron-bearing member there has never been found by analysis more than a slight trace of lime, although microscopic sections have been made which show a considerable quantity of this carbonate. In these cases, however, the distribution of the calcite shows that it is an impregnation, derived from another source—probably the calcareous layer of the upper slates itself—and that it is not indigenous in the rock. The small amount of calcite which is found in analyses is seen under the microscope to be of a secondary nature, resulting from the disintegration of the original green chloritic substance. It cannot be affirmed that the original rock was not calcareous, but it is certain that the essential characteristic, which has brought on the metasomatic change, was not its calcareous nature. lt is true that the formation of ore-deposits through the replacement of calcite by iron is very common, as has been abundantly proven in many cases;* but on the Mesabi range the features of ferration are totally different from those which are found in these replaced limestones. Had any such replacement on an extensive scale taken place, we should expect to find the layer which is now an impure limestone also replaced, since it overlies the main body. To this objection it, might be well replied that the close grained overlying slates have acted as a protection against the complete changes, and that the ferrating waters need not necessarily have come through the slates, but have entered at the outcrop of the permeable strata, and from there have 'penetrated to the more remote parts. And, indeed, the fact that in parts this layer has been ferrated to a considerable extent, and the lime replaced by iron carbonate, shows that there has actually been some such process, and suggests that the patches of little-altered limestone are accidental residual fragments. But in the main body of the iron-bearing member a still greater obstacle to this view is found. In ore-bodies, which owe their origin to the ferration of limestones, the iron is derived from extraneous sources, and penetrates into the limestone strata by reason of their permeability. In the Mesabi iron-bearing rocks, however, the iron is found to have existed in the rocks from the beginning, so far as can be seen, although. in a disseminated condition; and the ore-bodies have formed by concentration of this scattered iron. In the concentration, moreover, there has been a replacement of certain parts of the rock by iron; but in

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*Kentucky Geol. Survey. Report of Progress, Vol. III, New Series; by N. S. Shaler; 1877, p. 164.

this case it is silica that has been replaced, and this silica itself is a secondary product. We can find no analogue of this process in the proven cases of the formation of ore-deposits by the replacement of limestone.

The theory of the formation of the ore-deposits by the replacement of a limestone was that first adopted by Prof. R. D. Irving,* but he afterwards abandoned it, considering that the original rock must have been an iron carbonate and not carbonate of lime. Prof. N. H. Winchell† also suggested a theory similar to this as the possible origin of some of the Minnesota ores. This theory, however, did not ascribe all of the phenomena to the process of replacement, but considered that the banding was original in the rock, and that the difference between the bands was due to the original distribution of impurities in varying quantities in the alternating layers.

Since we cannot, then, ascribe the origin of this rock, in the light of our present knowledge, to any of the ordinary forms of the commoner sedimentary rocks, we are driven, if we still hold the rock to be sedimentary, to the more unusual forms of sediments, namely, those of chemical or organic origin.‡

The various theories of chemical origin have been more earnestly urged and have met with a more general favor than any other. Careful observation has in nearly every case led to this belief; for both the field characters and the microscopic peculiarities of these rocks are such as are not compatible with any theory of direct sedimentation, but point to an immediate chemical source. One of the most evident of these characters is the ordinary finely cryptocrystalline or chalcedonic condition of the silica, which cannot represent directly clastic material.

The principal theories of chemical origin of the iron-bearing rocks, including the ores themselves, may be separated into two chief divisions. First, those which assume the ores and the iron-bearing rock to have been precipitated in practically their present condition, and to have undergone little change since that time. This view has been chiefly championed by N. H. and H. V. Winchell, and was originally applied to the ores of the Vermilion in Minnesota,§ but was afterwards ex-

*Origin of the Ferruginous Schists and Iron Ores of the Lake Superior Region. Am. Jour. Sci. (III). Vol. XXXII. Oct., 1886.

†Fifteenth Ann. Rep. Geol. and Nat. Hist. Survey of Minnesota, p. 246.

‡Tenth Ann. Rep. U. S. Geol. Survey, p. 380.

§On a Possible Chemical Origin of the Iron Ores of the Keewatin in Minnesota, American Geologist, Vol. 4. pp. 291-300, November. 1889. Also in Bulletin No. 6 of the Minn. Geol. Surv., 1891, pp. 391-399.

tended to the Mesabi ores.* Briefly stated, this theory explained the origin of the banded silica and iron by direct precipitation from the waters of a hot primordial ocean, highly saturated with the minerals of the crust with which they came in contact. Alternating conditions produced from these waters alternating precipitations of iron and of silica. These alternations continued throughout the whole time of the formation of the iron-bearing rock, and the banding thus represents the original stratification. Inasmuch as the present discussion is confined to the Mesabi ores, the possibility of such an origin for the Vermilion ores will not be fully discussed. The writer, however, following the expressed opinion of nearly all the Lake Superior geologists,‡ and for many private reasons, which do not need to be detailed in this paper, believes that the iron-bearing rocks of the Mesabi and of the Vermilion have originated in the same manner, and that whatever restricts the theories of origin on the Mesabi, must be applied to the Vermilion also.

The principal reasons for holding this view of direct precipitation have been:

1. The regularly alternating bands of the "jaspilyte" of the Vermilion, which has been taken a priori to be original stratification, and hence must be explained by the alternating deposition of iron and silica from the waters of the ocean. Since this iron and silica was found to be in a condition which was almost surely the result of direct chemical precipitation, and could in no way be assigned to the sedimentation of detrital material, it naturally followed that the oceanic waters had been the agents of this precipitation. But for this purpose it was

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* Iron Ores of Minnesota, Bull. No. 6, Geol. Surv. of Minn., p. 144.

‡ N. H. and H. V. Winchell, p. 144, v. s. " We see no reason to exempt the Taconic ores from those methods and principles that we have found obtained in Keewatin time. We see, on the other hand, only evidence to convince us that the Taconic ores date from the origin of the rocks themselves, and that the conditions that governed the origin of the rocks were but a modification of those that governed the accumulation of the Keewatin rocks."

C. R. Van Hise, Iron Ores of the Marquette District of Michigan, Am. Jour. Sci., Vol. XLIII, February, 1892, p. 130.

"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."

then necessary to imagine that the condition of oceanic waters was entirely different at the time of the formation of the ores from the condition at present,—that they were still intensely heated, and highly charged with acids, and the minerals which these materials held in solution.*

2. A section of the siliceous part of a typical Vermilion "jaspilyte" contained the silica in a form which was held to indicate that the silica was precipitated in the amorphous form, in the shape of spherical minute globules, to the compression of which the occasional hexagonal outlines of the present grains was thought to be due.† In the section examined the silica was held to be amorphous, and not crystalline, (1) by the highly colored concentric rings which each grain showed in in polarized light, and (2) by the absence of fluid or gaseous inclusions.

To the first reason the answer is of course that the *a priori* assumption that the bands were original sedimentary layers is not warranted. Upon the Mesabi the whole process of the growth of these bands by the process of concentration along parallel lines of weakness has been carefully observed; the final result of this concentration has been to produce in certain phases alternations quite as fine as those of the Vermilion rock, and it is highly probable that both were formed in the same way. In the original condition of the rock upon the Mesabi, these bands do not exist, and they are well developed only in the more advanced stages of change. Upon the Vermilion the changes have gone on more completely, and under slightly different conditions.

Upon the Mesabi, again, the condition of the strata associated with the iron-bearing member are such as to forbid the assumption of the heated and turbulent primordial ocean, which is necessary for the direct precipitation of both iron and silica. Before the deposition of the iron-bearing rocks, the sediments were of sand,—just such sand as is deposited at the present day. The sharply outlined rounded form of the original grains shows that there was no appreciable corrosion by oceanic waters before deposition; while if the waters had been in the condition supposed by the theory under discussion, these grains must have been entirely dissolved. If the silica of the iron-bearing rocks‡ is still considered to represent a sudden change

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* Iron Ores of Minnesota, p. 75.
† Iron Ores of Minnesota, p. 74.
‡ H. V. Winchell. The Mesabi Iron Range. Twentieth Ann. Rep. Minn. Survey, p. 138.

from the conditions of deposition of the originals and grains of the quartzyte; and that under these changed conditions, the waters were capable of dissolving silica and precipitating it in the finely divided cryptocrystalline or chalcedonic form in which it is usually found, there is another obstacle in those parts of the iron-bearing rock, near the contact with the quartzyte, which contain in the ground-mass of finely divided silica scattered grains of detrital crystalline material, exactly like those found in the quartzyte beneath; with their outlines regular and uncorroded, and exhibiting no sign of any transition to the finer variety. It thus seems clear, if the iron-bearing rock is considered truly sedimentary, that the conditions of temperature and solvent power of the water were nearly the same during its formation as during the deposition of the basal quartzyte; and these conditions were not evidently greatly different from those of the present day. The rocks above the iron-bearing member show the same conditions of ordinary sedimentation, and the existence of the impure limestone belt, immediately above, is especially opposed to any extraordinary conditions.

The condition of the silica, which was the second chief reason urged in favor of its chemical precipitation, has been subsequently shown to have been misunderstood. Exceptions to the observations of Dr. Hensoldt, who made the original investigation, have been taken by Professor C. R. Van Hise,[*] and subsequently and independently, by Dr. U. S. Grant of the Minnesota survey. Of the two reasons that were given for considering the silica as amorphous instead of crystalline, the first, the polarization phenomena, was found to be due to the thickness of the sections examined by Dr. Hensoldt. Thinner slides showed the ordinary polarization phenomena of quartz. In regard to the second reason, it was found that the quartz actually contained numerous liquid inclusions.

Nearly all of the silica of those phases of the iron-bearing rock which have gone far in the process of change is made up of these interlocking quartz grains. In less advanced stages the silica grains are much smaller in size and less highly crystalline, the crystallizing motive often having worked so little that it is hardly distinguishable from truly amorphous silica; but the larger grains which make up the "jasper" are never of this variety. Since these larger grains are, then, not original, but

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[*]Ann. Rep. Arkansas Geol. Survey, 1890, vol, III., p. 184.

are formed during crystallization by the union of many smaller particles, neither their size nor their shape can be taken as any indication of the conditions of their original deposition.

The second class of theories of chemical precipitation asserts that since the precipitation of the iron and silica, there have been great metasomatic changes, which have brought the rocks to their present condition and have induced the formation of the ore-bodies. This is the view which has been adopted by Irving and Van Hise, in their monograph on the Penokee-Gogebic iron range, and extended to the Animikie series in Minnesota.* Their opinion of the origin of the chief constituents of the iron-bearing rock, the iron and the silica, may be best learned by quotations. Concerning the original form of the iron (which has subsequently concentrated into the present deposits), the following is a concise statement:†

"Whether the iron was originally precipitated as a carbonate, or was decomposed and precipitated as a hydrated sesquioxide, just as limonite now forms from iron carbonate in places where bog ore is depositing, is uncertain. If the latter is taken to be the case, and it is perhaps the more probable supposition—it is necessary to believe that the organic matter with which the limonite was associated reduced the latter to the protoxide, and by decomposition furnished the carbon dioxide to unite with the protoxide, and thus reproduce iron carbonate."

Concerning the origin of the silica, the discussion is summed up as follows:‡

"Our conclusion is then: First, that the chert was mainly deposited simultaneously with the iron carbonate with which it so closely associated; and second, that it is probable that the chert is of organic origin, although we have no positive proof that it is not an original chemical sediment, while it may in part be from both sources."

The conditions which are supposed to have prevailed in the time of the precipitation of these materials, while somewhat different from those of the present day, do not involve so great a departure from the uniformitarian belief as do the theories of direct precipitation in the present form. It is supposed that the atmosphere was more highly charged with carbon dioxide than at present, and that the general temperature of the earth's crust was somewhat higher. Under these conditions atmospheric waters, by virtue of the greater amount of carbonic acid, would decompose the rocks far more actively than at present,

*Tenth Ann. Rep. U. S. Geol. Survey. The Penokee Iron Bearing Series, by R. D. Irving and C. R. Van Hise.
†Ibid., p, 396.
‡Ibid., p. 397.

and these waters, escaping into the sea, would cause the ocean to become charged with the irony solutions. It is, however, added, that although these conditions were probably present, yet the deposition of the original iron may be accounted for by the same process as carried on under ordinary conditions at the present day, and which leads to the formation of bog ores. At any rate, it is supposed that the waters of the ocean were in a condition which permitted the existence of abundant organic life.*

From these homogeneous original rocks, which, so far as can be seen, were originally of iron-carbonate and silica, metasomatic changes have produced all the multitudinous phases of the iron-bearing rocks, including the ore-bodies.

Since so far we have discussed the various possibilities on general grounds only, reserving the specific study which points to the probable origin for the final discussion, we will here mention only the general objections to this explanation. These objections have already been pointed out by other investigators to the theory of a direct precipitation in oceanic waters. We have at the present time no instance of a precipitation of this exact kind. The precipitation of iron oxide from waters bearing iron carbonate in solution is one of the most common processes in nature, and has produced a not inconsiderable supply of ore, locally; but the conditions under which such ores are precipitated are not such as obtain in the oceanic waters, and it is difficult to understand how such a precipitation could come about. When chalybeate waters emerge from the rocks or the soil from which they have obtained their iron, they are soon exposed to the oxygenating influences of the atmosphere, their carbon dioxide escapes, and the iron which the waters held in solution by virtue of this is precipitated as the hydrated sesquioxide. If the water has thus found its way into a running brook, the surface of the pebbles of the brook for some distance become coated with the oxide. The motion of the water quickly precipitates, by bringing successively all parts of the water under the oxidizing influence, all the iron that is unstable under these conditions. If the waters ooze into a shallow swamp or bog, the oxidation is somewhat slower, but since the iron-bearing waters remain in the same position till the process is completed, the amount of iron eventually concentrated is much greater, and the continuation of the process brings about a workable deposit of ore. But nearly all the iron which is

*Ibid., p. 395.

thus brought by waters to the surface is very quickly precipitated in these ways, and very little of it can ever find its way into the sea. It may be even possible that stagnant lakes, or land-locked lagoons, might form upon their beds a precipitate in this way, but we cannot easily conceive of its taking place in the ocean. What iron reaches the main body of the ocean is quickly diluted by the great mass of water, so that the amount of iron in the ocean at the present time is very small, and would have to be increased enormously for any precipitation to take place; and this increase would seem to necessitate conditions entirely unlike the present, or even those which are supposed by the advocates of this explanation to have existed. It is difficult to understand how strata which are known to extend somewhat uniformly for a hundred miles, and are nearly a thousand feet thick, can have been wholly or in part formed by any such precipitation. The extent and uniformity of the strata, as well as their thickness, do not accord with the idea of land-locked lagoons; and yet this seems the only possible explanation. Above and below the iron-bearing member are strata in which there is neither iron nor cryptocrystalline, chalcedonic, or amorphous silica, and yet they were formed, according to this theory, in the same oceanic waters.

If it is supposed that the quartzyte was first deposited in the open sea; that at the close of the deposition an elevation changed this region to coastal swamps, in which the rocks of the iron-bearing member accumulated; and that at the close of this period a subsidence brought on the formation of the simple detrital series again: this explanation may be held to explain the origin of the iron, but the silica can hardly be thus accounted for. J. W. Judd,* in discussing this question in connection with the theories of the origin of the Northamptonshire iron ores, shows that iron is thus found in chalybeate springs and in still bodies of water; but not in running streams or other moving water, because here the access of oxygen precipitates the iron as hydrated peroxide.

* * * "I do not believe, therefore, that the waters of any great river, or of the sea, can ever contain more than the minutest trace of iron in solution." * * * * But the Northamptonshire iron ore contains "from 30 to 50 per cent. of the metal; a rock which we cannot possibly conceive of as being deposited in an open sea or river."

We thus find ourselves obliged to lay aside the theories of chemical precipitation of the iron in the form of oxide or car-

* The Geology of Rutland, etc., p. 130.

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bonate. Besides the explanation which we shall present, there is only one other theory of the origin of the ores which has received firm support. This is the theory of their eruptive origin. That the iron-bearing rocks of the Lake Superior region were erupted in practically their present condition was early held by Professor J. D. Whitney,[*] and Foster and Whitney.[†] Afterwards the view was adopted by Dr. M. E. Wadsworth for the Marquette District.[‡] Dr. Wadsworth believed that the alternating bands of silica and iron were the result of the flowage of the original molten rock (subsequently greatly modified by the chemical action of the percolating waters), and analogous to the flowage banding of rhyolites and trachytes, among acknowledged lavas.[§] For this species of volcanic rock, having a higer content of silica than the rhyolites, he proposed the name of "jaspilite."[‖]

The objections to the directly eruptive origin of the Mesabi iron-bearing rock are numerous and rest in part upon the same grounds that show the directly chemical origin to be probably not the true explanation,—the circumstance that the banding is not primary, but secondary, and so can no more be regarded as the fluidal structure of a lava than as the layers of an original chemically precipitated rock.

Having thus briefly spoken of the most prominent theories which have been introduced to explain the origin of the ores, and named the objections to which, on general grounds, they are severally open, we will proceed to discuss the results to which our investigations have led us, and to offer an explanation, which does not come under any of the theories discussed or any of the objections named.

It became evident to the writer while engaged in field work that all of the multitudinous kinds of rock which were associated with the iron deposits passed into one another by gradual changes, and were probably derived from a single original type by the alteration of atmospheric influences. The recognition of this fact is considered to be the most important part of the present discussion, since it effectually does away with all at-

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[*] Metallic Wealth of the United States, 1854, pp. 37, 429-437, 477, 478.

[†] Senate Documents, Spec. Sess. 32nd Congress, III, 1851.

[‡] Bulletin of the Museum of Comparative Zoology at Cambridge, 1880, Vol. VII, (Geological series, Vol. I.) First paper, Proc. Boston Soc. Nat. Hist., 1880, XX, 470-479.

[§] Further studies and evidence caused Wadsworth to abandon his former ideas and to hold that most, if not all, of these iron rocks were of mechanical origin, but that they had subsequently been modified greatly by chemical agencies. (See Report of the State Board of the Geological Survey, Michigan, 1893, pp. 104-121).

[‖] Bull. Mus. Comp. Zool., Vol. VII, p. 76.

tempts to explain the formation of the rocks in their present condition, which must necessarily lead to the greatest confusion. At the time of the discovery of the fact of the derivation of the rocks from a single original type, the writer's acquaintance with the literature of the region was incomplete; and it was not until some time after this that he had opportunity to read the monograph on the Penokee-Gogebic iron range, by Irving and Van Hise;* in which for the first time he found that the same proposition had already been conceived and established for the iron ranges of the South Shore, and had been extended to the Animikie series in Minnesota. That the fundamental principle in the monograph referred to and in the present paper should be the same and should have been arrived at independently in each case, is significant as to the correctness of the conclusions.

In the course of our comparative study of the rocks of the Mesabi, however, it has been possible to go somewhat further back in the history of the iron-bearing member than has been done for the Penokee-Gogebic region. The iron carbonate, which, according to the researches of Irving and Van Hise, was the oldest type which could be found, and therefore was held to represent nearly the condition of the original rock, has been found on the Mesabi to be in nearly all cases of undoubtedly secondary origin, and to have been formed by the carbonatization of iron oxides. It was found, moreover, that all of the constituents of the rocks, including the iron carbonate and oxides, and the silica, could be shown to have been derived from a substance which appeared to be original, and which in the description has been designated as "greenish chloritic substance," or "original green silicate."

This substance was thickly scattered in bunches through the less altered rock, but from the very beginning began to undergo rapid disintegration. The chief products of this decomposition were silica, in the cryptocrystalline to nearly amorphous form, and the oxide of iron; there were also various secondary products resulting directly from the change, or from the combination of the separated products. These were calcite and siderite in small quantities, actinolite, epidote, residual clayey matter, and the like. The details of these changes have already been gone into, as have been the various stages which mark the striving towards stability of the loosely arranged products of

*Tenth Ann. Rep. U. S. Geol. Survey.

the decomposition, so that they need not be repeated here; and it only remains to inquire more minutely into the nature of the green material, and to discover, if possible, its origin.

In the macroscopic and microscopic features of the great mass of the iron-bearing rock there is no evidence of its original nature. All the constituents are evidently of secondary origin, and suggest no more a detrital than an igneous rock. Irving and Van Hise have noted the same characteristic for the rocks of the Penokee-Gogebic iron-bearing member.* The result of the studies of the Mesabi rocks led at first to the assumption that the original rock, of which the structure was thus almost totally obliterated, and which was represented only by the "greenish chloritic substance," might be either an excessively basic lava, or some peculiar kind of sediment, outside of those which have been discussed. It was evident that the original rock had been one of excessive instability under atmospheric influences, and, therefore, was formed under somewhat extraordinary conditions. The idea of a lava therefore became to be seriously considered as the solution to the problem. It is generally acknowledged that portions of the inner crusts are more highly basic than any identified volcanic rocks; and it is regarded as highly probable † that the interior of the earth may be formed almost exclusively of the simple metals, especially iron. A lava, then, originating in the deeper regions, might be so composed that while it would be quite stable under the freedom from atmospheric influences in which it had its beginning it would be extraordinarily unstable under conditions of freer oxidation. It might be basic from an excess of iron, and this iron might be originally in the protoxide form, combined with silica to form proto-silicates. From this uncrystallized, undifferentiated mass, which the original "greenish chloritic substance" might represent, there would be formed by decomposition exactly the same materials which we have—the separation of the silica and the iron oxides, and the removal of the more soluble decomposition products. Neither the thickness of the iron-bearing member nor the extent of the formation could be urged as objections to this hypothesis, for even in historic lavas such quantities of erupted material may easily be paralleled, without appealing to the unusual conditions which may well have existed at this early period of the earth's history.

*Tenth Ann. Rep., supr. cit., p. 380.

†De Launay: Formation des Gîtes Métallifères.—Paris, 1893. Posepny: The Genesis of Ore-Deposits, p.

The other possibility was that there might be formed, in the depth of the ocean, a class of sediments distinct from those which had yet been proposed; that detritus of certain compositions might, by uniting, undergo chemical changes under certain conditions, and produce a compound which might be stable in the ocean depths, but unstable when the region was elevated, and brought within the domain of freer oxidation. This compound, again, might be represented by the greenish chloritic substance, and the results of its decomposition, again, would be exactly those which we find.

It has been already stated that at the lower edge of the iron-bearing member there are intermingled with the non-fragmental material grains of truly detrital quartz, like that of the underlying quartzyte. But since these grains did not evidently lie in any well-defined zones, they were regarded as equally applicable to either theory. On the eruptive hypothesis, a lava, at its lower contact, might take up into its mass some of the sand from the sand-beds over which it flowed. These grains would work up for a short distance from the contact, and in the viscous state in which this outer edge of the cooling mass would be, the heat would be insufficient to melt, or even greatly corrode them. On the sedimentary hypothesis, on the other hand, the scatttered grains, diminishing as the distance from the basal quartzyte increased, would be held to indicate the progress of the change of conditions from those necessary for the formation of a quartzyte to those which governed the new sediment. This change was then probably in the form of a subsidence of the ocean floor, and the sand-grains indicate the last contributions of sediment from the shore-region, where the deposition of sand still went on.

But these possibilities were again limited by the discovery, near the *upper* contact of the iron-bearing member, of scattered material which was almost certainly of a detrital nature, surrounded as before, by non-fragmental secondary material. In many cases this was suspected, but in one the evidence seemed quite satisfactory. This was in the specimen called 53-1, which was from the iron-bearing rock at the immediate contact with upper slates, which are represented by 53-2. From 53-1 seven sections were made, of which one has already been described. (See page 68). The rock was less altered than any other specimen found in the whole iron-bearing member, probably on account of the protective capping of the slates to which it lay so closely. It seems clear from an examination of this that the

rock was of a detrital nature, for the forms which are scattered through the rock have rounded shapes and positions which are those of detrital grains. Naturally, these grains are not of quartz, like those at the lower contact, but suggest the approach of the conditions which produced, first, the bed of impure limestone, and then the argillaceous sediments into which this graded. The grains of detrital form are of two kinds.—First, those of a crystalline carbonate, which may be calcite, but from the analysis of 53-2 (see p. 70), is probably in part at least magnesite. In some of the sections these grains have been found to increase in numbers locally to such an extent that they formed a solid layer, very thin, but continuous, which in this case was exactly like the dolomitized limestone above, but was limited above and below by the characteristic secondary silica of the iron-bearing rock. There can be no doubt that this is detrital material, originally lime, which subsequently to its deposition has become dolomitized and crystallized.

The second class of detrital grains in these sections are those which are composed principally of the "greenish chloritic substance" which is found all through the least altered parts of the iron-bearing member, in whatever horizon. Some of these are somewhat shattered and torn, but many show rounded and uncorroded outlines which appear to be those of detrital grains. In many cases where the silicification of the original green material has been begun and even carried on to a large extent, there are still preserved the outlines of an original rounded body, which seems to have been made up almost wholly of the original green substance.

The discovery of such detrital material is not explicable by a consideration of the original rock as a lava, and hence we are driven to accept the other possibility,—that the rock was a sediment, formed under the conditions which have been hinted at.

With an especial view to the ascertaining the nature of this original mineral, as well as advice upon other points, selected sections, all of which have been described at some length, were sent to Dr. J. E. Wolff of Harvard University, who kindly examined them and returned the following comments:

"*Section 78.* Composed essentially of aggregate silica. The rounded grains have typical rolled clastic outlines; are filled with fine aggregate silica and dotted with black ore. Cement is pure chalcedonic silica, with occasional rhombs of carbonate and octahedra of magnetite, both of which, from their perfect crystal form, must have formed in place and contemporaneously

with the silica. Other carbonate areas, irregular, are within the grains; and the magnetite or iron ore dots within the same are residual.

"*125.* Cement much coarser grained silica than in 78— quartz, probably—sometimes arranged around fragments in brickwork structure, showing secondary deposition around these bodies. The round grains are here a brownish-green to clear green color, partly isotropic, partly aggregate polarizing, in feebly-polarizing dots and specks Hardly any pleochroism; no cleavage. They resemble in all physical characters *glauconite* grains. In some cases a little carbonate is mixed with the probable glauconite.

"*215.* Rather indistinct clumps of limonite or hematite, with the same siliceous ground-mass. Outline of clumps too vague to identify directly with the round grains of 125, without transitional forms.

"*213.* Same as 215. The rounded outline of some clumps shows that they are those of 125. Carbonate seems secondary in these clumps.

"*27-A.* Here the round clastic bodies are distinct, some hematite, some magnetite. Silica very fine-grained; banded parts of slide seem due partly to crushing of round grains. Carbonate is secondary and not primary, because some of the rhombs are half in, half out,.of the clastic grains.

"*14.* In light-colored part are the remains of green areas passing into tufts of actinolite (?), which, with aggregate quartz, forms the ground-mass.

"I only suggest here an outline of what appears to me to be the explanation of these slides:

"1st. The round grains in these slides owe their round form to attrition (although the resemblance to the form of oölitic grains should be noted.)

"2d. The green glauconite (?) is the earliest stage in these slides.

"3rd. Silicification, which is complete in the groundmass, in attacking these grains was accompanied by the breaking up of the glauconite into iron oxides.

"4th. The completed stage, as far as these slides go, is complete silicification of everything, the iron oxide either remaining in the clumps or more or less scattered about.

"5th. The original rock, a little back of slide 125, was a glauconitic greensand."

ANALYSES OF THE ORIGINAL MATERIAL.

That the material was essentially a hydrous silicate of iron, the analyses had already shown. Those rocks which contained a large amount of the original green mineral showed stead-fastly a small amount of alumina, a very small amount of the alkalies, and a large amount of iron oxide, and this oxide appeared to be normally the protoxide. The analyses of numbers 14 (page 103), and 217 (page 87), especially show these characteristics. To determine more exactly the chemical composition of the mineral, rock 125 was selected, which was almost entirely made up of silica and the green mineral, with a good deal of siderite and some magnetite, but free from other impurities. From the powdered rock the magnetite was drawn out with a magnet, and the remainder of the rock, consisting only of silica, siderite, and the green material, submitted for analysis to Mr. A. D. Meeds, who made the following report:

REPORT OF ANALYSIS OF SPECIMEN 125 (CHEMICAL SERIES NO. 247).

Insoluble in hydrochloric acid....................	75.09 per cent.	
Soluble in hydrochloric acid.....................	24.91 " "	
Total.....................................	100.00 " "	

The insoluble portion was made up of:

Silica.................................SiO_2	74.53 per cent.	
Sesquioxide of iron......................Fe_2O_3	0.34 " "	
Alumina............................ ...Al_2O_3	0.23 " "	
Total	75.09 " "	

The result of the combined analyses of the soluble and the insoluble portions was as follows:

Silica.......................................SiO_2	74.53 per cent.	
Alumina..................................Al_2O_3	1.57 " "	
Sesquioxide of iron.......................Fe_2O_3	2.30 " "	
Protoxide of iron..........................FeO	14.84 " "	
Lime..CaO	.63 " "	
Magnesia..................................MgO	.92 " "	
Water.......................................H_2O	.62 " "	
Carbon dioxide..............................CO_2	5.10 " "	
Soda ....Na_2O	0.11 " "	
Potash ....K_2O	0.10 " "	
Total	100.72	

The soluble portion alone, which represented the bases of the siderite and of the green mineral, had these proportions, expressed in percentages of the entire rock:

Alumina	Al_2O	13.35	per cent.	
Sesquioxide of iron	Fe_2O_3	1.96	"	"
Protoxide of iron	FeO	14.84	"	"
Lime	CaO	0.63	"	"
Magnesia	MgO	0.92	"	"
Water	H_2O	0.62	"	"
Soda	Na_2O	0.11	"	"
Potash	K_2O	0.10	"	"
Carbon dioxide	CO_2	5.10	"	"
Total		25.63		

Since the carbonic acid must all belong to the siderite, it was then removed from the calculation, together with the necessary amount of ferrous oxide to satisfy the composition of siderite (8.35 per cent. of FeO), and the remainder, signifying the proportions of the bases in the green mineral alone, was as follows:

Alumina	Al_2O_3	1.35	per cent.	
Sesquioxide of iron	Fe_2O_3	1.96	"	"
Protoxide of iron	FeO	6.49	"	"
Lime	CaO	0.63	"	"
Magnesia	MgO	0.92	"	"
Water	H_2O	0.62	"	"
Soda	Na_2O	0.11	"	"
Potash	K_2O	0.10	"	"
Total		12.18		

We thus obtain the exact proportion of the respective bases of the green mineral; but do not find the percentage of silica which belongs to it, since upon solution the silicate is broken up, and the silica is precipitated and cannot be separated from the original free silica of the rock. But if we assume that the mineral is a variety of glauconite, as appears from its association and optical characters, we may provisionally assign it a proportion of fifty per cent. of silica, that being about the average content of silica of this mineral, according to Dana. If, then, we figure the proportions of the other constituents as given above, to the scale of one hundred, we have the following composition of the green mineral:

Silica	SiO_2	50.00	per cent.	
Alumina	Al_2O_3	5.54	"	"
Sesquioxide of iron	Fe_2O_3	8.05	"	"
Protoxide of iron	FeO	26.56	"	"
Lime	CaO	2.59	"	"
Magnesia	MgO	3.78	"	"
Soda	Na_2O	0.45	"	"
Potash	K_2O	0.41	"	"
Water	H_2O	2.54	"	"
Total		99.92		

From the same rock another portion was treated in a different way. The rock was pulverized as before, and carefully sifted and sorted into grains of nearly uniform size. As before, the magnetite was drawn out with a magnet, leaving only the silica, the siderite, and the green mineral. The different parts of this powder were then separated according to their specific gravity, by the Thoulet solution. The powder was first put into the solution having a specific gravity of 2.95. At this density about one-third of the powder was precipitated. The portion which was not thus precipitated was then put into a solution having a density of 2.80, and at this about one third of the remaining portion came down. What still floated was then put into a solution having a specific gravity of 2.50, and in this all the remainder was quickly precipitated, leaving a clear liquid.

From this it appeared evident that the specific gravity of the green material was greater than that of the silica, probably greater than 2.80; and that the silica was therefore the lightest mineral in the section. The last portion, whose specific gravity was between 2.5 and 2.8, and which was mostly silica, was therefore thrown away; and the first two portions, whose specific gravity was over 2.8, were mingled and submitted to Mr. A. D. Meeds for analysis. This portion then consisted essentially of siderite and the green silicate, although the silica and the other minerals were so closely intermingled in the rock, owing chiefly to the fact that the silica is derived from the silicification of the green mineral, that a separation of absolute correctness could not be expected. The result of the analysis was as follows:

ANALYSIS OF GLAUCONITE AND SIDERITE FROM SPECIMEN 125 (CHEMICAL SERIES NO. 248.)

Silica	SiO_2	47.12	per cent.
Alumina	Al_2O_3	2.60	" "
Sesquioxide of iron	Fe_2O_3	3.51	" "
Protoxide of iron	FeO	28.48	" "
Lime	CaO	.61	" "
Magnesia	MgO	1.94	" "
Potash	K_2O	.11	" "
Soda	Na_2O	trace	
Water	H_2O	2.70	" "
Carbon dioxide	CO_2	13.49	" "
Total		100.56	

The carbon dioxide in this analysis, which belongs to the siderite, combines with 22.07 per cent. of ferrous oxide in order

to make the exact composition of this mineral, making 35.56 per cent. of ferrous carbonate (siderite, $FeCO_3$.) and leaving 6.41 per cent. of the ferrous oxide for the glauconite.

At the withdrawal of the siderite, there remains 65 per cent. of the rock, which is composed principally of glauconite, although with a considerable impurity of free silica, which was minutely interwoven with the siderite and glauconite, and was thus brought down at a specific gravity greater than that of silica alone. By computing the elements of this residue to a scale of 100, we get the following results:

COMPOSITION OF GLAUCONITE (WITH SOME FREE SILICA.)

Silica...........................SiO_2	72.50 per cent.
Alumina.................................Al_2O_3	4.00 " "
Sesquioxide of iron.......................Fe_2O_3	5.40 " "
Protoxide of iron...........................FeO	9.86 " "
Lime.....................................CaO	.94 " "
Magnesia..............................MgO	3.00 " "
Potash.................................K_2O	.17 " "
Soda...................................Na_2O	trace
Water...................................H_2O	4.15 " "
Total...............................	100.02

It is probable that in this case the impurity of free silica is sufficiently important to bring down the percentage of combined silica in the glauconite to about fifty per cent. of the mineral; and then the percentages of the other components would be correspondingly greater than here appears. For this reason, it is probable that the computed composition on an assumed percentage of 50 per cent. silica, in the previous analysis, is more nearly the actual condition of the mineral.

We are thus able to draw our conclusions as to the nature of the mineral. Chemically, it is essentially a hydrous protosilicate of iron, with a small amount of alumina, variable small amounts of calcium and magnesium, and trifling quantities of the alkalies. Chemically, it seems more closely related to glauconite than to any other mineral, and differs chiefly in the absence of the usual larger amount of potash. Another way in which it differs from the ordinary glauconite is that the iron here is normally in the protoxide state, while in nearly all the reported analyses of glauconite it is mainly in the sesquioxide condition. The nearest approach in composition of any analyzed glauconite which we can find is that from French Creek, Pa., given by Dana.*

*Descriptive Mineralogy, 6th Ed,, 1892, p. 684.

The analysis of this is as follows:

Silica...................................SiO_2	52.86 per cent.	
Alumina..................................Al_2O_3	7.08	" "
Sesquioxide of iron......................Fe_2O_3	7.20	" "
Protoxide of iron ..:....................FeO	19.48	" "
Magnesia.................................MgO	2.90	" "
Lime ....CaO	trace	
Potash...................................K_2O	2.23	" "
Soda....... ....Na_2O	trace	
Water....................................H_2O	8.43	" "
Total............................	100.18 per cent.	

As an example of the chemical composition of the commoner varieties of glauconite, that from the Grodno Valley, Russia,* may be taken.

Silica.. ....SiO_2	49.76 per cent.	
Alumina.................................Al_2O_3	8.18	" "
Sesquioxide of iron.....................Fe_2O_3	16.80	" "
Protoxide of iron.......................FeO	3.77	" "
Magnesia................................MgO	3.97	" "
Lime....................................CaO	0.41	" "
Potash..................................K_2O	7.57	" "
Soda....................................Na_2O	0.52	" "
Water...................................H_2O	9.82	" "
Total............................	100.00 per cent.	

It is seen that the specimen from French Creek represents a departure from the ordinary composition, in the predominance of the protoxide of iron and the diminution of the amount of potassium; and the accentuation of these deviations characterizes the mineral which we have under consideration.

The specific gravity of glauconite is given by Dana† as from 2.29 to 2.35; while we have found that of our mineral as probably higher than 2.8. But the glauconite of the St. Lawrence limestone (Cambrian) of Minnesota, analyzed by Professor S. F. Peckham,‡ has, according to him, a specific gravity of 3.634; and from the chemical composition of the mineral it must be that in many cases the density rises above 3.

Optically, the mineral has been found by Professor Wolff to have all the characters of glauconite.

Its habit, so far as can be made out, is also that of glauconite, in that it occurs in disseminated grains through a sedimentary bed, and that these grains appear to have had originally rounded outlines, due to attrition.

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*Ibid., loc. cit.
†Ibidem.
‡The Geology of Minnesota, Vol. 1I, p. 120.

We must conclude, therefore, that the mineral is probably a variety of glauconite. The characters by which it differs from the ordinary mineral may be explained in two ways. In regard to the small amount of potash, it may either be believed that this substance was absent from the original composition of the mineral, or that it has subsequently been removed by solution. But since its absence is accompanied by the presence of iron in the ferrous condition, we find it difficult to believe the latter supposition; for the same agents which would remove the alkalies would probably effect the oxidation of the iron. In regard to the excess of protoxide, again, it may be believed either that the iron of glauconite is normally a protosilicate, and that the analyses which show an excess of the sesquioxide are from more or less oxidized specimens; or, as seems more probable, there may have been an original difference. The reasons for this difference will form the grounds for future study.

THE ORIGIN OF GLAUCONITE.

The existence of the mineral glauconite has long been recognized as characteristic of the "greensand" deposits. As early as 1823 Alexander von Humboldt* mentioned the occurrence of the "green or chloritic earth" in several sandstones and limestones of different horizons in Europe. Previous to this time the glauconite had been confounded with earthy chlorite, but in 1821 the analysis by Berthier† of the greensand of the Calcaire Grossier at Paris first showed definitely its true nature, that it was essentially a silicate of iron.

Its method of formation was for a long time afterwards, however, a mystery, but in 1855 Ehrenberg‡ announced the occurrence of glauconite grains as the casts of the internal parts of species of Foraminifera, and gave the results of examinations into greensand deposits in many parts of the world. He showed that the mineral was often to be proven as having formed within these shells, and he arrived at the conclusion that in all cases this was the method of its formation, although most of the grains did not show any direct evidence of this organic origin. He not only showed this for the greensands of the more recent geological periods, but succeeded in establishing the same facts as far back as the Silurian greensand of Russia.§

*Geognostisches Versuch, p. 292.
†Annales des Mines, Ser. I. VI. 1821.
‡Uber den Grünsand und Seine Erläuterung des Organishen Lebens, Berlin, 1856, p. 112. Abhandl. d. k. Akad. d. Wissenschaften zu Berlin für 1855.
§Ibid., p. 172.

In 1856, Professor J. W. Bailey* made the very important announcement that the formation of glauconite is now going on in many parts of the sea-floor, and is forming in the shells of small organisms, in the same way as had been supposed by Ehrenberg from his microscopic researches upon fossil glauconite. This discovery was brought about chiefly by material obtained by Count Pourtales† from soundings made for the United States Coast Survey.

The most recent and thorough examination of the nature and manner of formations of glauconite resulted from the work of the Challenger Expedition, sent out by the British government. The result of this investigation is found in the volume upon Deep Sea Deposits, written by Professors Murray and Renard.

Since the time of Ehrenberg, the best authorities have practically agreed that the formation of this silicate of iron is restricted in its origin to the internal chambers of organisms, in which it forms casts. Ehrenberg concluded that its origin could only be accomplished in this way. In treating of the glauconitic grains in limestone from Alabama, he writes:‡

The formation of the Greensand consists in a gradual filling up of the interior space of the minute bodies with a green-colored, opal-like mass, which forms therein as a cast. It is a peculiar species of natural injection, and is often so perfect, that not only the large and coarse shells, but also the very finest canals of the cell walls, and all their connecting tubes are thus petrified, and are separately exhibited. By no artificial method can such fine and perfect injections be obtained.

Concerning the formation of glauconite grains, Prof. J. W Bailey wrote as follows,§ in 1856:

They are now forming in the muds as they are deposited, and we have thus now going on in the present seas, a formation of Greensand by processes precisely analagous to those which produced deposits of the same material as long ago as the Silurian epoch. In this connection, it is important to observe, that Ehrenberg's observations and my own, establish the fact that *other* organic bodies than Polythalamia produce casts of Greensand, and it should also be stated that many of the grains of Greensand accompanying the well-defined casts are of wholly unrecognizable forms, having merely a rounded, cracked, lobed, or even coprolitic appearance. Certainly many of these masses, which often compose whole strata, were not formed either in the cavities of Polythalamia or Mollusks. The fact, however, being established beyond a doubt, that Greensand does form casts in the cavities of various organic bodies, there is

*American Journal of Science, Second Series, Vol. XXII, November, 1856. "On the Origin of Greensand, and its Formation in the Oceans of the Present Epoch," pp. 280-284.

†Report of U. S. Coast Survey for 1853, Appendix, p. 83.

‡Op. Cit., p. 115. "Die Bildung des Grünsandes besteht nämlich," etc. Translated by Professor J. W. Bailey, op. cit., p. 282.

§Op. Cit., p. 284.

a great probability that all the masses of this substance, however irregular, were formed in connection with organic bodies, and that the chemical changes accompanying the decay of the organic matter have been essentially connected with the deposits in the cavities, of green and red silicates of iron, and of nearly pure silica.

The opinion of Murray and Renard[†] is best shown by the following quotation:

From all that we have already stated in this chapter it appears certain that glauconite is principally developed in the interior of foraminiferous shells and other calcareous structures, and that all the transitions can be observed from chambers filled with a yellowish-brown mass to grains which have almost completely lost the impress of the organisms in which they were formed. From this fact, as well as from direct observations of the various constituents of the deposits, it is uncertain, and indeed little probable, that there are any minute grains of glauconite formed in a free state in the mud.

It appears, therefore, that glauconite is, so far as is known, always formed in the inner parts of organisms, and that very often the completely filled shell forms a cast which is an indication of the mode of origin. In many cases, however, the growing of the mineral inside has brought about the breaking of the shell. After the breaking of this restraining wall the shapes grow more irregular, and it seems certain that there is an enlargement of the original grain by concretionary growth from the materials which surround it. The grains which thus result may become rounded by attrition, or they may be broken so as to present angular forms; and these rounded or shattered forms vary from large grains to those of the minutest dimensions. They are thus incorporated in large numbers in the sediment, together with those rarer forms which by fortune still preserve the shape of the chambers in which they were formed.

According to Murray and Renard, the formation of glauconite is restricted to areas occupying certain positions, in regard to the shore-line and the deposition of sediment. The necessary conditions appear to be a slow deposition of very fine detrital silt, derived from terrestial erosion, and representing the outer fringe of the land-derived sediments. Ordinarily, therefore, the glauconite-forming area is a broad zone (but much broken up by irregularities of the ocean-bottom and by currents), which lies between the Shallow-water and the Deep-water zones,—at a depth, that is to say, of from 100 to 900 fathoms. This belt follows the shore-line of the continents. It represents the transition belt between the inorganic or de-

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†Reports Challenger Expedition. Vol. Deep Sea Deposits, p. 387.

trital sediments, and the mainly organic deposits. The transitional zone has a very slow rate of deposition, much more so than the landward zones where the purely detrital rocks are deposited; while it is more rapid, by the amount of land-sediment, than the beds composed exclusively of organic remains.

The union of detrital and organic matter to produce the silicate of iron, glauconite, which is characteristic of this greensand, takes place after a manner that is not well understood. It is supposed that the detrital material washes into and fills the shells, and that it is the action of the decaying organic matter inside which operates to break up the existing combinations, and to form the silicate of iron. Concerning the chemistry of the process, Murray and Renard make the following suggestions:

It is certain that very fine mud is washed into the Globigerina shells, and may penetrate through the foramina. If we admit that the organic matter inclosed in the shell and in the mud itself transforms the iron in the mud to sulphide, which may be oxidized into hydrate, sulphur being at the same time liberated, this sulphur would become oxidized into sulphuric acid, which would decompose the fine clay, setting free colloid silica, alumina being removed in solution; thus we have colloid silica and hydrated oxide of iron in a condition most suitable for their combination.

In greensand deposits the rounded and angular forms of the glauconite grains formed in this way make up varying percentages of the rock and are scattered throughout the finer groundmass. This ground-mass may be siliceous, or calcareous, or both; and in either case it may be made up in a considerable part of the finer glauconitic material. It is often phosphatic, bearing phospate of lime in nodular forms. Where best developed, these glauconite grains form the larger part of the rock, making as much as 85 per cent.* This represents the most favorable conditions for the formation of this deposit. It means that the proportion of mechanical detritus and the accumulation of organic matter was almost exactly that required for the formation of the silicate. In other places, however, the glauconite is scattered sparingly, through a sandstone or a limestone. If the material is a sandstone, it was deposited nearer the center of deposition than the glauconite zone, and the diminution of glauconitic grains may be said to mark the approach to the shore. If it is a limestone, it was probably deposited in deeper waters and further from the centre of deposition than the glauconite belt, and the diminution in number of the glauconite grains marks the increasing distance from the shore.

*Ann. Rep. New Jersey Geol. Survey, 1892, p. 205.

The freshest parts of the iron-bearing rock of the Mesabi have a structure which appears to be almost exactly like that of the typical greensand, although hardened and consolidated. The grains of glauconite have a similar shape and arrangement, and in the sections cut from specimen 53-1, they are somewhat intermingled with grains of carbonate. Between these grains there is the same fine ground-mass, which in this case seems to be of finely divided silica. In this specimen, moreover, the consolidation is not so great as in the more altered common varieties; the fracture is irregular, and the surface of fracture granular, instead of being smooth and conchoidal, as happens when the processes of change have gone on to a greater extent. The shapes of the green grains and their distribution through the ground-mass show a decided resemblance to the figures of sections of greensand made by Ehrenberg* and Murray and Renard. †

This same structure is characteristic of the more altered rocks, where it has been called the spotted-granular structure. Professor Wolff, in the letter quoted on a former page, first called attention to the fact that the granules as a whole bore evidence of detrital origin, and suggested that they represented the altered original glauconitic grains. Subsequent study has brought the writer to believe that most of these areas owe their existence primarily to the original grains of glauconite, although their form and composition has been altered by various mechanical and chemical changes. The stages of transition from the simply glauconitic granules to those where the granules are formed only of the decomposition products, chiefly silica and the iron oxides, make this seem evident. In the later stages of the rock, however, not only have the changes profoundly altered the original granule, but these forces have often produced new granules, simulating closely the older ones which were derived from the truly detrital grains. These new granules are composed chiefly of the material derived from the alteration of the old ones, but they occupy new positions and have new forms. The nature of these secondary forces and their effects have already been described, as granular-brecciation, concretionary action, impregnation, and other forces, in various combinations.

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*Op. cit. plate VI. Lower Silurian greensandstone of Russia.

†In Challenger Reports. Reproduced by New Jersey Geol. Surv. for 1892, p. 242, plate V. fig. I.

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We have probably, therefore, in the Animikie (the Upper Huronian of the United States Geological Survey) one of the most extensive deposits of greensand which have ever been known to accumulate. The succession of strata here is suggestive, as complying with the present conditions of the deposition of glauconite. The basal quartzyte represents the deposition of a considerable period, when the area lay near the shore-line, and in the region of direct arenaceous sediments. The conglomeratic phase near the base seems to have represented a still nearer approach to the shore, and during the subsequent deposition there may have been a slight subsidence. At the close of the deposition of the quartzyte, and the beginning of the deposition of the iron-bearing member, we may believe that there was a marked subsidence, which brought the area out of the reach of direct arenaceous sediments, and into a depth and distance from shore which was favorable for the formation of glauconite, with intermixed siliceous and calcareous matter.

At this time there was sparing detrital mud from the land area, and we must believe, in accordance with the known conditions for the formation of glauconite, that there was abundant organic life. The essential result of the combination of this decaying organic matter and the detrital mud was the union of the iron and the silica to form glauconite. This glauconite, as already stated, seems to have been originally a hydrous protosilicate of iron, without much potash or any other essential constituent. For these peculiarities we must look for the reason in the peculiarities of the sediment which prevailed, since it is to the variations in the composition of this that the varying composition of glauconite appears to be due.

The most marked characteristic is perhaps the absence of potash. But it must be remarked that this constituent, while commonly an important feature, does not seem to be essential. Glauconite from the Calcaire Grossier of the Paris Basin, analyzed by Berthier,[*] gave the following results:

Silica	SiO_2	40.00	per cent.
Alumina	Al_2O_3	1.00	" "
Protoxide of Iron	Fe_2O_3	} 24.70	" "
Sesquioxide of Iron	FeO		" "
Lime	CaO	3.30	" "
Magnesia	MgO	16 60	" "
Potash	K_2O	1.70	" "
Water	H_2O	12.60	" "
Total		100.00	per cent.

*Annales des Mines, 6, 1821, p. 459.

It is seen in this analysis that the potash is one of the least important constituents of the rock. In another analysis * by the same chemist, no potash nor soda were reported. These analyses were the first to determine the actual nature of glauconite, and were accepted as the standard composition of the mineral. Many analyses† show only between three and four per cent. of potash; while a specimen analyzed by Murray and Renard,‡ from off the coast of Australia, afforded less than one per cent.

While the iron and the silica for the formation of the glauconite are derived directly from detrital mud, it is stated by Murray and Renard that the potash must be derived from the sea-water in which it exists in solution. The sea-water derives it from the fragments of the land-derived rocks which accumulate upon the bottom. The discussion is concluded as follows:

If we recall the observations with reference to the geographical distribution and mineralogical and lithological association, it seems possible to suggest, with a considerable degree of certainty, the relative abundance of potash in the deposits where glauconite is forming. It was pointed out that glauconite was always associated with terrigenous minerals, and in particular with orthoclase, more or less kaolinized, and white mica, and with the debris of granite, gneiss, mica-schists, and other ancient rocks. We cannot fail to be struck with these relations, for it is just those minerals and rocks that must give birth by their decomposition to potassium, derived from the orthoclase and the white mica of the gneisses and the granites.§ The minute particles of these rocks and minerals, which make up a large part of the muddy matters settling on the bottom beyond the mud-line around continental shores, would readily yield under the action of sea-water the chemical elements that are deposited in the form of glauconite in the chambers of foraminifera and other calcareous organisms.

In this case, it becomes necessary to consider what was the nature of the rocks whence the sediments of the glauconite-building zone were derived. Older than this formation, except the basal and underlying quartzyte, which is conformable and therefore can have contributed little sediment to the glauconite zone, there are only the altered and schistose rocks and granites of the pre-Animikie formations. The granite of the Giant's

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*Annales des Mines, 6, 1821, p. 459.
†Ann. Rep. New Jersey Geol. Survey, 1892, p. 228.
‡Reports Challenger Expedition, Vol. Deep Sea Deposits, 1892, p. 387.
§It has been shown, in fact, by Guignet and Telles, that the water of the Bay of Rio Janeiro contains a large amount of potassium salts, evidently due to the presence of ancient rocks in this bay. (See Comptes Rendus, tom., lxxxiii, p. 919, 1876).

range has already been briefly described, as well as those Kee-
watin schists which lie to the south of the granite belt, on the
Mesabi range. It is not as yet possible to say exactly what
was the land surface at the time of the deposition of the iron-
bearing member, but it seems to have been of the general na-
ture of the complex of pre-Animikie rocks which occupies the
whole north-eastern part of the state, to the north of the
Giant's range, and it may well have included this actual region.
These schists, gneisses and granites appear to have been in
practically the same condition as now, at the time of the depo
sition of the Animikie sediments, as previously shown.

It seems at first as if we have here rocks which, according to
Murray and Renard, in the quotation just made, should furnish
an abundance of potassium, and that the glauconite should
normally contain a larger percentage of the same mineral, if
this region were actually the land surface adjacent to the shore-
line. There has as yet been made no thorough study of the
rocks of this region, but so far as is known, these rocks, in-
stead of containing an unusally large amount of potash, have
an unusually small quantity. Several analyses of granites from
this region have invariably shown that the rock was a soda-
granite, with a small, often insignificant amount of potash.*
One of these analyses is of granite from the Kawishiwi river,
and contained 5.01 per cent. of soda, with 1.68 per cent. of pot-
ash. Another, of the granite at Saganaga lake, contained 4 33
per cent. of soda, and 0.71 of potash. Although these are per-
haps extreme cases, they do not seem to be uncommon, and
the other analyses support the statement that, so far as has
yet been ascertained, the ancient granite of this area, which is
of pre-Animikie age, is pre-eminently a soda-granite, and con-
tains an unusually small amount of potassium.

Concerning the schists, which is the other source from which
the sediments of the iron-bearing member must have been
chiefly derived, we have, as in the case of the granites, not
enough knowledge to make positive assertions; but so far as
is known, there is in these rocks the same small amount of
potash. These schists are mainly basic, and a large part of
them are probably of either direct volcanic origin, or have
been derived from volcanic rocks through some assorting and
rearranging under atmospheric conditions.

* Twenty-first Ann. Rep. Minn. Geol. and Nat. Hist. Survey, pp. 41 and 43.

An analysis of Keewatin green schist from Tower gave the following results: *

Silica	SiO_2	50.47 per cent.	
Alumina	Al_2O_3	18.45 " "
Sesquioxide of iron	Fe_2O_3	2.13 " "
Protoxide of iron	FeO	7.74 " "
Lime	CaO	6.61 " "
Magnesia	MgO	6.90 " "
Potash	K_2O	0.30 " "
Soda	Na_2O	2.58 " "
Phosphoric acid	P_2O_5	traces.
Water	H_2O	2.34 per cent.
Total		97.52

Another analysis of a rock of this sort,† from the falls of the Kawishiwi, south of Fall lake, shows the following composition. Analysis by C. F. Sidener:

Silica	SiO_2	43.96 per cent.	
Alumina	Al_2O_3	16.03 " "
Sesquioxide of iron	Fe_2O_3	10.50 " "
Protoxide of iron	FeO	8.73 " "
Lime	CaO	9.54 " "
Magnesia	MgO	6.56 " "
Potash	K_2O	0.27 " "
Soda	Na_2O	1.62 " "
Water	H_2O	1.84 " "
Total		99.06

Professor G. H. Williams, in his work on "The Greenstone Schist Areas of the Menominee and Marquette Regions of Michigan,"‡ has made a more thorough study of these older schists in another part of the Lake Superior country. As far as can be seen, the schists of Minnesota are identical in very many respects with the rocks here described, and so the results of this work may be compared with interest, although with caution. These rocks were found in a large part to be altered eruptives, mainly basic in character; and most of the analyses given show a large amount of soda, and a small quantity of potash.§ Occasionally the reverse is the case, but in the region as a whole, the small amount of potash is marked.

Thus, so far as we can go, the region from which the iron-bearing rocks derived their sediments was one in which the rocks contained potassium in very sparing quantity, both in the schists and in the gneissic and granitic rocks. It will probably lead to interesting results to investigate this subject

* Seventeenth Ann. Rep. Minnesota Geol. Survey, p. 126.
† Bulletin No. 6, Minn. Geol. Survey, p. 38.
‡ Bulletin of the U. S. Geol. Survey, No. 62.
§ Ibid., pp. 76, 89, 91, 104, 113, 119. 12), 121, etc.

still further, and to discover whether this rule actually holds for the whole or a large part of this area.

While thus neither the granites nor the schists could contribute much ·potassium to the formation of the glauconite, the detritus from the basic schists contained a large quantity of iron, and formed an abundant supply for the growth of the deposits.

The change at the top of the iron bearing member to the calcareous horizon indicates a further subsidence of the area, so that the distance from the shore-line became so great that under the conditions very little mechanical detritus was brought, and the deposit was mostly made up of calcareous matter, probably of organic derivation. There is mingled with the lime, however, much fine green material which appears to be glauconitic, and so it is probable that through this zone there was still some of this substance formed. Above the limestone horizon comes the great body of siliceous slates. This indicates a rather sudden change from the previously existing condition, and an abundant supply of fine sediment. This was probably the result of an elevation of the area, so as to bring it within the mud zone; but the change of sediments may have been occasioned simply by a change of currents, caused by disturbances in some other locality.

In the Cretaceous and Eocene greensand of New Jersey * there is a succession of strata which is somewhat similar to that which is found in the Animikie rocks, resulting from a gradual subsidence of the area of deposition. Immediately below the glauconitic beds is the Raritan formation, composed chiefly of sands and clays; and a shallow water sediment, as is shown by various evidences.† The conditions of its deposition may be somewhat broadly held to correspond with that of the lower quartzyte of the Animikie. Above the Raritan formation the beds are glauconitic for a considerable thickness, though the amount of glauconite varies in different horizons, appar-- ently according to changing conditions of deposition. These beds are called the Clay Marl Formation, the Lower Marl Bed, the Red Sand Formation, the Middle Marl Bed, the Upper Marl Bed, and the Shark River Marl. Throughout these divisions the glauconitic beds contain horizons which are largely argil laceous or calcareous. The whole series is overlaid by shallow-water Miocene sediments.

In extent these greensands are comparable with the iron-bearing beds of the Animikie. The estimated thickness of the

* Annual Rep. New Jersey Geol. Survey, 1892, pp. 169-239.
† Ibid., 1892, p. 183.

various beds of the glauconitic zone amounts to over five hundred feet, and the lateral extent was great. In the preliminary map of portions of Monmouth and Middlesex counties, accompanying the report of the New Jersey Geological Survey referred to, and apparently including only a small portion of the greensand districts, these glauconitic beds occupy an area of over three hundred square miles.

For the characteristics by which the Mesabi iron-bearing rock differs from more recent greensand deposits, we have to consider the extreme length of time during which it has been exposed to degradational and reconstructive processes. Not only the structure of the rock, but also the chemical composition, has thus been permanently changed. In the ground-mass which originally surrounded the glauconitic grains, we may believe that there was originally some calcareous matter, as well as siliceous; but this limy matter would be one of the first things to be removed by the dissolving waters. The poverty of the rocks in phosphates is probably to be explained in the same way, as compared with the phosphates in the New Jersey and other greensand deposits. The phosphate of lime, which we may believe, from analogy with more modern deposits, was present, in the shape of nodular masses scattered through the ground-mass, was easily soluble and quickly removed. To the great lapse of time must also be chiefly ascribed the possibility of decomposing so thoroughly the glauconite, and concentrating the resulting minerals. Deposits of iron ore of workable value arising in this manner are not known by the writer to have been described in any of the more recent formations, although Penrose* suggests that "the glauconites of the Upper Cretaceous of Texas may have in part afforded a supply of iron for the Tertiary deposits, while the Tertiary glauconites have probably had but little to do with the formation of Tertiary ores, though they may become a source of iron for future ore deposits."

Possibility of Finding Traces of Organic Forms.

With a view to finding whether the forms in which the glauconitic grains sometimes occur have any resemblance to organic bodies, a thin section from the freshest specimen collected, 53-1, was submitted to Dr. Robert T. Jackson of Harvard University, and to his kindness the following expression of opinion is due:

"I have examined your slide carefully and should say that there is no evidence of organic structure in any part of it. The

*The Iron Deposits of Arkansas, Ann. Rep. Ark. Geol. Surv., 1892, vol. I, p. 120.

round or rounded grains of crystallized calcite (as I suppose), are apparently concretionary aggregations, and cannot safely be considered as organic or replacements of organic matter. The 'glauconite' particle in the centre of the indicated field shows superficial striated structure, but is unlike anything I know in Foraminifera. It has no appearance of organic matter, and its structure is doubtless of mechanical origin.

"In rocks as old as those under consideration, you would need very good material to prove organic material. This slide certainly does not show it. I showed the slide to Mr. B. H. Van Vleck, who is a very competent judge in the microscopic structure of plants and animals, and he positively affirmed that it showed no organic structure. I also showed it to Professor Alpheus Hyatt, who coincided in the opinion."

It is not impossible, however, that further study of more favorable sections may succeed in finding the traces of the organisms which may once have existed in these rocks. A close comparative study of the glauconite grains would very likely be rewarded as well as research in any other field; and the light that such discoveries would throw upon the conditions of this as yet almost unknown period would be of the greatest value.

NOMENCLATURE.

Although the various rocks of the iron-bearing member have been minutely described, yet no name has been found which seems to be applicable even to the more ordinary phases of the rock. Originally the rock was probably a greensand, with more or less siliceous and calcareous matter; but in the greater part of the rocks there are very few traces of the original structure and composition. The term "greensand" is hardly applicable to a firmly consolidated rock. Ehrenberg calls the consolidated greensand of Russia "greensandstone" (grünsandstein); but neither is this term applicable to this altered rock. A greensandstone bears the same relation to greensand as does sandstone to sand; but the rock of the iron-bearing member of the Animikie may be supposed to bear a relation to greensandstone somewhat similar of that of a profoundly altered quartzyte to a sandstone. It seems necessary, then, to have a means of designating this altered greensand.

Upon the Mesabi range, the term "taconyte" has come into very general use as a designation of the iron-bearing rock in general. This term was first proposed by Mr. H. V. Winchell for the rock enclosing and constituting the ore-bodies.*

*Twentieth Ann. Rep. Minn. Geol. Survey, p. 124.

Whatever may be the opinion as to the fitness of derivation of this word, it has obtained such currency, especially upon the Mesabi Iron range, as seems to warrant its retention. It is therefore proposed that the term be applied to rocks of this character, which appear to be altered greensandstones. The nature of the typical taconyte may then be briefly described as follows: •

The rock consists of a ground-mass of silica, which is usually cryptocrystalline, although it may be finely phenocrystalline, or chalcedonic. In any case, the silica is evidently secondary, and a precipitation from solution. Through this ground-mass are scattered rounded or angular bodies, which have been called granules. These perhaps average a thirtieth of an inch in diameter. They represent partly original grains of glauconite, partly the result of the processes of metasomatosis, and are composed of glauconite, siderite, hematite, magnetite, limonite, or cryptocrystalline silica, these minerals occurring either singly or associated in all proportions in the different granules of different phases of the rock. There are the accessory minerals actinolite, calcite (magnesite), chlorite? kaolin? pyrite, epidote and apatite. There is no original crystal form in the rock, and the essential minerals generally do not show it. As a result of secondary crystallization, it is often seen in the magnetite and siderite, and always in the actinolite. Among the most important minerals, where several occur together, the relation is such as to show that one is derived from the other, and that the glauconite has been the original mineral whence all the others have been formed, as the more or less reconstructed products of its decomposition. Among its physical peculiarities, the rock may be said to be generally hard, with a fracture that varies from conchoidal to irregular; no cleavage, but a tendency to a prismatic vertical and a parallel horizontal jointing. In color it may be various shades of gray, red, or green, according to the varying composition.

Taking this rock as a type, the more altered types which are derived from the same source may be designated by prefixing the word "taconyte," indicative of their origin, to the word which expresses their physical peculiarities. Thus there may be "taconyte slates," "taconyte clays," "taconyte chert," "taconyte jasper," and so on. No word, however, can be used as the last term in these appellations which implies an origin contrary to the one explained. It is not possible, for example, to have a "taconyte sandstone" or a "taconyte quartzyte,' although the rock may in its physical peculiarities somewhat simulate a sandstone or a quartzyte.

CHAPTER XII.

SUMMARY STATEMENT*.

In the few succeeding pages a concise statement of the more important principles with which this bulletin deals will be attempted.

LIMITS OF THE MESABI RANGE.

The Mesabi range in Minnesota may be for convenience separated into three geographical divisions, characterized by sufficient geological differences: The Western Mesabi, which extends from the Mississippi river to the Embarras lakes, on the eastern edge of range 16 W.; the Eastern Mesabi, reaching from the Embarras lakes to the region of Gunflint lake; and the International Boundary division, which stretches from Gunflint lake east to Pigeon point. In the Western Mesabi region lie all the mines at present worked, and it is to this section alone that the observations made in this chapter are intended to be strictly applicable. The chief ore-bearing district lies between the Mesabi Chief mine on the west and the Hale on the east, a distance of about forty miles.

GENERAL STRUCTURE.

The lowest rocks of the region are greenish schists, which belong in the Keewatin formation. These schists are cut by a great belt of intrusive granite, which runs the entire length of the iron-bearing district and usually forms the summit of the divide between the Mississippi and the Red River basins. Unconformably upon these older rocks lie the gently dipping Animikie strata.

There are three chief members of the Animikie in the iron-bearing regions, as definitely known at present. Lowest is a

quartzyte; upon this lie the iron-bearing rocks; and finally there is a great thickness of black slates. The base of the slates is calcareous, and becomes in places an impure limestone, often dolomitized or sideritized.

The iron-bearing rocks occupy a definite and constant horizon between the quartzyte and the slates. They are marked by peculiar and characteristic features, and have always been recognized as invariably associated with the ore deposits. They seem to have a nearly uniform thickness, which may be estimated as between 500 and 1,000 feet, with an average of perhaps 800 feet.

MINOR STRUCTURE OF THE ANIMIKIE.

The ore-bearing region of the Western Mesabi affords a peculiarly valuable field for investigation, for the rocks have suffered only very slight disturbance since the time of their deposition. The general structure is a monocline, which dips slightly east of south, at a gentle angle, which averages perhaps ten to fifteen degrees. On the eastern end of the Western Mesabi there has been some slight additional disturbance. There is evidence leading to the belief that a wedge shaped area eight or ten miles in length, lying mainly in T. 58-17, has been faulted up above the surrounding rocks; the amount of vertical displacement being perhaps 500 feet. This may be called the Virginia area, from the town of that name which is in the vicinity. To the east of this upthrust area there is as far as the Embarras lakes at least (a distance of five or six miles), a gentle folding of the strata, which appears to have been contemporaneous with the faulting. These disturbances may be provisionally believed to have occurred in later Keweenawan or post-Keweenawan time, and to have been contemporaneous with the monoclinal tilting.

CHARACTER OF THE IRON-BEARING ROCKS.

The rocks of the iron-bearing member exhibit great diversity. The most common sort is massive and siliceous, and is thickly spotted with small round darker areas, consisting mainly of iron oxide. From this there are many deviations; and often the different varieties cannot be said to resemble one another in any way, either in the field or under the microscope, or on chemical investigation. But specimens are constantly found which show one variety changing into another. Thus it soon became evident to the writer that all the rocks of the

iron-bearing member, however different, were closely allied in origin, and were probably derived from a single primitive type. This same principle has already been shown by Irving and Van Hise for the Penokee-Gogebic rocks.*

NATURE OF THE ORIGINAL ROCK.

A careful macroscopic and microscopic study of a large number of carefully selected specimens was made, with very satisfactory results. Nearly every detail of the changes from one phase into another could be made out and the causes assigned. The changes were seen to be those of metasomatosis, and the inciting agents seemed mainly atmospheric. The original rock of the series was quite unmistakable. Typically it may be briefly described as follows:

In a ground mass of cryptocrystalline, chalcedonic, or finely phenocrystalline silica, are thickly strewn rounded or sub-angular bodies, made up chiefly of a green mineral, very slightly pleochroic, and without cleavage; under crossed nicols it appears in some places amorphous, in others extinguishing as an aggregate.

Analyses showed this mineral to be essentially a hydrous silicate of iron, and selected sections kindly examined by Dr. J. E. Wolff, of Harvard University, were stated by him to "resemble in all physical characters *glauconite.*" In one especially fresh specimen there were also rounded grains of calcite (probably magnesian), apparently originally detrital, and in some limited areas these increased in number till they formed nearly the whole bulk of the rock. These glauconitic carbonate layers are nearly identical in appearance with the glauconitic St. Lawrence (Cambrian) limestone of Minnesota, of which sections were cut and compared. Dr. Wolff suggested tentatively that the rock was an altered greensand. This appears to the writer to be the correct view. There is, however, a peculiar feature shown by chemical analyses—a constantly very small amount of potash.

THE PROCESSES OF CHANGE.

It is quite certain that from this rock are derived nearly all the other phases in the iron-bearing member. In the alterations there are various processes, differing by reason of the varying forces which have been brought to bear upon the rocks.

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*Tenth Ann. Rep., U. S. Geol. Survey.

The most common, which may be called the *normal process*, appears to take place under scant access of atmospheric agents. The decomposition of the green mineral is the noteworthy event. It breaks up, forming chiefly silica and the iron oxides or carbonate, so that in by far the commoner phases of the rocks the rounded bodies or granules are composed entirely of these decomposition products.

The various stages in the rearrangement of the silica and the iron oxides or carbonate constitute the succeeding phases. The chief cause of their separation lies in the different conditions under which these two chief constituents are taken into solution. From very careful study of the separation and concentration of the silica and the iron, there may be deduced two rules. First, in regions of comparatively free oxidation, chalybeate waters deposit iron and remove silica. Thus bands of iron are formed along cracks and fissures, whether macroscopic or microscopic, replacing the silica; and isolated spots weakened by weathering become by replacement blotches of iron oxide. Conversely, in regions of extremely scant oxidation, waters deposit silica and remove iron in solution. Thus the portions which are most porous become richer in iron and lose their silica; this iron is derived mainly from the adjacent unoxidized parts of the rock, and into these unoxidized parts the silica from the oxidized portions is constantly carried. The final result is an almost complete separation of iron and silica.

CHEMISTRY OF THE PROCESS.

The chemistry of this process seems to be approximately as follows:

Most atmospheric waters contain, among other things, carbonic acid, oxygen, and certain amounts of the alkaline salts. Carbonic acid gives water the power of taking iron into solution; while the alkaline salts are slower but ready solvents of silica, especially in the finely divided cryptocrystalline or chalcedonic state in which it is usually found in these rocks. These waters find their way into the rock, and to some degree into the firmest portions. As they begin to penetrate inward from the crevice along which they came, the oxygen unites with the unoxidized elements of the rock, decomposing some of the minerals, and extending the *weathered zone*. By the decomposing action of this oxygen, carbonic acid may be set free; and the same product may result from the action of

acids, either brought in by the water or developed during decomposition. The water thus passes further into the rock free from oxygen, but highly charged with carbonic acid. Aided by the pressure under which it is placed, it readily dissolves the iron. The affinity of the alkaline solvents for the silica is so much weaker than that of the carbonic acid for the iron that the water becomes saturated with iron, without any appreciable quantity of silica being taken up. The solution finally finds its way again out into a zone of greater oxidation, such as a crack. Upon the access of oxygen and the release of pressure, most of the iron is precipitated. As the solvent power of the water is now renewed, the alkaline salts become able to take silica into solution. Thus iron replaces silica. Next the water again finds its way into an unoxidized region, and under these conditions again takes iron into solution, which compels the precipitation of some of the silica; so that here silica replaces iron. Finally, this process brings about an almost complete separation of the two minerals.

THE CONCENTRATION INTO BANDS.

Most often weak and firm parts alternate closely in the rock, usually being arranged in narrow horizontal zones. If the weak zone is one of comparatively scanty oxidation, the iron may be deposited as carbonate; if of freer oxidation, as the hydrous sesqui-oxide. So in the final concentration we may have a very well defined banding of cherty silica with siderite; or, more usually on the Western Mesabi, bands of silica (usually ferruginous), alternate with bands of iron oxide (usually siliceous). The crytallization of the latter gives the typical "jasper and ore," which is occasionally found on the Western Mesabi, but is not so common as in others of Lake Superior iron regions.

RESULTS OF ACCUMULATED STRAINS.

The change from the oxides of iron to the carbonate, and from the carbonate back to the oxides, has been found by study with the microscope to be very common, and the same iron may repeatedly undergo the metamorphosis, with changing conditions. When the most of the rock is thus altered, there is an appreciable change of bulk, the oxidation of the carbonate being attended by contraction, and the carbonatation of the oxides by expansion of the rock. The loss of the more soluble products of decomposition has also a marked

contractile effect, very early in the rock's decay. These contractile and expansile tensions, occurring sometimes in different parts of the field, often successively in the same part, have given rise to many of the physical peculiarities of the rock. Among the effects of the contractile tensions there is a very common smooth, vertical, prismatic jointing, and the development of closely set horizontal joints, which somewhat simulate cleavage. It is these horizontal joint-cracks which become the seat of deposition of the iron from the percolating waters; and thus the parallelism of the banding is explained. With the advance of decomposition, the horizontal cracks become more numerous, and the bands of iron which are formed along them often grow till they unite. It is to this cause that the beautifully bedded character of the ore-deposits must be chiefly ascribed.

The expansile strains lead to breccias, and to local faulting and folding, especially in the ore bodies. They also give rise to shearing movements, which have in many places altered the rocks for a limited distance and induced a schistose or slaty structure. This shearing process forms one of the chief deviations from the normal process of change.

VARIATIONS FROM THE NORMAL PROCESS.

Another important modification of the usual manner of change follows the exposure of a considerable area to freely oxidizing forces. This condition is nearly always found at the surface, and often deep into the rock, following zones of weakness, induced chiefly by regional disturbances. In these parts of the rock the various stages of decomposition and concentration are hurried forward with such comparative swiftness that the phases of rock thereby produced are different than those produced by the normal process. In these rocks the iron is concentrated into large bodies and impure disintegrated silica and clay is left behind. Thus, among the ferrated rocks, the ore-bodies are formed. Among the leached rocks the most common are the "paint rocks," which have, subsequent to their leaching, usually become iron-stained, so that they form a stiff clay, red, yellow or brown in color; also a cream white residual clay, which has been mistaken for kaolin. On analysis the last proves to be mainly free silica, with a small amount of silicate of alumina and impurities; and, in one place at least on the Western Mesabi, it is a nearly pure silica powder.

Least important among the causes of change has been the impregnation of the rocks by minerals apparently derived from without the iron-bearing member and brought by percolating waters. Calcite is the chief of these minerals; and the calcitized portions of the iron-bearing rock are distributed near the contact with the calcareous stratum of the black slates.

THE FORMATION OF THE ORE-DEPOSITS.

It has already been stated that the bands of iron owe their existence to previously formed zones of weakness. From the narrow band there may be found every gradation upward in size, till the body of iron becomes large enough to merit the name of an ore-deposit. These ore-deposits are often very large, being occasionally nearly a mile in their longest extent. The ore is usually hematite, loose and granular, and when of best quality is of a blue or brown color. Typically there is a portion, near the surface, which has become hydrated into yellow limonite or göthite. Often these ore-bodies rest upon the basal quartzyte; often again they rest upon the hard and little-altered iron-bearing rock itself. The conditions under which they form seem identical with those necessary for the growth of the narrow bands of iron in the banded "jasper and ore." In both cases the iron has concentrated in an area of especial weakness. In the case of the band the cause of the small area of weakness has already been explained. In considering the cause of the formation of the ore-bodies, it is only necessary to find the cause of the development of so great regions of weakness.

The richest ore-producing region thus far developed is that which lies in T. 58–17, and surrounds the Virginia area, following the supposed fault lines. Immediately east of these lies another rich group, near Biwabik, in the somewhat disturbed strata adjacent to the upthrust area. At the Mountain Iron mine there is strong microscopic evidence of a disturbance, probably a fault, while at the other important mines there has not been sufficient exploration to enable one to determine their peculiarities. So the conclusion may be reached that the most important of the ore-bodies owe their existence to regional disturbances which have produced large areas of weakness. Faults, especially, are accompanied by the development of such areas, and in folded regions the summits of anticlines, and to a less degree the troughs of synclines, are weakened.

In the opening up of a great area of weakness, moreover, such as attends a fault-plane, a channel for the surface waters to find their way down is often afforded, and the shallow underground drainage for a considerable distance is deflected into the fault-fissure. The increased supply of water, emerging saturated with iron from percolating through the decomposing iron-bearing rocks, is an important factor in the formation of the ore. The chemistry of the process is practically the same as for the small oxidized areas which produce bands. Waters emerge heavily laden with iron into this zone of oxidation; here they precipitate their iron and are enabled to take into solution and carry away some small quantity of silica. The effect of the underlying impermeable quartzyte is important, since it deflects the surface waters into the weak zone, instead of absorbing them. Owing to the crystalline nature of its quartz, it is hardly or not at all replaced by iron, and thus it forms an unaltered stratum, even in the weakened zone, upon which the ore-body may accumulate.

In addition to this, smaller ore-bodies may be formed near the surface, at the bottom of the highly weathered zone, and resting upon the little-altered rock below. Inequalities in the decomposition produce small basins in the hard rock below, in which waters collect and finally deposit their iron.

It may be noted that the impervious dikes, which have been shown by Irving and Van Hise to have been important in the concentration of the iron in the ranges of the South Shore, especially in the Penokee-Gogebic, have played no part upon the Mesabi. Upon the whole length of the Western Mesabi there has not yet been discovered a single dike or other igneous rock in the Animikie.

It must be remembered that in no single case has an ore-body been mined out, or even explored sufficiently to give a complete knowledge of its features, so that much valuable information must come to light in the future.

DATE OF THE CONCENTRATION.

There is no positive evidence as to the exact time of the disturbances which ultimately brought about the formation of the great ore-bodies. It may be considered, however, pending evidence to the contrary, that they were contemporaneous with the monoclinal tilting, and that they occurred in later Keweenawan or immediately post-Keweenawan time.

The Eastern Mesabi.

The Eastern Mesabi differs in regard to its iron from the Western Mesabi in that it contains a much larger proportion of magnetite, which is associated with somewhat more crystalline silica. As these peculiarities are associated with the presence of the igneous rocks of the Keweenawan, and since they fade out as the distance from the Keweenawan area increases, it appears probable that, as has been suggested by H. V. Winchell,* the advent of these rocks was in some way connected with the magnetic condition of the iron. If this be the case, we must conclude that most of the banded magnetite of the Eastern Mesabi has been concentrated prior to Keweenawan time. But the lack of large ore-bodies in this region shows that up to this time the concentration had not occurred on a very large scale. It is probable that the same force which produced magnetization put a serious check upon the separation and concentration of the constituents of the rocks, causing the degree of concentration in that region at the present time to be behind that of the Western Mesabi.

The Cretaceous Conglomerates.

There are upon the Mesabi small patches of Cretaceous rocks, lying upon the Animikie strata. In the area examined, they are chiefly conglomeratic, and the fragments are mainly derived from the iron-bearing rocks. A study of these fragments shows two things; first, that at the time of the formation of the conglomerate there existed hard iron ore in the iron-bearing member; and, second, that much of the rock has been decomposed and has had its iron concentrated subsequently to being taken into the Cretaceous beds.

We may conclude that the process of concentration has been going forward since early Keweenawan or pre-Keweenawan time, and there is abundant evidence that it is going on at the present day.

SUMMARY.

The most important conclusions to which the study of the iron-bearing rocks of the Mesabi have led may be briefly recapitulated as follows:

I. At the beginning, the rock was probably of sedimentary nature, consisting mainly of glauconitic grains, with probably

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*Twentieth Ann. Rep., Minn. Geol. Survey, p. 136.

some associated calcareous and siliceous matter. All these materials are believed to have been derived by the reconstructive action of marine organisms, upon fine detrital silt from subaerial erosion, in moderately deep seas, somewhat remote from shore.

II. The elevation of these beds brought them under the reach of atmospheric influences. Percolating surface waters dissolved out whatever calcareous ingredients there may have been, and brought about the decomposition of the glauconite. This silicate, from its unstable form, quickly broke up, forming, chiefly, silica and iron oxide.

III. The various stages of decomposition of this original rock, as well as those of certain reconstructive processes of the same, have brought about the variations which characterize the present phases of the iron-bearing rock.

IV. The normal last stage of the decomposition of the original rock and the concentration of the resulting products, is the separation of the silica and the iron into separate bands or bodies.

V. The iron is concentrated in the regions of greatest oxidation; the silica in the regions of least oxidation. Large bodies of iron, therefore, have collected in extensive areas of great oxidation. The formation of these weak areas is accomplished in various ways, but on the Mesabi chiefly by disturbances of the strata arising from regional strains. The development of these strains is supposed to have taken place in later Keweenawan time.

PLATE V.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

Figure 1.

Section 53-1-C. From a well at the camp of the Chicago mine, S. E. ¼ S. E. ¼ Sec. 4, T. 58–16. Specimen taken from the iron-bearing rocks at the contact with the upper slates. In the ordinary light; magnified about 60 diameters. This rock represents the least altered phase found upon the Mesabi range. The ground-mass is of very finely divided quartz. Through this are seen thickly strewn the rounded and irregular forms of the granules. The dark granules are of glauconite, green, or brown from separation of iron oxide. In the large granule at the right the process of silicification has gone on, so that now most of its bulk is occupied by the cryptocrystalline silica which has replaced the glauconite. In the central and lower part of the figure, grains of carbonate (calcite or dolomite), probably originally detrital, may be recognized by their cleavage. Some of the clear spots in the glauconite areas, especially at the extreme left of the figure, are grains of quartz, which are probably directly detrital.

Figure 2.

Section 130. From S. E. ¼ S. E. ¼ Sec. 18, T. 58–19. In the ordinary light; magnified 25 diameters. The ground-mass is of very finely divided phenocrystalline quartz; the granules, whose outlines are seen in the figure, as in the section, with all degrees of distinctness, are made up chiefly of uncrystallized iron carbonate and cryptocrystalline silica, with small residual areas of glauconitic material. The original glauconitic material has been in this section almost entirely decomposed, resulting in the separation of silica, and iron in the form of carbonate, with a very slight amount of iron oxide. The peculiar ringed and spotted structure (see Plate VI), which characterizes the silicification process, is still preserved, and may be dimly seen in the large granule near the lower right-hand corner. This figure is especially intended to illustrate the process of *granular-brecciation*. Here the breaking up of the granules under the stress of tensions, developed within the rocks as a result of the chemical changes, may be noted.

Figure 1.
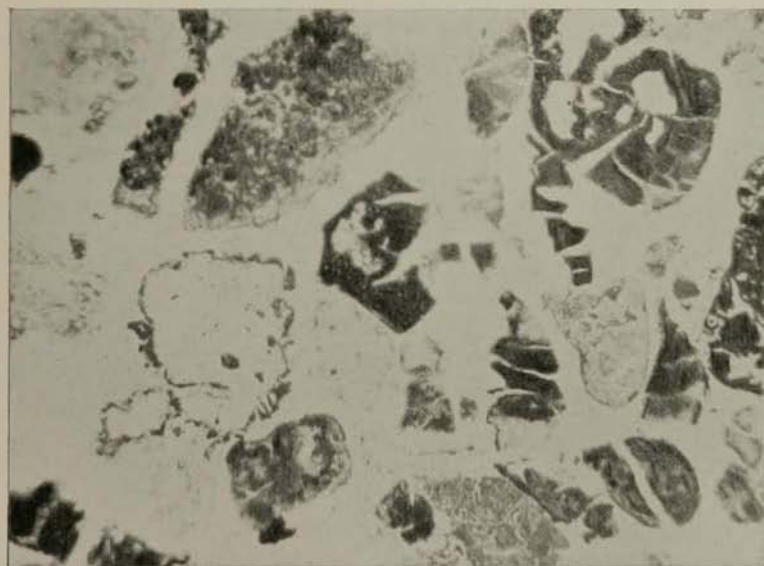
Figure 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

PLATE VI.

Figure 1.

Section 125. From Section 17, T. 58–19. In the ordinary light; magnified 20 diameters. Ground-mass of silica, finely divided phenocrystalline to finely divided cryptocrystalline. The solid dark granules are of green glauconite. The spotted and faintly outlined granules are composed mainly of cryptocrystalline silica, always markedly finer in grain than that of the ground-mass, together with siderite, both uncrystallized and crystallized, and a very small amount of iron oxides, chiefly magnetite. All stages of the formation of these siliceous and fast disappearing granules from the unaltered glauconitic bodies may be seen. In this section also, some of the effects of granular brecciation may be seen.

Figure 2.

Same section as figure 1; magnified 50 diameters. In this section the large dark granule is the same as that seen in the upper left-hand corner of figure 1. This is intended to show the phenomena of the process of decomposition of the glauconite. The solid dark granules are entirely of unaltered glauconite. The granule just above the solid dark granule in the lower left hand corner shows the beginning of decomposition; the large irregular granules in the center show the process well advanced; while in the area in the extreme lower left-hand corner it is almost completed. Note the small rings of silica which characterize the process, which are surrounded by glauconite and enclose a core of the same material.
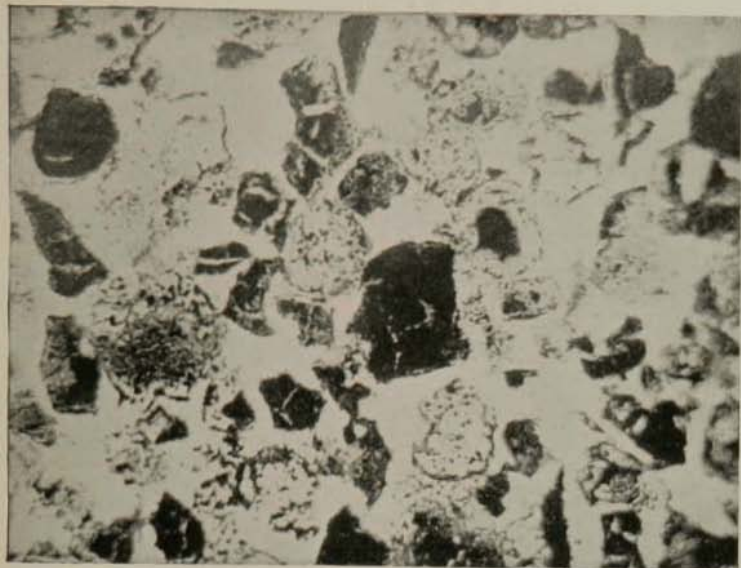
FIGURE 1.
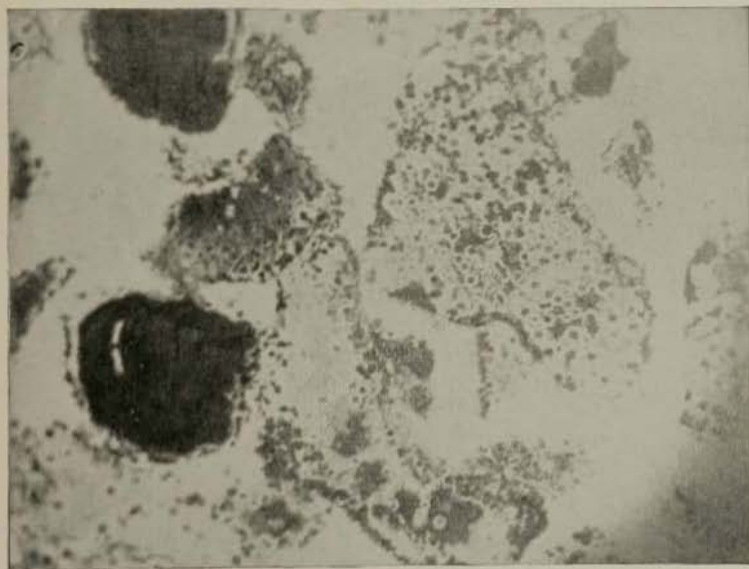
FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

PLATE VII.

Figure 1.

Section 78. From N. W. ¼ S. W. ¼ Sec. 2, T. 58-18. In the ordinary light; magnified 50 diameters. The lighter colored portions of the figure are of very finely divided cryptocrystalline silica. In polarized light the rounded forms of the granules are very distinct, on account of the somewhat finer grain of the silica of which they are made up. Otherwise the granules are characterized in general only by some disseminated iron oxide, which is usually hardly more than a staining, and often is not present at all. The result of the disintegration of the original glauconitic material (small residual fragments of which are still seen in some parts of this section), has been the separation of the silica and the removal of most of the iron. The spotted-granular structure is thus nearly effaced, as is evident from the figure, and the rock approaches the condition of a chert. The scattered iron is beginning to crystallize as siderite, in granules and ground-mass alike. The rock is thus an intermediate stage between the normal spotted-granular rocks and the sideritic cherts. Note the zonal structure of the siderite crystals, showing their growth by successive additions.

Figure 2.

Section 143. From N. E. ¼ N. E. ¼ Sec. 19, T. 58-19. In the ordinary light; magnified 20 diameters. The lighter colored parts of the figure, both in the ground-mass and in the granules, are of very finely divided silica. The dark portions are entirely of iron oxide, mostly magnetite. The iron oxide shows a concentric arrangement which is probably due, in part at least, to concretionary action. The nuclei around which these rings have formed, however, are usually the granules which have been figured and described above. Where the iron has been removed from these they are hardly visible, especially in the ordinary light; such granules may be distinguished in the upper and right hand parts of the figure. No trace of the original glauconitic material remains in this section.
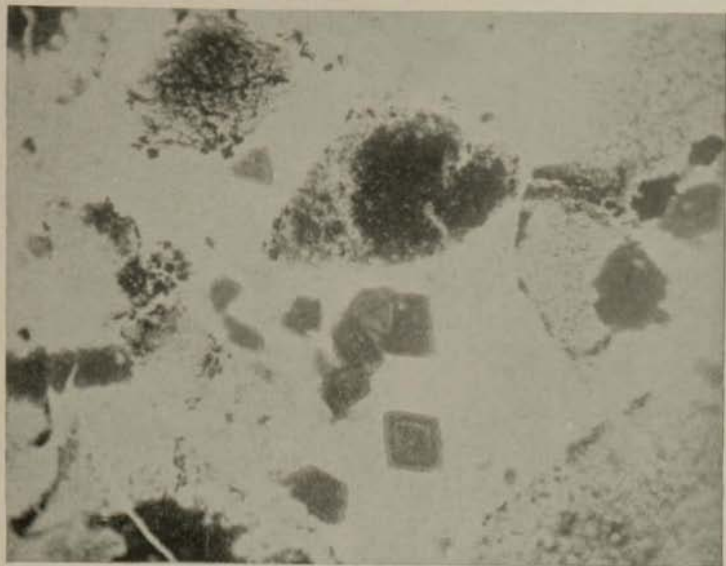
FIGURE 1.
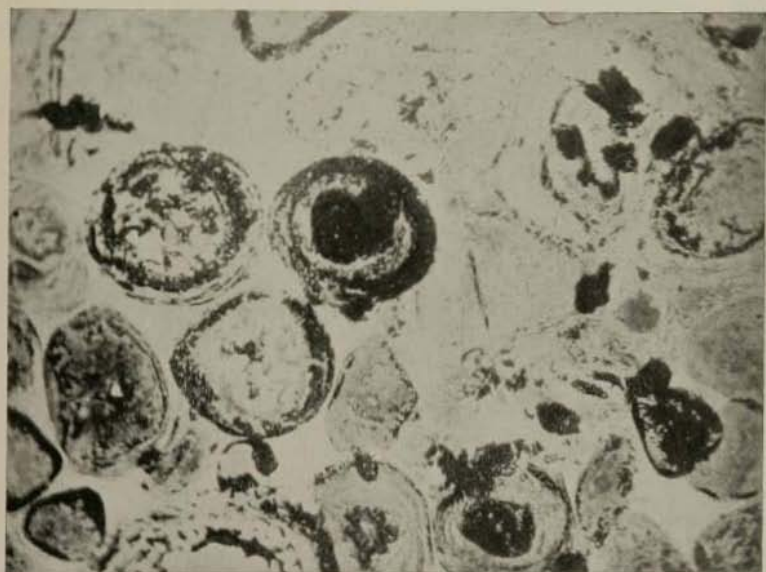
FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS.

PLATE VIII.

Thin Sections from the Iron-bearing Rocks.

Figure 1.

Section 53-1-B. From same specimen as Plate V, figure 1. In the ordinary light; magnified 30 diameters. This is at the beginning of the process of change. The ground-mass is of cryptocrystalline to finely phenocrystalline silica. The dark granules are mainly of the dark-green glauconitic material. There is a good deal of carbonate (mainly calcite or dolomite) scattered through the section. Grains of this, apparently originally detrital may be recognized by their cleavage, in the upper left-hand part of the figure.

Figure 2.

Section 10. From N. W. ¼ N. W. ¼ Sec. 2, T. 58-17. In the ordinary light; magnified 30 diameters. This is near the end of the process of change. The section is composed entirely of silica and magnetite. The silica varies from finely phenocrystalline. In general the original ground-mass cannot be distinguished from the original granular areas; in some cases, however, under crossed nicols, the granules may still be distinguished. The distribution of the magnetite has no relation to the nearly-obliterated granular areas. In this section the decomposition of the original material has been quite completed. The iron, moreover, instead of remaining to mark the position of the granules, as in an earlier stage, has been leached out and has crystallized throughout the rock. In the figure the angular crystal outlines of the magnetite masses may be distinguished.

FIGURE 1.

FIGURE 2.

THIN SECTIONS FROM THE IRON-BEARING ROCKS

PLATE IX.

Figure 1.

Specimen 36. From the Chicago property, in the S. E. ¼ S. E. ¼ Sec. 4, T. 58–16. Slightly reduced from actual size. This rock is in the process of decomposition, and the decay is proceeding from centers scattered throughout the mass, thus giving the peculiar pitted appearance. The pits start around a cluster of iron oxide or carbonate, which has segregated during the stages of dissolution and concentration. From these centers the decay spreads till the whole rock becomes disintegrated.

Figure 2.

Specimen 68. From N. W. ¼ N. W. ¼ Sec. 2, T. 58–18. Slightly reduced from actual size. This is one of the brecciated taconyte jaspers which are common upon the Mesabi. In a dark-gray spotted-granular ground-mass are scattered fragments of finer-grained rock, jasperoid, with a conchoidal fracture. These fragments are usually completely oxidized to a bright red color, although in some cases only the periphery has been oxidized, and the rest of the fragment remains in color gray, like the ground-mass. A large fragment of this sort, with an oxidized border, may be seen in the right-hand part of the figure, just below the specimen number. Under the microscope, the structure of the unaltered fragments is found to be essentially the same as that of the ground-mass. The origin of this breccia is in chemical causes. The rock has been shattered by the discharge of accumulated strains arising from metasomatic changes.
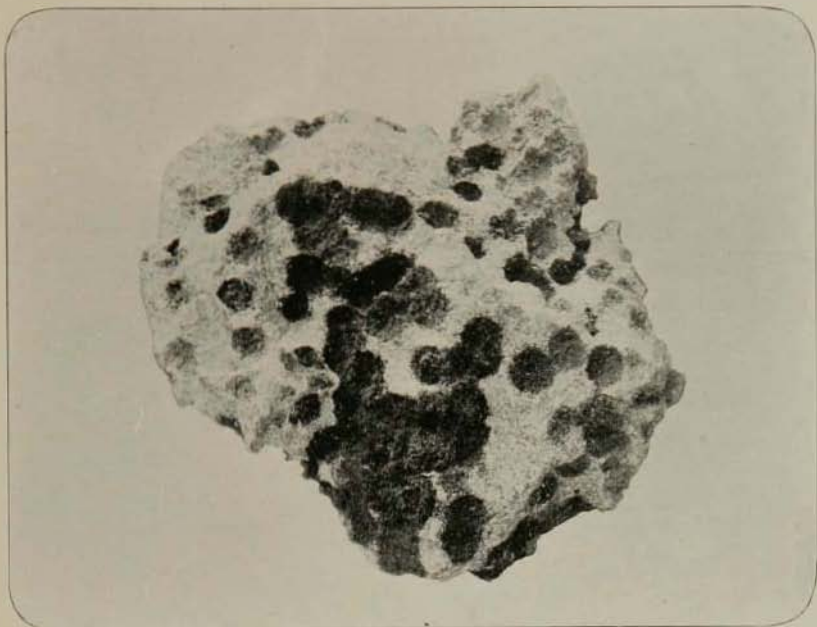
FIGURE 1.
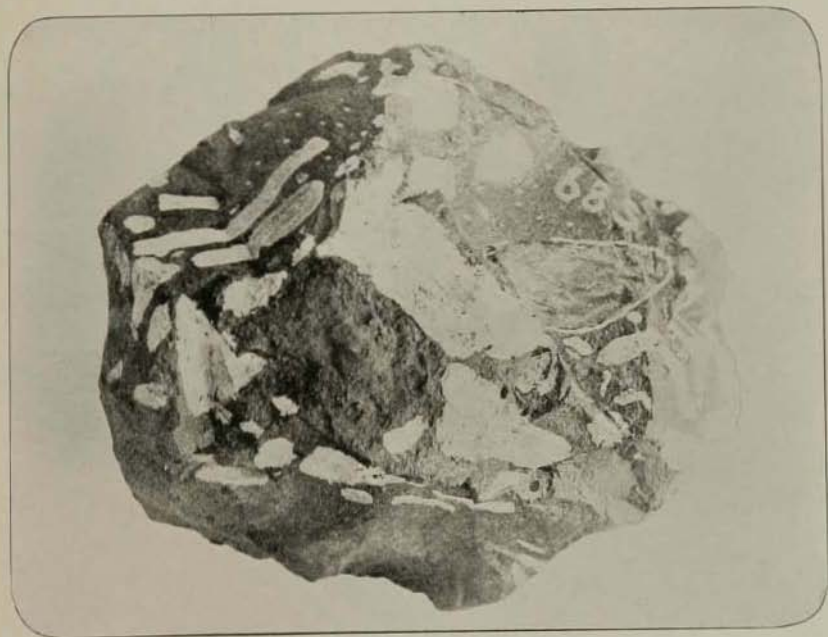
FIGURE 2.

PECULIAR STRUCTURES OF THE IRON-BEARING ROCKS.
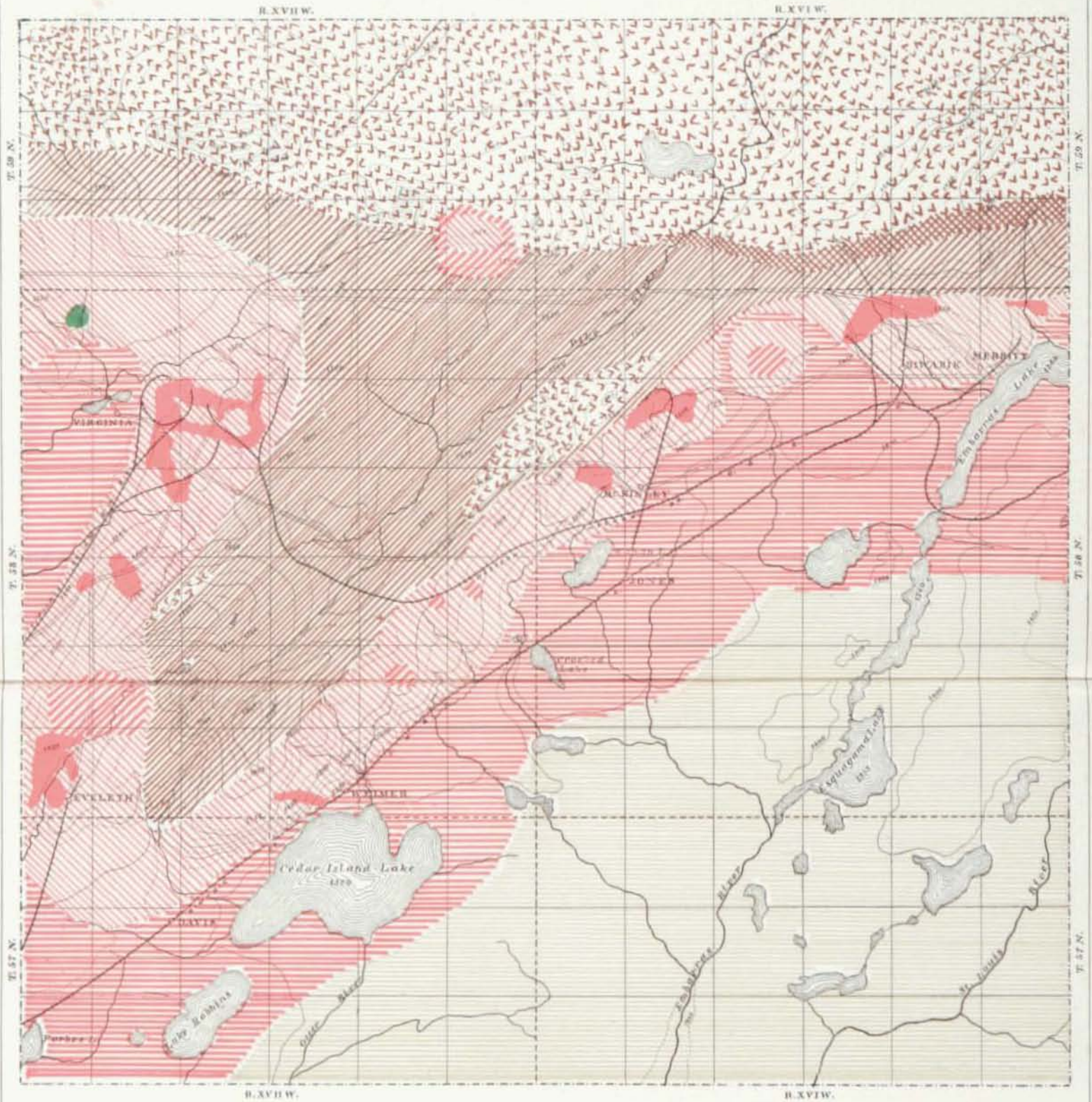
GEOLOGICAL AND NATURAL HISTORY SURVEY OF MINNESOTA.

McKINLEY PLATE OF THE MESABI IRON RANGE,

BY J. E. SPURR.

(DRAUGHTED BY L. A. OGAARD.)

Contour Lines are drawn approximately for each fifty feet above the sea.

EXPLANATION OF COLORS.

GLACIAL DRIFT.		CRETACEOUS.	TACONIC (ANIMIKIE.)				ONTARIAN.		
Concealing other formations. Till	Modified.	Conglomerates and shales.	Black Slates.	Iron Bearing Member, Barren Rock. Ore-bodies		Quartzite.	Post-Keewatin. Granite (Intrusive.)	Keewatin & Coutchiching* Green, sericitic schists.	Hornblende and Mica schists.

*The Coutchiching is a lithological modification of rock whose age is to be considered the same as the Keewatin.
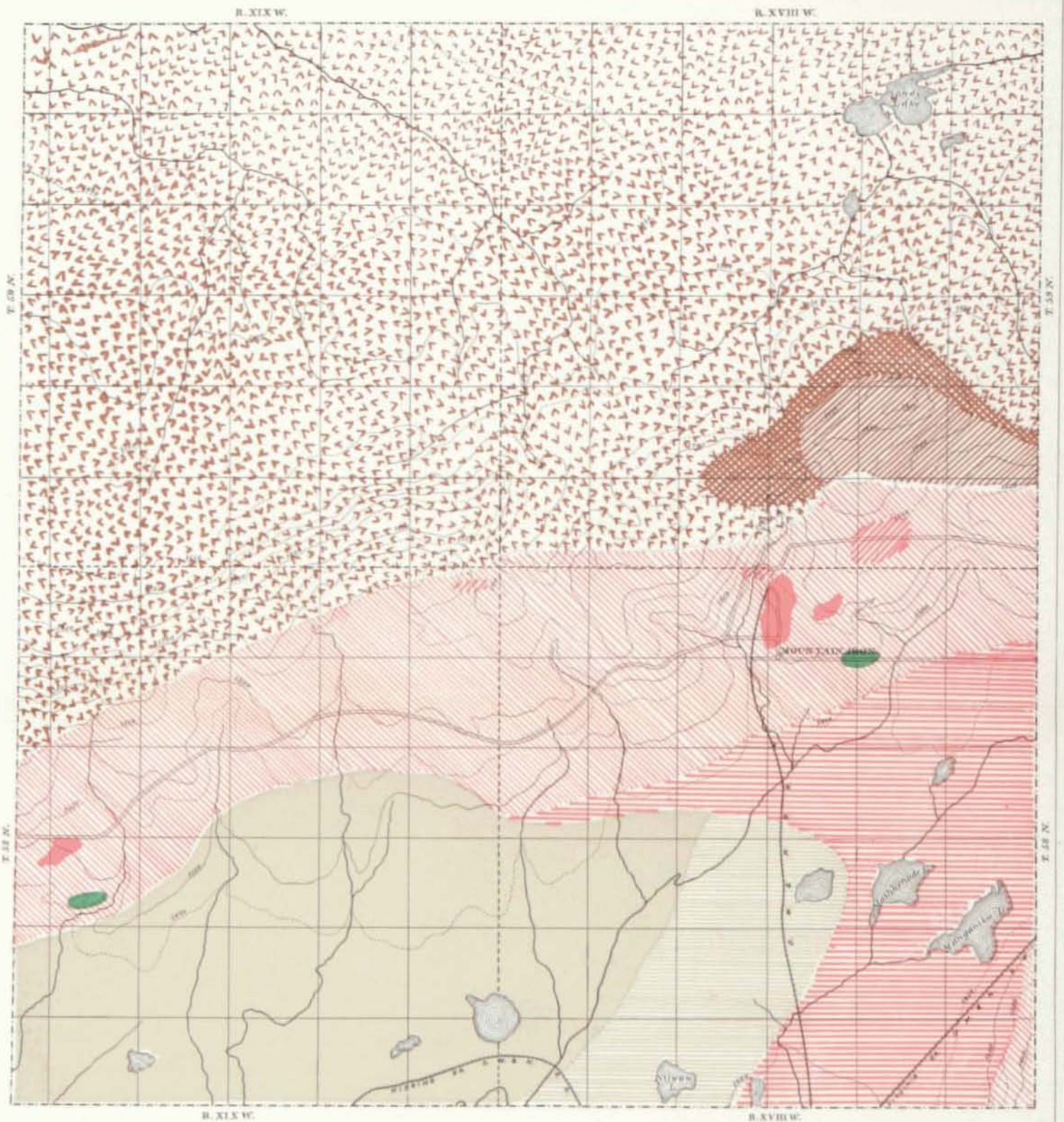
GEOLOGICAL AND NATURAL HISTORY SURVEY OF MINNESOTA.

MOUNTAIN IRON PLATE OF THE MESABI IRON RANGE,

BY J. E. SPURR.

(DRAUGHTED BY L. A. OGAARD.)

Contour Lines are drawn approximately for each fifty feet above the sea.

EXPLANATION OF COLORS.

GLACIAL DRIFT.		CRETACEOUS.	TACONIC (ANIMIKIE)				OSTARIAN.		
Concealing other formations. Till.	Modified.	Conglomerates and shales.	Black Slates.	Iron Bearing Member. Barren Rock. Ore-bodies		Quartzyte.	Post-Keewatin. Granite (Intrusive).	Keewatin & Coutchiching* Green, sericitic schists.	Hornblende and Mica schists.

* The Coutchiching is a lithological modification of rock whose age is to be considered the same as the Keewatin.

GEOLOGICAL AND NATURAL HISTORY SURVEY OF MINNESOTA.

HIBBING PLATE OF THE MESABI IRON RANGE,

BY J. E. SPURR.

Contour Lines are drawn approximately } for each fifty feet above the sea. }

EXPLANATION OF COLORS.

GLACIAL DRIFT.	CRETACEOUS.	TACONIC (ANIMIKIE)				ONTARIAN.		
Concealing other formations. Till. / Modified.	Conglomerates and shales.	Black Slates.	Iron Bearing Member. Barren Rock. / Ore-bodies.		Quartzyte.	Post-Keewatin. Granite (Intrusive).	Keewatin & Coutchiching Green, sericitic schists.	Hornblende and Mica schists

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